

## Anonymous Referee #1

The paper addresses the magnitude and direction of surface currents under the presence of strong wind forcing, assessed using drogued and undrogued surface drifters. Given the large uncertainties of today's theoretical and numerical models with respect to surface currents and their vertical variation, this is an urgent topic. The presented study uses an extensive data set in a dynamic interesting setting, and provides results that can serve as exemplary quantification of surface currents under strong wind forcing. The work therefore has a potential to become a useful reference for such dynamics. There are a few shortcomings in the analysis and the presentation of the work, requiring major revision before the work should be published.

*We would like to thank Referee #1 for his or her constructive feedback on the manuscript*

A potential flaw in the analysis lies in the determination of a pre-existing circulation field that is supposed to be constant throughout the remainder of the experiment. As justification, the authors refer to very general descriptions of circulation in the region and to a sudden increase in wind-speed, but Fig. 2 rather shows that there is a steady increase of winds over one day. In addition, any pre-existing current is subject to further development and changes typically occur within one inertial period. For example, previous wind or buoyancy forcing events could have set up near-inertial oscillations that continue to change throughout the next wind event. This has to be addressed in a revised paper, potentially involving another method to identify background currents that are allowed to be time-variable. A snapshot at one arbitrary time step is not convincing enough, even if subtraction of that current field helps to collapse scatter in wind-versus current comparison.

*We have adapted the figure showing the LAVA estimates (fig. 3 in original version) into 2 new figures (Figs. 6-7) showing the addition of AVISO SST maps plotted beneath the velocity fields. SST maps from AVISO are created every 24-hours centered on the 0<sup>th</sup> hour of each day. Two SST maps are shown with identical LAVA estimates to show that during and even after the window of analysis under high winds, the structures seen in the velocity fields appear consistent with AVISO observations throughout each high wind event. The SST maps show structures that are qualitatively similar to the velocity fields created with LAVA, even over the 24-hour product created after our analysis period.*

*Descriptions of these figures (6-7) and their implications can be found on:*

*Page 10, lines 12-28*

*Page 12, lines 9-23*

*Page 16, lines 17-24*

A second shortcoming of the study that is straightforward to address is the structure and organisation of the paper. Introductory material, methods, result and discussion is often mixed up

in the paper and it would help to re-organize or re-write some parts. For example, A description of the applied method is given in the first paragraph of the introduction, which should be given in section 3 or in the abstract. Some background information and literature reviews are given in later parts of the paper, that should have better fitted in the introduction, e.g. page 5 line 5-24 and page 13 line 19-31. In the second-last paragraph of the introduction, results are given. A major part of the results is provided in the discussion section. These jumps in the paper make it very difficult to read. At the same time, a lot of needless redundancies are made, suggesting that the paper could be shortened and sharpened to some extent.

*Some of the paper has been reorganized based on the reviewer's suggestions.*

*The first paragraph of the introduction has been combined with a later paragraph of the introduction in order to reduce redundancy. (Page 3, lines 15-26).*

*The background information on Page 5 line 5-24, of the previous version of the paper, pertain specifically to the drifters used in this study, therefore the authors feel it appropriate to leave this description under the section titled 2.1 CARTE drifter.*

*The authors also feel it appropriate to leave the description on what was formerly Page 13 line 19-31 in the previous version of the paper as is, as it acts a review of the significant body of work available on the topic. This lines act to help the reader remember specific details from the studies, we wish to reiterate in comparison to our results.*

*In the second to last paragraph no change was made. A brief description of the outcome from the subtraction of the regional circulation estimate, as well as a reference to a previous study, is presented to act as motivation for the method proposed.*

*Two paragraphs from the discussion section were moved to the results section, as requested by reviewer. They now reside on Pages 13, line 28 – page 14, line 11. As a result of this edit, we also rewrote part of the discussion, seen on page 15, lines 1-6.*

*Attempts were made to reduce redundancies in the discussion section, with the omission of Page 12, lines 2-6, in the original version.*

Specific comments:

- A motivation for the study should be given in the abstract. I first realized what the overall motive was when I read the discussion.

*We have added more on motivation to the abstract.*

*Page 1. Lines 9-10.*

- Page 2 line 17-21. Beside CODE and SVP drifters, undrogued SVP's and co-called iSpheres, and bamboo plates have been used to measure currents at the very surface.

*These other types of drifters are mentioned elsewhere in the paper. This point was made to show other studies have missed the vertical shear in the top 1m.*

- Page 2 line 22: It is quite possible to measure surface currents using ADCPs, for example using Nortek's Signature 1000 ADCP.

*To our knowledge it is very difficult to measure surface currents at shallow depths, less than ~0.5m, in the presence of surface gravity waves due to side lobe contamination caused by the surface wave motion (Cole and Symonds 2015).*

*Cole, R., & Symonds, D.: A 25 year collaboration using ADCPs. In 2015 IEEE/OES 11th Current, Waves and Turbulence Measurement Workshop, St. Petersburg, FL, USA, March 2015, 1–10, 2015.*

- Page 3 line 9-1 and page 15, line 12-15: The authors claim novelty with regard to estimating vertical shear between the 0-5cm and 0-60cm layers. Notice that the difference between undrogued drifters and drifters with drogue at ~1m depth has been quantified in Röhrs, J. & Christensen, K. H. Drift in the uppermost part of the ocean. Geophys. Res. Lett. 42, 1–8 (2015), and in Morey, S. L., Wienders, N., Dukhovskoy, D. S. & Bourassa, M. A. Measurement Characteristics of Near-Surface Currents from Ultra-Thin Drifters, Drogued Drifters, and HF Radar. Remote Sens.-Basel 10, 1633 (2018).

*These references have been noted and added to the manuscript and claims of novelty have been revised.*

*Page 2, lines 24-29*

*Page 3, lines 3-10 and lines 23-26*

*Page 15, lines 24-27*

*Page 16, lines 3-9*

*Page 17, lines 18-31*

*Page 18, line 23*

- page 9, line 1-8 should be re-written

*lines have been rewritten in addition to extra explanation*

*Page 10, line 2 – Page 11, line 6.*

- Possible windage of the used surface drifters should be addressed.

*The exact windage on the drifters, especially for the undrogued drifter in the real ocean is not known to an extent in which we can apply a meaning correction. We have tried to be as transparent and straight forward to the extent to which possible errors pertaining to windage are expected.*

*Page 17, lines 24-26 and lines 10-13*

*Page 6, lines 7-10.*

## **Anonymous Referee #2**

*We would also like to thank Referee #2 for his or her time and insight to the current manuscript*

The paper by Lodise et al concerns the behavior of undrogued and drogued so-called CARTE drifters. I agree with Ref #1 that lack of structure is a major problem in this paper, it is surprisingly hard to follow the authors as they describe their methods and present their results. A few recent papers are lacking, although Ref #1 mentions that as well.

*References mentioned by Ref 1 have been added.*

*Page 2, lines 24-29*

*Page 3, lines 3-10*

*Page 15, lines 24-27*

*Page 16, lines 3-9*

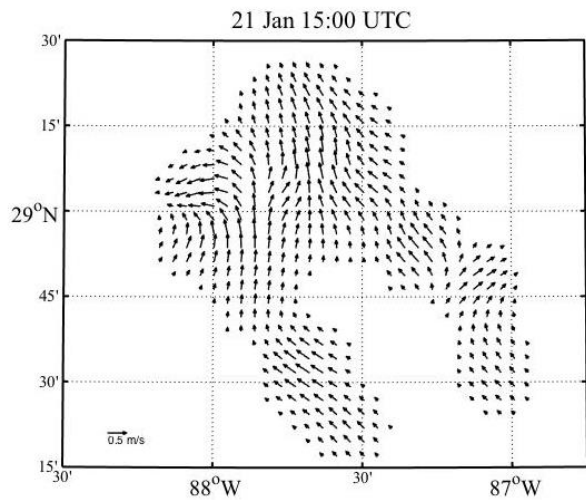
*Page 18, line 23*

What concerns me the most is the mix of tools used here in combination with a lack of uncertainty estimates: A coupled atmosphere-wave-ocean modeling system is used to provide the physical quantities needed to analyse the drift, but instead of using the ocean model results for the vaguely defined "pre-existing" circulation, the drifter trajectories are used to provide ocean circulation estimates that are later used in the analysis of the drifters themselves. Even though one can argue that the circulation estimates are independent of the drifter observations from the "high wind" periods later on, I still wonder how representative this "pre-existing circulation" is and feel uncomfortable about this circular use of the drifter data. Why discard the ocean model component entirely? Isn't the upper layer in the model even representative of the background circulation? If not, what is the point of the ocean coupling? And surely there are other ocean models that could be used, at least for comparison to the LAVA results?

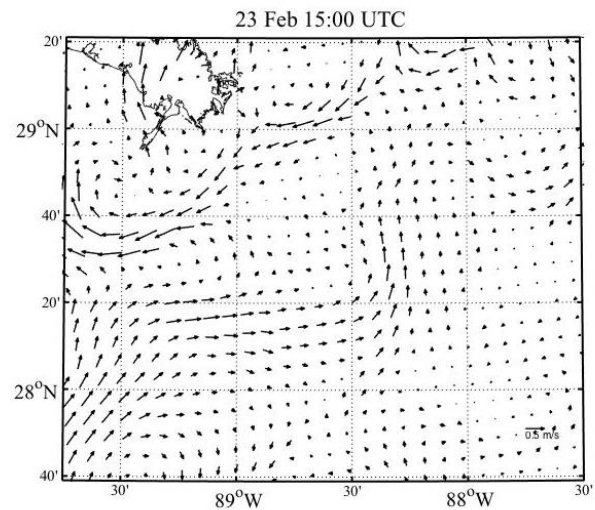
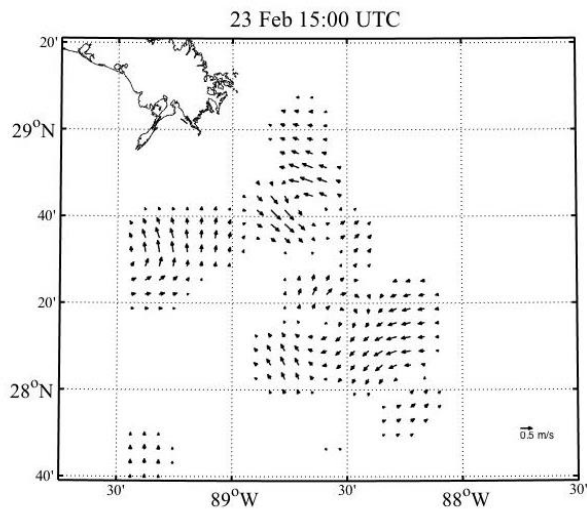
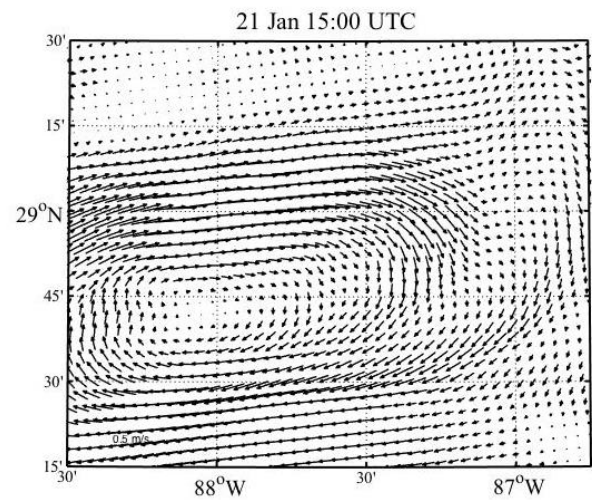
*When compared to the LAVA velocity fields created using the CARTHE drifters, the surface velocity fields from the ocean circulation component of the UWIN-CM, qualitatively, do not agree (shown in the figure here). At the scales sampled by the drifters in this study, it becomes very difficult to model ocean circulation due to the lack of data to serve as initial conditions, especially in an area rich in frontal activity such as this. This has been tested in a number of previous papers (e.g. Chang et al., 2011; Taillandier et al., 2008), where drifter based LAVA fields were compared to model outputs and used to improve model performances. The drifters themselves would serve as the best validation for any ocean circulation model, therefore using the drifter data itself to come up with estimates of the regional circulation is expected to be more accurate.*

*The model runs were performed during the LASER experiment not only to be used as a data set for later analysis, but also for operational procedures of the experiment itself. Even though the ocean circulation model doesn't seem to be representative of reality in this region, the wind and wave data from the other 2 model components perform well when compared to observational data.*

*LAVA Drogued Velocity Field*



*UWIN-CM Ocean Circulation at 0.5 m*



**REFERENCES:**

- Chang, Y., D. Hammond, A. Haza, P. Hogan, H.S. Huntley, A.D. Kirwan, Jr, B.L. Lipphardt, Jr., V. Taillandier, A. Griffa, T.M. Ozgokmen, 2011. Enhanced Estimation of Sonobuoy Trajectories by Velocity Reconstruction With Near-Surface Drifters. *Oc. Modelling*, 36, 179-197
- Taillandier, A. Griffa, P.M. Poulain, R. Signell, J. Chiggiato, S. Carniel, 2008. Variational analysis of drifter positions and model outputs for the reconstruction of surface currents in the Central Adriatic during fall 2002. *J. Geophys. Res.*, 113, C04004, doi.1029/2007/JC004148

The model coupling will also need to be better described: How is the coupling implemented? Are wave-dependent air-sea momentum fluxes part of the coupling (both to atmosphere and ocean) for instance? It is precisely in situations with rapidly changing weather conditions that these couplings become important (see Rohrs et al., Ocean Dyn., 2012, for estimates of wave dependent fluxes from directional wave rider data and an analysis of upper ocean drift relevant to the paper under review).

*The coupling implementation has been described in the manuscript.*

*Page 7, lines 1-6*

Although it appears to be a good idea to split the upper ocean drift velocity into "wave", "wind" and "background" components, it really depends on the ability to delineate them, and I'm not entirely convinced in this case. The CARTHE drifters are influenced by the Stokes drift, how much of the LAVA circulation estimates still contain some Stokes drift despite making model based corrections etc.?

*The average Stokes drift during the selected hours over which the pre-existing circulation has been estimated using LAVA is 0.02 m/s and 0.04 m/s for the drogued and undrogued drifter cases, respectively. Due to the velocity spreading and averaging performed by LAVA, the uncertainty which arises from the Stokes drift component is small during these time periods.*

*Page 10, lines 21-28*

I'm not sure what the authors should do to present a more convincing case, but I would at least need to see a much clearer presentation with more emphasis on the various potential sources of error in the estimates. Alternatives to the LAVA circulation estimates should definitely be considered (and compared to the LAVA estimates). This work would constitute a major revision of the current manuscript.

*In addition, we have added 2 new figures (Figs 6 and 7) to make a more convincing case that the LAVA velocity fields are fair estimates of the pre-existing circulation by plotting the velocity fields on top of 2 consecutive 24-hour averages of SST data from AVISO. The first 24-hour averages for the SST span the time periods over which the high wind analysis windows are defined, where the second 24-hour periods, span the 24-hours*

*following the high wind event. The structures seen in the SST fields line up very well with the LAVA velocity estimates of the pre-existing circulation and the second 24-hour period of SST shows qualitatively how much these structures changed during the high wind event. With these figures, we've hoped to have further convinced the reader that the estimates for the pre-existing regional circulation are adequate for our velocity deconstruction.*

*Descriptions of these figures (6-7) and their implications can be found on:*

*Page 10, lines 12-28*

*Page 12, lines 9-23*

*Page 16, lines 17-24*

Some minor comments:

Eq. (1) isn't an average, " $1/h$ " is lacking.

*You are correct. Thank you, the change has been made.*

*Page 3, line 31*

A short description of the typical hydrographic structure of the upper ocean in the region (mixed layer depths, buoyancy frequencies, salinity/temperature profiles etc.) would be nice.

*A short description as well as a new figure (Fig. 2) has been added to describe the typical stratification and mixed layer depth in terms of temperature, salinity and potential density, in the presence of a typical frontal feature observed during the experiment.*

*Page 7, lines 22-31.*

Please add some info about the spectral resolution in the wave model as well. Eq. (2) is not correct for a model with the limit at infinity, there is a cutoff frequency, and presumably a specific shape of the spectrum is assumed.

*Proper limits for the wavenumber have been assigned in Eq. (2), and concerns about the spectral resolution have been addressed.*

*Page 6, lines 21-25*

**Fabrice Ardhuin (Referee)**



ardhuin@ifremer.fr Received and published: 3 May 2019

General comments: This paper presents very interesting data on near-surface drifter velocities that are interpreted in terms of near surface currents. This interpretation probably requires a clearer explanation of how the drifter velocity related to the surrounding water motion. I strongly encourage the authors to clarify this and resubmit their paper.

*We would like to thank Dr. Ardhuin for his constructive review of the current work.*

Specific comments:

1. The author write about "surface current" when they actually mean "drifter motion". The distinction is important as the drifter without the drogue will move due to the direct effect of the wind and of the waves, in addition to that of the current. In Novelli et al. (2017), the undrogued drifter moves at a speed that is significantly larger than the surface current (their figures 10 and 11), of the order of 10 cm/s for 10 m/s wind. However, it is unclear how this difference scales to the open ocean with very different wave ages and vertical mixing: this cannot scale with the Stokes drift (the Stokes drift in the lab is under 0.5% of the wind speed... ). It is very unclear how the difference between water and drifter motion is estimate or corrected.

*We agree that it is very difficult to determine how the wave action and especially the wind will affect the movement of the undrogued drifters during the conditions being analyzed here. For this reason, we do not make any correction of the drifter velocity, but choose to leave the manner in which we describe the "surface currents" unchanged. We believe it makes sense to describe the drifter velocities as the average current over the draft depth of the drifter, given the definition portrayed in Eq. (1). We have tried to be more precise in our description of the surface current estimate and the errors associated with the drifter movement due to velocity slip.*

*Page 6, lines 7-10.*

*Page 17, lines 24-26 and lines 10-13*

2. The idea of a "purely wind-driven current" should be clarified, in particular how the time varying wind produces a time-varying current, including a phase shift in time. On page 9, line 9, I guess there is some wind influence already in the "pre-existing regional circulation,  $u_{rc}$ "

*Effect of wind and waves on drifters during the low wind period over which the regional circulation estimates have been described in section 3.2, along with new Figures showing*

*SST for validation (Figs. 6-7).*

*Page 10, lines 21-29*

*Response time of surface currents has also been addressed with supporting literature.*

*Page 11, lines 1-5*

3. There is not a single mention of density, temperature or salinity in the paper. It is expected that the surface response to the wind is very sensitive to the stratification (slippery layers, e.g. Kudryavtsev et al. JPO 1990). So that the present data is impossible to interpret without that information in the context of the wider literature.

*A new figure (Fig. 2) has been added to show a typical transects of salinity, temperature, and potential density across a frontal zone in the region measured during the experiment, however not during one of the high wind periods. Fronts like this one were frequently measured during this experiment showing transects very similar to the one shown in Fig. 2.*

*Page 7, lines 22-31.*

*Effects of stratification have also been referenced in Introduction*

*Page 3, lines 10-14.*

4. Numerical models or parameterizations of waves primarily design to get wave heights can disagree a lot on the short wave purely wind-driven current components that contribute to the Stokes drift (e.g. Peureux et al. 2008). Hence it would be good to show a specific model validation on the wave spectrum in the 1 m to 40 m wavelengths regime that dominates the Stokes drift.

*We've added a new Figure (Fig. 4) to the manuscript to provide wave validation with available observations from the model during one of the high wind events, showing significant wave height, mean wave direction, wavelength, and mean wave period. With only hourly averages from NDBC buoy 42040 to compare to the model too, we felt this figure was more appropriate than trying to calculate wave spectrum from hourly averaged data.*

*Page 8, lines 11-19*

Technical corrections:

- Page 1: line 28: replace CARHTE with CARTHE

*We have replaced this. Thank you*

- in the paragraph "Observational data that captures the vertical shear within the first meter of wind-driven surface currents is very limited in the real ocean as well" the authors could reference some important work (Santala & Terray 1992)

*We have cited Santala and Terray (1992)*

*Page 2, lines 13-15*

- Page 2, line 28: "twice as fast as the average current over the first 1m and four times as fast" is misleading as a casual reader could think that over a 2 m/s Gulf Stream he would also have a 2 m/s wind shear. Please give a velocity difference in cm/s and / or scale it with the wind speed. Please also note that these shears should be mixed by wave breaking and should thus be much smaller in the open ocean than in the lab or in coastal areas / weak winds. As a result, lab studies are largely irrelevant for the open ocean. In that respect, Sutherland et al. (2016) is a relevant reference.

*A reference velocity has been provided in regard to this description of the vertical velocity shear. A note about breaking waves and mixing in regard to decreased velocity shear has also been referenced, citing Sutherland et al. 2016*

*Page 2, line 24*

*Page 17, lines 22-26*

Page 2: line 31. Classical Ekman theory stricto sensu (in particular the 45° !) does not apply to the real ocean. Please consider at least realistic mixing (Madsen 1977 or Raschle et al. 2009 are better).

*Raschle et al. 2009 has been described and cited.*

*Page 3, Lines 13-14*

Page 2: line 24: 0.5 m is optimistic

*0.5 m was the value from references listed.*

Page 3, line 5: "anywhere from 0.4 % to 5 %" is not a scientific statement. The uncertainty is much less than this range, as most of the variability in horizontally homogeneous conditions is known function of the wind speed and stratification (Ardhuin et al. 2009). Besides, I did not find

in Berta et al. a clear number on a "wind-only" component.

*This range of findings for the wind-driven current is based off the range of results reported by the different studies cited. The lines were edited for clarity. Berta et al. 2018 states their ageostrophic component, which is dominated by the wind, travels at ~2 % of the wind speed.*

*Page 3, lines 7-8*

Page 4, line 31: please replace "current" with "drifter velocity"

*We would like to keep the present convention of referring to the drifter velocities as measurements of the surface currents themselves, with potential errors described.*

Page 5, line 9: The acceleration is not just due to Stokes drift as shown in Novelli et al. (Stokes drift at low wind is under 1% of wind speed).

*We were referring to lab experiments where there was no wind influence. This point has been clarified in the text.*

*Page 5, line 22*

Page 5: lines 16-19: I would not expect that separation changes so much the mean wind speed in the ocean over the near-surface 10 cm. The radiation stress of the short waves dissipated / reflected by the object can be relevant, see Longuet-Higgins 1977.

*The mechanics of radiation stress on the effect of the drifters is non-trivial to diagnose, and is thus beyond the scope of this paper.*

Page 5: Given the very different wave age in the lab and in the field, it is not clear at all that the "velocity slip" in the lab can be scaled to the field conditions.

*We agree it probably cannot, which is why we choose not to perform a velocity correction to the measured drifter velocities.*

Page 6: Please show / give reference to proper validation of wave model in terms of Stokes drift.

*Wave model validation provided in Fig. 4*

*Page 8, lines 11-19*

Page 10 line 4-5: please be more specific and replace "wind-driven velocities" by "wind driven drifter velocities"

*Again, we would like to keep the present convention of referring to the drifter velocities as measurements of the surface currents themselves, with potential errors described.*

Page 12, line 31: "possibly the most significant" is a pretty bold comment given the history of the field (Munk 2002). I would contend that stratification is the elephant in the room here.

*Paragraphs have been edited with the stratification mentioned as well.*

*Page 15, line 15.*

Page 13: Please do not use the word "current" unless you are properly explaining how you go from drifter velocity to water velocity.

*We refer to the drifter velocities as measurements of the surface currents themselves, with potential errors described.*

Page 13, line 22: please clarify if that includes the Stokes drift or not. Also, it should be important to discuss the effect of proximity to coast as the wind-driven current are rectified by the shoreline in many datasets.

*Clarification of the inclusion of stokes drift and effect of shoreline rectification has been made.*

*Page 16, lines 4-9*

Page 15, line 1: "The momentum input from large breaking waves into the surface currents" what about rather, "the momentum input and surfing behaviour of undrogued drifters in large breaking waves"

*Statement has been changed to include this phenomenon.*

*Page 10-13*

Page 15 line 11: " twice as fast " does not make much sense, please provide some scale (wind, Stokes drift ...) you do not expect to go twice as fast in the top meter above a 2 m/s Gulf Stream. Also please discuss stratification.

*Absolutely velocity measurements have been provided.*

*Page 17, lines 22-25*

# Vertical Structure of Ocean Surface Currents Under High Winds from Massive Arrays of Drifters

John Lodise<sup>1</sup>, Tamay Özgökmen<sup>1</sup>, Annalisa Griffa<sup>2</sup>, Maristella Berta<sup>2</sup>

<sup>1</sup>RSMAS, University of Miami, Miami, FL, 33149, USA

<sup>2</sup>CNR-ISMAR, Lerici, Italy

Correspondence to: John Lodise (jlodise@rsmas.miami.edu)

**Abstract.** Very near surface ocean currents are dominated by wind and wave forcing and have large impacts on the transport of buoyant materials in the ocean. Surface currents, however, are under resolved in most operational ocean models due to the difficulty of measuring ocean currents close to, or directly at, the air-sea interface, with many modern instrumentations. Here, observations of ocean currents at two depths within the first meter of the surface are made utilizing trajectory data from both drogued and undrogued CARTE drifters, which have draft depths of 60 cm and 5 cm, respectively. Trajectory data of dense, co-located drogued and undrogued drifters, were collected during the LAGRangian Submesoscale Experiment (LASER) that took place from January to March of 2016 in the Northern Gulf of Mexico. Examination of the drifter velocities reveals that the surface currents become strongly wind- and wave-driven during periods of high wind, with the pre-existing regional circulation having a smaller, but non-negligible, influence on the total surface velocity. During these high wind events, we deconstruct the full surface current velocities captured by each drifter type into their wind- and wave-driven components after subtracting an estimate for the regional circulation which pre-exists each wind event. In order to capture the regional circulation in the absence of strong wind and wave forcing, a Lagrangian variational method is used to create hourly velocity fields for both drifter types separately, during the hours preceding each high wind event. Synoptic wind and wave output data from the Unified Wave Interface-Coupled Model (UWIN-CM), a fully coupled atmosphere, wave and ocean circulation model, are used for analysis. The wind-driven component of the surface current exhibits a rotation to the right with depth between the two surface layers measured. We find that the averaged wind-driven surface current from 0-5 cm (0-60 cm) travels at ~3.4-6.0 % (~2.3-4.1 %) of the wind speed, and is deflected ~5°-55° (~30-85°) to the right of the wind, reaching higher deflection angles at higher wind speeds. Results provide new insight to the vertical shear present in wind-driven surface currents under high winds, which have vital implications for any surface transport problem.

## 1. Introduction

Very near surface currents are especially sensitive to wind and wave forcing, which dominate the dynamics in the upper few centimeters of the ocean (Wu, 1983). Plastics at the surface have been observed to be transported to our coasts by wind- and wave-induced currents and can be transported differentially depending on their buoyancy, which dictates their

Deleted: , but

Deleted: have proved

Deleted: to

Deleted: e

Deleted:

**Deleted:** We use drogued and undrogued CARTE drifters, having draft depths of 60 cm and 5 cm, respectively (Novelli et al., 2017), in order to measure the average very near surface currents in the Northern Gulf of Mexico. The data used for analysis were collected during the LAGRangian Submesoscale Experiment (LASER), a campaign in which over 1000 biodegradable CARTE drifters were deployed during the winter of 2016 (Haza et al., 2018). Utilizing a subset of the CARTE drifters from the experiment, we focus on three synoptic scale, high wind events during which, wind and waves seem to dominate the forcing of the surface flows measured by both drifter types. The velocities of both drifter types are calculated along the drifter trajectories during periods of increasing winds. During these high wind events, we deconstruct the full surface current velocities captured by each drifter type into their wind- and wave-driven components after subtracting an estimate for the regional circulation which pre-exists each wind event. We then report on the vertical shear of the wind-driven component of the surface current between the two surface layers measured.

positioning in the upper water column (Isobe et al., 2014). Through numerical modeling, Le Hénaff et al. (2012) found that wind- and wave-induced currents had a strong impact on the fate of surface oil during the Deepwater Horizon oil spill in 2010. Another modeling study showed that in extreme events like hurricanes, Stokes drift, or the forward velocity induced by the depth decaying orbital motion of waves (Stokes, 1847), plays a major role in accurately predicting the movement of Lagrangian particles at the surface (Curcic et al., 2016). Despite the drastic impact on the dispersal of buoyant pollutants, wind- and wave-driven dynamics in the upper few centimeters are poorly understood and not resolved in modern operational ocean models, which have used a wide range of parameterizations of wind-driven dynamics over relatively deep surface layers, forced with climatological winds (Chassignet et al., 2003; Chassignet et al., 2007).

Observational data that captures the vertical shear within the first meter of wind-driven surface currents is very limited in the real ocean as well. This is mainly due to the limitations of the instrumentation used to gather this physical data. The majority of Lagrangian drifter studies have used classic drifter designs (e.g. CODE (Davis, 1985) and SVP drifters (Lumpkin and Pazos, 2007)) that span depths ranging from 1–30 m (Lumpkin et al., 2017), and are therefore unrepresentative of the wind forced current at the very surface. Santala and Terray (1992) describe the difficulty in measuring surface velocities, as well as near surface shear, due to wave bias present when utilizing any instrumentation whose motion is dependent on wave action. Acoustic Doppler Current Profilers (ADCP's) are not able to accurately measure velocities near an undulating boundary, making it difficult to sample surface layers above depths of 0.5 m (Cole and Symonds, 2015; Sentchev et al., 2017). High Frequency (HF) radars are known to measure vertically integrated surface currents, with about 80 % of the radar signal originating in the upper 1 m, depending on the electromagnetic wavelength of the radar, such that vertical shear within this depth is not detectable in the measurement (Stewart and Joy, 1974; Röhrs et al., 2015).

Using a novelty suite of instruments in the Gulf of Mexico, Laxague et al. (2017) observed wind- and wave-induced surface currents within 1 cm of the surface, under low winds ( $U_{10} = 4 \text{ m s}^{-1}$ ), to be twice as fast as the average current over the first 1 m and four times as fast as the average current over the upper 10 m (the upper 10 m average being equal to  $\sim 0.16 \text{ m s}^{-1}$ ). Another study using drifters of multiple draft depths and HF radar data led to a similar result, showing that HF radar velocity measurements taken at  $\sim 2\text{-}3 \text{ m}$  depth, were on average, only 55.7 % of that measured with ultra-thin drifters with 5 cm draft depths, whose absolute velocity was on the order of  $0.3 \text{ m s}^{-1}$  (Morey et al., 2018). Comparison of surface velocities measured with ultra-thin drifters of 5 cm and 10 cm drafts depths also showed a rapid decay of velocity away from the surface, with the 10 cm drifters traveling 10 % slower on average (Morey et al., 2018). The sharp change in wind- and wave- induced velocities observed in these two studies reveal the need for increased vertical resolution of these surface measurements (Laxague et al., 2017; Morey et al., 2018).

Classical Ekman theory states that wind-driven currents at the very surface travel at a deflection angle of  $45^\circ$  to the right of the wind in the northern hemisphere, when one assumes a balance between Coriolis and friction under stationary, homogeneous conditions (Ekman, 1905). Laboratory studies have shown that total surface drift currents induced by wind and

Deleted: .

Deleted: er

Deleted: ,

Deleted:

Deleted: ing



waves combined, travel at  $\sim 3.1\%$  of the wind velocity, with the wind-induced drift decreasing and the wave-induced drift increasing, with increasing fetch (Wu, 1983). Various observational studies on wind-driven currents over the upper  $\sim 1$  m of the surface, which utilized a range of different instruments including HF radars, ADCPs, and drifters of various types ( i.e. CODE, iSphere or undrogued SVP drifters) have reported a wide range of deflection angles ranging from  $15^\circ$  to  $90^\circ$  to the right of the wind at varying wind speeds (Ardhuin et al., 2009; Poulain et al., 2009; Kim et al., 2010; Röhrs and Christensen, 2015; Sentchev et al., 2017; Berta et al., 2018). Individual results and details of these studies are presented in Table 1. Combined results of these studies produce a range of estimates for the magnitude of wind-induced currents, with reported values ranging from  $0.4\%$  to  $5\%$  of the wind velocity, over the upper  $\sim 1$  m, showing that results may vary significantly based on environmental conditions and methodology (Ardhuin et al., 2009; Poulain et al., 2009; Kim et al., 2010; Röhrs and Christensen, 2015; Sentchev et al., 2017; Berta et al., 2018). Changes in upper ocean stratification and mixed layer depth have been shown to have large effects on the deflection angle and relative velocity of surface currents with respect to the wind (Kudryavtsev and Soloviev, 1990; Sutherland et al., 2016). Rascle and Ardhuin (2009) showed how the complicated relationship between wave-induced mixing and varying stratification can result in quasi-Eulerian wind-driven surface currents ranging from  $\sim 1$  to  $3\%$  of the wind speed, having deflection angles ranging from  $\sim 35^\circ$ - $90^\circ$ .

Here, we use drogued and undrogued CARTE drifters, having draft depths of 60 cm and 5 cm, respectively (Novelli et al., 2017), in order to measure the average very near surface currents in the Northern Gulf of Mexico during high wind conditions. The data used for analysis were collected during the LAgrangian Submesoscale ExpeRiment (LASER), a campaign in which over 1000 biodegradable CARTE drifters were deployed during the winter of 2016 (Haza et al., 2018). Utilizing a subset of the CARTE drifters from the experiment, we focus on three synoptic scale, high wind events during which, wind and waves seem to dominate the forcing of the surface flows measured by both drifter types. During these high wind events, we deconstruct the full surface current velocities captured by each drifter type into their wind- and wave-driven components after subtracting an estimate for the regional circulation which pre-exists each wind event. We then report on the vertical shear of the wave- and wind-driven components of the surface current between the two surface layers measured. To the authors' knowledge these findings are the first reported estimates of vertical shear in upper 1m, involving a direct velocity deconstruction and differentiation between wind- and wave-driven components under high wind conditions ( $\sim 12$ - $20$   $\text{m s}^{-1}$ ).

Upon inspection of the total velocity of the drifters during the high wind events, we hypothesize that there are three dominant components that drive the surface currents being measured: A wind-driven component, a wave-driven component, and the regional circulation that pre-existed each high wind event. Assuming a simple linear superposition of the velocity components, we define the total depth averaged velocity captured by each drifter type as the integral:

$$\bar{u}_T = \frac{1}{h} \int_0^h [u_s(z) + u_w(z) + u_{rc}(z)] dz, \quad (1)$$

**Deleted:** CODE or undrogued SVP drifters,

**Deleted:** or

**Deleted:** ,

**Formatted:** Font:Not Bold

**Deleted:** These observational studies also report wind-induced currents

**Deleted:** alone to be anywhere from

**Deleted:** Using drogued and undrogued CARTE drifters, we are able to fill in part of this observational gap by observing the vertical shear between the 0-5 cm and 0-60 cm layers of surface currents, during high wind conditions ( $\sim 12$ - $20$   $\text{m s}^{-1}$ ). Additionally, we deconstruct the measured velocities in both surface layers to arrive at an estimate for the purely wind-driven current over the two surface depths.

**Formatted:** Font:(Default) Cambria Math

where  $u_w$  is the purely wind-driven velocity,  $u_s$  is the Stokes drift velocity,  $u_{rc}$  is the regional circulation that exists before the increase in synoptic winds,  $z$  is the depth being evaluated and  $h$  is the draft depth of the respective drifter. Given this definition of the total surface current, we neglect possible nonlinear interactions between velocity components, which will be considered in future investigations.

The three components in Eq. (1) were estimated as followed:  $u_s$  was calculated numerically with the Unified Wave INterface-Coupled Model (UWIN-CM, Chen et al., 2013) during the LASER campaign and stored for later analysis,  $u_{rc}$  is estimated from the dense population of drifters in the region in the hours preceding substantial increases in synoptic winds using the LAGrangian Variational Analysis (LAVA, Taillandier et al., 2006) to create Eulerian velocity fields of the regional circulation, and we solve for  $u_w$  by subtracting the estimated regional circulation and Stokes drift velocity from the total depth averaged velocity measured by the drifters.

In the Northwestern Mediterranean Sea, the underlying geostrophic currents were shown to retain their structure and influence the surface flow under high wind forcing for time periods on the order of 2-3 days (Berta et al., 2018). In the present study, the timescales over which the flow features of the regional circulation,  $u_{rc}$ , retain their structure under strong winds is difficult to determine given the current dataset. However, the subtraction of the pre-existing regional circulation from the total velocity of the drifters during the high wind events, shows a-posteriori, that the pre-existing regional circulation retains its structure, to a reasonable extent, during the high wind analysis periods on which we focus. After subtracting the pre-existing regional circulation and numerically calculated Stokes drift velocity,  $u_s$ , from the full velocity,  $\bar{u}_T$ , of the drifters during each period of high wind, we are left with an estimate for the average, purely wind-driven current,  $u_w$ , over the two surface depths measured by each drifter type.

The paper is organized as follows: Section 2 describes the CARTE drifters and the configuration of the Unified Wave INterface-Coupled Model. Section 3 explains the LAGrangian Variational Analysis (LAVA) used to create the estimated Eulerian velocity fields of the pre-existing regional circulation, as well as the calculations involved in the deconstruction of the total surface current,  $\bar{u}_T$ , along each drifter trajectory during the high wind events. Results are presented in section 4, with a discussion of the results following in section 5. Concluding remarks are presented in section 6.

## 2. Data

### 2.1 CARTE Drifter

The CARTE drifter is a biodegradable surface drifter that consists of a Spot Trace GPS unit by Global Star, a torus float which contains the GPS housing, two interlocking panels that form the drogue, and a flexible rubber tube that connects the drogue and float (Novelli et al., 2017). During the LASER experiment, over 1000 CARTE drifters were deployed with drogues, however, over the first 7 weeks of the experiment approximately 40 % of the drifters lost their drogues (Haza et al., 2018). Drogued and undrogued drifters have draft depths of 60 cm and 5 cm, respectively, and have been extensively analyzed with respect to their specific drift characteristics during laboratory experiments performed by Novelli et al. (2017).

For this study, a subset of co-located drogued and undrogued drifters from the LASER campaign are used for analysis, due to their opportunistic location during the passage of large atmospheric fronts across the Northern Gulf of Mexico.

Drogue loss during the experiment mostly coincided with large storm and wave events and the precision of the determined time of drogue loss was 0.5 to 3 hours for 85 % of the drifters (Haza et al., 2018). The method for drogue loss detection is based on the differential velocities of the drifters, as the undrogued drifters are preferentially accelerated by the higher velocities of wind- and wave-driven currents present in the shallower surface layer in which the undrogued drifters reside. In addition, undrogued drifters display a decreased, more sporadic GPS transmission rate, due to their tendency to be flipped by large or breaking waves, which points the GPS antennae downwards, and reduces the ability of the GPS to transmit until the drifter is flipped upright again. Despite this, 80 % of the time intervals between transmissions by undrogued drifters are still between 4.5 and 5.5 minutes, but with notably higher outliers than the drogued drifters (Haza et al., 2018). The algorithm for drogue detection used by Haza et al. (2018) was validated using a subset of 50 drifters with known drogue status and was shown to distinguish drogued and undrogued drifters with an accuracy of 94-100 %. This very successful drogue detection algorithm has provided the opportunity to utilize both drogued and undrogued drifters to study the variation of very near surface currents with depth (Haza et al., 2018).

GPS transmissions reported each drifter's location every 5 minutes during the experiment, with an accuracy of about 7 m. In addition to the extensive categorization of drogued and undrogued drifters, the drifter trajectory data were also quality controlled for missing transmissions and linearly interpolated to regular 15-minute intervals (Haza et al., 2018). Velocities were then calculated, resulting in estimates for the average velocity of each drifter over 15-minute intervals.

When using drifters to study ocean currents, concerns about different sources of velocity slip must be addressed. Extensive laboratory testing performed by Novelli et al. (2017) using half-scale drogued and undrogued drifters showed that in the absence of wind and waves drogued (undrogued) drifters travel within  $0.01 \text{ m s}^{-1}$  ( $0.02 \text{ m s}^{-1}$ ) of the mean Eulerian current averaged over the draft depth of the given drifter. Under the effects of waves, observed in the absence of wind, the undrogued drifter unsurprisingly feels an acceleration due to Stokes drift, but the drogued drifter feels a reduced wave-induced acceleration due to the flexible tether holding together its float and drogue. This mechanical decoupling partially removes the effect of the Stokes drift acting on the drogued drifter, mainly dampening the effects of Stokes drift above the drogue (Novelli et al., 2017).

To characterize the slip velocity associated with wind, waves, and Eulerian current, Novelli et al. (2017) defines the "absolute" slip velocity as the difference between the velocity of a drifter and the depth integrated current over each drifters' draft. The absolute slip velocity of both drogued and undrogued drifters during laboratory testing was found to decrease with increasing wind speed, decreasing from  $3 \text{ cm s}^{-1}$  to  $0.1 \text{ cm s}^{-1}$  for the drogued drifter and from  $14 \text{ cm s}^{-1}$  to  $1 \text{ cm s}^{-1}$  for the undrogued drifter, for wind speeds from  $8.1 \text{ m s}^{-1}$  to  $23 \text{ m s}^{-1}$ . This phenomenon is thought to be caused by wind separation from the ocean surface due to the presence of surface gravity waves (Novelli et al., 2017). Another laboratory experiment, focused on measuring the turbulent air flow over wind generated waves in a similar wind-wave tank, found wind separation

Formatted: Indent: First line: 0.5"

to occur over 90 % of short wind waves at 10 m wind speeds of  $\sim 16 \text{ m s}^{-1}$  (Buckley and Veron, 2017). The extent to which wind separation occurs and its effectiveness of sheltering the drifters from wind-slip in the real ocean is difficult to quantify given the scale differences between the laboratory wave tank and open ocean. However, another recent experiment using full size CARTHE drogued and undrogued drifters in the real ocean, alongside a suite of instruments including an ADCP and polarimetric camera, showed that velocities calculated using both drifter types fell within the range of velocities measured by other instrumentation over the corresponding draft of each drifter (Laxague et al., 2017). Because the extent to which velocity slip affects the drifters in the real ocean is not well known during high wind and wave conditions, we choose not to attempt a correction of the drifter velocities to account for such measurement errors. Following the definition of the total surface current measured by each drifter (Eq. 1), we treat the drifter velocities as measurements of the surface current itself, but remain mindful of the potential errors, especially for the undrogued drifter case.

## 2.2 UWIN-CM

During the extent of the LASER campaign, daily 72 hour real-time forecasts were produced using the Unified Wave Interface-Coupled Model (UWIN-CM), running a fully-coupled atmosphere, surface gravity wave, and ocean circulation system (Chen et al., 2013; Chen and Curcic, 2016). The UWIN-CM model atmospheric component is comprised of the atmospheric non-hydrostatic Weather Research and Forecasting (WRF) model featuring Advanced Research WRF dynamical core with 4 km horizontal resolution over the Gulf of Mexico with 36 vertical layers (Skamarock et al., 2008; Haza et al., 2018).

The surface gravity wave model is the University of Miami Wave Model v2 (UMWM, Donelan et al., 2012), with the same 4 km resolution as the atmospheric component. The three-dimensional Stokes drift velocity fields are calculated as the full integral:

$$u_s = \int_0^{2\pi} \int_{k_{min}}^{k_{max}} \omega k^2 \frac{\cosh[2k(d+z)]}{2\sinh^2 kd} F(k, \theta) dk d\theta, \quad (2)$$

where  $\omega$  is the angular frequency,  $k$  is the wavenumber,  $d$  is the mean water depth,  $z$  is the depth being evaluated,  $F$  is the wavenumber energy spectrum, and  $\theta$  is the direction of the waves (Stokes, 1847; Phillips, 1977). Over the entirety of LASER,  $k$  ranged from  $0.0039 \text{ rad m}^{-1}$  to  $16.0739 \text{ rad m}^{-1}$ , in 37 logarithmic increments, which corresponds to a range of wavelengths from 1611 m to 0.39 m, respectively. The Hybrid Coordinate Ocean Model (HYCOM) v2.2 is used as the ocean circulation model, however no model output from this circulation model is used for the analysis of wind-driven currents. The surface layer of the HYCOM model has a minimum thickness of 3 m, which makes the model unrepresentative of the depths sampled by the drifters and very difficult to validate with observational data (Wallcraft et al., 2009). Comparison of drifter data and surface velocities from the circulation model showed obvious discrepancies at the spatial scales necessary for this study.

Deleted: 0

Deleted:  $\infty$

Deleted:

Deleted:

The coupling between the model components is as follows: WRF passes radiative and heat fluxes, as well as precipitation rates to the ocean model, as well as the air density and wind profiles to the wave model. The wave model (UMWM) passes vectorial atmosphere stress and vectorial ocean stress to the atmosphere model and ocean circulation model, respectively. The ocean circulation model passes SST to the atmosphere model and surface current fields and ocean density to the wave model. WRF and UMWM fields are exchanged every 60 s, while HYCOM fields are exchanged every 120 s (Chen and Curcic, 2016).

The UWIN-CM model is initialized daily using initial and boundary conditions from Global Forecast System (GFS) and global HYCOM fields along with the previous day's UMWM wave forecast. Coupling between models is executed using the Earth System Modeling Framework (ESMF) in which all components are exchanged between models every minute (Hill et al. 2004). Hourly 10 m wind (U10) and Stokes drift velocity data from the 24<sup>th</sup> – 48<sup>th</sup> hour of each daily 72-hour forecast were stored and used for the analysis performed in this study. Initially having a temporal resolution of 1 hour, the UWIN-CM model output was interpolated to 15-minute intervals to match the time resolution of the drifter data.

### 3. Methods

#### 3.1 High Wind Events and Region of Interest

The domain for this study lies to the east and southeast of the Mississippi River Delta spanning from 27.5°N to 30.5°N and 90°W to 86.5°W. The spatial extent of the data used for each high wind event are outlined in Fig. 1, along with NDBC buoy locations used for verification of the UWIN-CM wind data. Initial deployment of these drifters occurred during January and February of 2016 with the intent of capturing submesoscale dynamics on spatial scales of tens of meters to tens of kilometers (Haza et al., 2018). The large number of drifters deployed during the LASER campaign, and their relatively long transmission period of about 3 months, provided opportunity to collect data over a range of scales and environmental conditions. The region and time periods chosen exhibit large numbers of co-located drogued and undrogued drifters during the passage of synoptic atmospheric fronts, which drive a large momentum input into the oceanic boundary layer.

In order to characterize the vertical structure of flow features typical in this region, a moving vessel profiler (MVP) collected CTD measurements when possible during the first month of the experiment, focusing on the fronts and eddies that form at the intersection of cold, fresh Mississippi outflow water and the warmer, saltier Gulf of Mexico waters. Figure 2 shows a typical transect (outlined in Fig. 1) of potential density, salinity, and temperature across a frontal structure in the region. These transects display less dense Mississippi outflow waters extending down to ~30 m depth from the surface, flowing over the denser interior gulf water. The interior gulf water, seen to extend to the surface towards the eastern end of the transects, shows a well-mixed surface layer down to ~80 m depth. Other transects across frontal areas measured with the MVP show very similar structures in this region, making Fig. 2 representative of the typical stratification observed between these water masses.

Deleted: 72 hour

Formatted: Normal

Formatted: Font:(Default) +Theme Body (Times New Roman), 10 pt, Font color: Text 1

For this study, we choose to focus on three high wind events that occurred on January 22<sup>nd</sup>, February 24<sup>th</sup> and March 20<sup>th</sup> of 2016. Available wind data from nearby NDBC buoys (BURL1, 42040 and 42012), along with the UWIN-CM wind data associated with each drifter position during and before the high wind event are plotted in Fig. 3. The time periods over which we perform the deconstruction of the total measured surface currents during each high wind event are marked by vertical black lines, and the red solid and dashed vertical lines show the start of the hour over which the pre-existing regional circulation is estimated from drogued and undrogued drifters, respectively (Fig. 3). Validation of the UWIN-CM U10 output with available NDBC buoy data revealed that during the passage of atmospheric fronts through the domain there exists a fair amount of variability in the modeled wind magnitude resulting, at times, in a large difference between observed and modeled data. For this reason, we exclude any data associated with modeled wind magnitude ranges above  $6 \text{ m s}^{-1}$  at any given 15-minute time step.

Wave data from the UWIN-CM is also compared to the available NDBC wave data in Fig. 4. Only data from NDBC buoy 42040 during the January high wind event is shown for wave model validation, as there was no wave data collected from buoy BURL1, and buoy 42040 stopped functioning before the February event. Comparison of model output and observational data shows that the significant wave height is modeled accurately, especially under high winds, while the wave period could be slightly underestimated by the wave model. Mean wave direction is initially offset by  $\sim 30^\circ$  at the beginning of the high wind analysis period, but comes into good agreement about halfway through the analysis window. Wave data from buoy 42012 also showed good agreement to the UWIN-CM data near the buoy coordinates during the March event, but as drifters move further offshore during the high wind event, the nearshore location of the buoy becomes less representative of the conditions influencing the drifters.

### 3.2 LAgrangian Variational Analysis (LAVA) and Pre-existing Regional Circulation

Initial inspection of the total drifter velocities during each high wind event showed larger than expected spatial variation in drifter velocities, including velocities which depict surface currents traveling to the left of the wind, which challenges previous wind-driven surface current theory and observations. Previous works that have studied instantaneous wind-driven dynamics over a range of spatial scales have illustrated the need to account for the circulation present before the observed increase in synoptic winds in order to isolate the wind-driven component of the flow (Sentchev et al., 2017; Berta et al., 2018). Based on these studies, we hypothesize that the spatial variability observed in the total velocities is due to the regional circulation that pre-existed the period of increasing winds, which retains its structure on times scales long enough to influence the surface flow during each high wind event.

In order to resolve surface currents in our region of interest at adequate spatial and temporal resolution we utilize the Lagrangian Variational Analysis (LAVA, Taillandier et al., 2006) and the available drifter data in the region to estimate the regional circulation. Geostrophic velocities derived from altimetry data and surface Ekman current velocities parameterized using forecasted winds have been shown to have inadequate spatial and temporal resolution, in order to accurately estimate surface currents in the Northern Gulf of Mexico on scales less than the order of 100 km in space and 1 week in time (Berta et

Deleted: 2

Deleted: 2

Deleted: .

Formatted: Font color: Text 1

Deleted: .

... [1]

al., 2015). LAVA allows us to use the undrogued and drogued drifter trajectory data in the region, to create Eulerian velocity fields that are statistically robust and on the spatial and temporal scales on the order of 10 km and hours, respectively (Taillandier et al., 2006; Berta et al., 2015). LAVA has been used in previous studies to create velocity fields using purely Lagrangian data, as well as blending drifter trajectory data with Eulerian velocity fields derived from altimetry and HF radars. LAVA has proven especially useful when providing Near Real Time (NRT) information that can be useful to first responders of oil spills, search and rescue efforts and other surface transport problems (Taillandier et al., 2006; Chang et al., 2011; Berta et al., 2014; Berta et al., 2015).

Given our hypothesis that during the high wind events, the total velocity of the drifters is partly composed of the regional circulation that pre-existed the onset of high winds, an estimate for this circulation must be removed from the total velocity of the drifters in order to isolate the wind- and wave-driven components. We utilize LAVA and the available drogued and undrogued drifter data in the region to create semi-simultaneous hourly Eulerian velocity fields for both drifter types, separately. The drifters used for the velocity field construction for each event are plotted in Fig. 5. The January 22<sup>nd</sup> event occurred very close to the initial time of deployment while the drogued drifters were still tightly packed spatially and little drogue loss has occurred, leaving a smaller, but adequate, number of undrogued drifters to utilize for the estimate of the pre-existing circulation. The events on February 24<sup>th</sup> and March 20<sup>th</sup>, occur long enough after deployment, thus resulting in a more even amount of drogued and undrogued drifters that are also more evenly spread through the region, however drogued drifters do show a tendency to converge upon one another, evident in the spatial organization of the drifters seen in Fig. 5.

LAVA utilizes drifter trajectories in order to create average velocity fields over multiple time steps depending on the parameters  $R$ ,  $T_a$ ,  $\Delta t$  and  $\Delta x$ , which need to be prescribed before implementation of the analysis.  $R$  determines the spatial range over which the velocity of each drifter is spread from the drifter location through finite iterations of the diffusion equation and should be chosen as the typical length scale, or Rossby radius, for the targeted oceanic dynamics to be resolved in the given region. For this analysis,  $R$  is set to 10 km, which is same value used for a previous study which utilized drifter data in the same region of the Northern Gulf of Mexico (Berta et al., 2015).  $\Delta t$  for this study is 15 minutes, which is the time resolution of the quality controlled drifter trajectories which have been linearly interpolated to regular 15-minute intervals (Haza et al., 2018). The analysis time scale,  $T_a$  is the larger time window over which consecutive velocity fields created using LAVA are averaged and should be shorter than the Lagrangian time scale (Taillandier et al., 2006). Lagrangian time scales within this region have been calculated to be as small as ~1-3 hours, which corresponded to spatial scales ranging from ~4-3.5 km (Gonçalves et al., 2019), and as large as ~1-3 days corresponding to spatial scales ranging from ~10-35 km (Ohlmann and Niiler, 2005). Here,  $T_a$  is set to 1 hour, which is adequately short given our assignment of 10 km as the typical horizontal length scale being resolved by LAVA.  $\Delta x$  is the spatial resolution of the discretized velocity field and needs to be assigned such that  $\Delta x < R$ , defined here as  $\Delta x = 1.5$  km. (Taillandier et al., 2006; Berta et al., 2015). Drifter trajectories within  $2\Delta x$  of one another are averaged to become single drifter trajectories positioned along their center of mass before the production of Eulerian velocity fields (Berta et al., 2015).

Deleted: 3

Deleted: 3

After the Eulerian velocity fields are created, a kinetic energy mask is also implemented to exclude small velocities that are an artifact of assigning radially decreasing velocities away from drifter locations using LAVA. To avoid these unrealistically small velocities, any values in the Eulerian velocity fields that represent less than 10 % of the hourly averaged kinetic energy in the velocity field are discarded. This relatively low threshold of kinetic energy was chosen to maximize the coverage between the Eulerian velocity field estimates of the pre-existing regional circulation and drifter trajectory data during each high wind event.

The hourly velocity fields are created during low wind conditions, hours before the passage of synoptic scale atmospheric fronts, which produce very high winds over the entire region. To avoid unnecessarily smoothing the Eulerian velocity fields through averaging in time, we choose one hourly velocity field per event, per drifter type, to use for analysis.

Hourly Eulerian velocity fields are chosen based on the criteria that there are relatively low wind velocities present, the time gap between the velocity field and onset of high wind isn't needlessly long and how well the Eulerian velocity field overlies the drifter trajectories during the high wind event. The Eulerian velocity fields used for analysis are plotted in Figs. 6 and 7. Each hour over which these velocity fields are created are also indicated in Fig. 3. The Eulerian velocity fields are plotted on top of AVISO derived, 24-hour averages of SST temperature, in order to validate the flow structures that are seen in the reconstructed velocity fields using LAVA. AVISO SST products in the Gulf of Mexico are measured by 4 intercalibrated satellite infrared radiometers and have a resolution of 0.02° in latitude and longitude. Each 24-hour period, over which the SST measurements are processed and averaged, is centered on the 0<sup>th</sup> hour of each day. For each high wind event, the drogued and undrogued velocity fields are directly compared to two SST fields. One corresponding as closely as possible in time to the high wind event and one corresponding to the following day, in order to visualize the change in the pre-existing regional circulation during each high wind event (Figs. 6, 7).

Stokes drift estimates from the UWIN-CM during the time periods shown in Figs. 6 and 7, are on average an order of magnitude less than the total drifter velocities for both drifter types, having average magnitudes of 0.02 m s<sup>-1</sup> for the drogued case and 0.04 m s<sup>-1</sup> for the undrogued case. Smoothing of the constructed velocity fields that arises from the velocity spreading and averaging performed by LAVA over the length scale R, makes the uncertainties from the influence of Stokes drift insignificant during these low wind conditions. Inevitably there also exists some influence from the wind during these time periods, which is most likely greater than the magnitude of the Stokes drift. However, the qualitative agreement of the velocity field estimates and the SST fields, evident in Figs. 6 and 7, suggest that both drifter types are capturing the dynamics of the underlying circulation rather than the instantaneous wind-driven affects during these time.

### 3.3 Deconstruction of Total Surface Current

The total surface current,  $\bar{u}_T$ , calculated between each 15-minute drifter position during the high wind events, is stored at the later drifter coordinate used for each calculation. The time gap between the observation of the regional circulation,  $u_{rc}$ , and the beginning of the high wind analysis period, is chosen such that the increase in winds shows a

Deleted:

**Deleted:** The Eulerian velocity fields used for analysis are plotted in Fig. 4 and labelled with the beginning of the hour over which they were created. The hour over which these velocity fields are created are also indicated in Fig. 2.

Deleted: .

Deleted: T

Deleted: analysis during the

Deleted: period

**Deleted:** such that a widespread velocity change due to the wind is observed in the drifter trajectories and the drifters enter the region where an observation of the pre-existing regional circulation exists



noticeable change in all the drifter trajectories across the given domain. Investigation of wind-driven currents at high temporal resolution has shown that the surface current response time to changing winds can be described as quasi-instantaneous, with the surface currents lagging the wind by ~40 minutes (Sentchev et al., 2017). Having a temporal gap between these observations ensures the surface velocities, across the region, have ample time to adjust to the increasing winds before any calculations are made. In some cases, the time gap is extended to allow drifters to enter the region where the corresponding observation of the pre-existing regional circulation exists. In addition, we stop the analysis for each high wind event at the apex of the increasing wind velocity magnitude, beyond which the drifters exhibit large inertial motions due to the decrease in momentum input from the wind. The drifter trajectories, during the period over which the deconstruction of the total surface current are made, are shown in Fig. 8.

From the full drifter velocities, calculated on 15-minute intervals during each wind event, we subtract the nearest point velocity in the estimated Eulerian velocity field of the pre-existing regional circulation,  $u_{rc}$ . Each Eulerian velocity field has a spatial resolution of 1.5 km, which is adequate to preserve the flow features given the typical length scale of 10 km in the region (Berta et al., 2015). In the event that the nearest point to the drifter location in the regional circulation velocity estimate does not have a value, due to lack data in the velocity field created before the increase in synoptic winds, the data is discarded. The trajectories in Fig. 8 are color coded to show where the drifter trajectories and Eulerian velocity fields overlap during the high wind event and where data coverage is missing.

The subtraction of multiple hourly adjacent velocity fields, earlier and later in time, were examined a-posteriori for each event and found to produce similar end results. The hourly Eulerian velocity fields chosen for this analysis were those that had the most data points in common with the respective drifter trajectories during the high wind event, or those that retained a similar amount of data points during the subtraction (within 3.5 % of the maximum amount of retained trajectory data for each specific case) but resulted in larger decreases in the standard deviation of the deflection angle between drifters and wind velocity. This decision is motivated by the assumption that the isolated effects of wind and waves will result in a more directionally uniform velocity field, than that of a surface flow being influenced by the regional circulation estimates shown in Figs 6 and 7. Thus, by removing more variation in the deflection angles between the wind and drifter velocities, we better represent the combined wind- and wave-driven components, assuming the wind and wave directions are well aligned. All velocity estimates and calculations are performed using drogued and undrogued drifter data, separately.

After subtracting the pre-existing regional circulation from the full drifter velocities during the high wind events, the remaining velocity is an estimate for the combined wind- and wave-driven flow ( $u_s + u_w$ ), referred to here after as the wind-wave-driven velocity. To further deconstruct this velocity estimate, we subtract the UWIN-CM modeled Stokes drift velocity ( $u_s$ ) fields, again at the nearest point to each drifter location for each 15-minute interval. Because the large wind-driven events being analyzed are of synoptic scale, the UWIN-CM modeled Stokes velocity and U10 winds are relatively uniform in the region of study, making the 4 km resolution of the data adequate to perform meaningful calculations in this manner.

Deleted: 5

Deleted: 5

Deleted: . 4

Because the drogued drifters display a filtering characteristic of the surface Stokes drift, as illustrated in laboratory testing performed by Novelli et al. (2017), the Stokes drift at 0.4 m depth is used for the calculation with drogued drifter-derived velocities (0.4 m being the vertical center of the drogue). From the undrogued drifter associated velocities, we subtract the surface ( $z = 0$  m) Stokes drift velocity. After subtracting the wave-driven component,  $u_s$ , from the wind-wave-driven velocity, we are left with an estimate for the average wind-driven velocities,  $u_w$ , over each respective drifter draft depth. The average wind-wave-driven and wind-driven velocities are compared to the modeled U10 wind data, using the U10 wind velocity datum at the nearest point in the modeled Eulerian field to each drifter location at every time step.

#### 4. Results

The main flow features seen in the estimated Eulerian velocity fields and SST fields show evidence of flow features having spatial scales on the order of tens of kilometers (Figs. 6 and 7). Observations of smaller flow features in the velocity fields are limited by the 1.5 km resolution and typical length scale of 10 km set by the chosen LAVA configuration. The regional circulation observed, by either drifter type, prior to the wind events on February 24<sup>th</sup> and March 20<sup>th</sup> show an abundance of meanders, eddies and frontal features, whereas the regional circulation pre-existing the wind event on January 22<sup>nd</sup> suggests that a somewhat larger feature, closer to the order of 100 kilometers, is driving the majority of the flow to the northeast with some variability seen throughout the flow. The velocity field vectors for all panels in Figs 6 and 7, show good agreement to the structures highlighted by the SST data, supporting the validity of the LAVA estimated fields. Features on these spatial scales (10-100 km) are known to have characteristic time scales on the order of days to weeks (Özgökmen et al., 2016) which suggests that the main flow features observed in the pre-existing regional circulation, are likely retain their overall structure, to a certain extent, during of the high wind analysis periods presented here. This is also supported by the SST fields averaged over the 24-hour period following each high wind event shown in the right-side panels of Figs. 6 and 7. Although the SST field change somewhat during the high wind event, the pre-existing circulation estimates seem to be valid for an appreciable amount of time, evident in the overlap between eddies, fronts, and filaments observed in the SST field and the velocity vectors created with LAVA 2-3 days previously.

The trajectories of both drogued and undrogued drifters during the hours of increasing winds, over which the total velocity deconstructions were performed are shown in Fig. 8. Overall the trajectories show that the larger scale, synoptic winds and coinciding wave-induced motions are the dominant driving force in the drifter movement, evident in the similarities in drifter tracts across each domain. Influence of the pre-existing regional circulation can also be observed in the variability among drifter trajectories. The undrogued trajectories seem to show less variability across the domain than for the drogued case, suggesting the wind- and wave-driven components are even more dominant in the surface layer measured by the undrogued drifters.

Scatter plots of the difference between the wind direction and the direction of the total velocity of the drogued and undrogued drifters, i.e. deflection angles, along the trajectories segments shown in black in Fig. 8, are shown in Figs. 9a and 9b, respectively. Figures 9c and 9d show the deflection angles between the wind and drifter velocities, after the Eulerian

**Deleted:** Figure 4 shows the estimated Eulerian velocity fields of the regional circulation that pre-existed each given high wind event, for each drifter type.

**Deleted:** seen

**Deleted:** kilometers

**Deleted:**

**Deleted:** 5

**Deleted:** , evident

**Deleted:** 5

**Deleted:** 6

**Deleted:** 6

**Deleted:** 6

**Deleted:** 6

velocity field estimates of the pre-existing regional circulation (Figs. 6, 7) have been subtracted from the full velocity of the drifters. Any data points lost during the subtraction of the regional circulation velocity field, shown as red segments in Fig. 8, were also excluded from the scatter plots showing the full drifter velocities (Fig. 9a, b) for accurate comparison. Deflection angles are plotted against the point value wind magnitude from the UWIN-CM model, closest to the drifter location at the time of the velocity measurement. It is evident from Fig. 9 that the scatter of the total drifter velocity deflection angles has a wider, more disorganized spread than the deflection angles calculated after the pre-existing regional circulation has been removed from the full velocity. This is especially apparent for the drogued drifter case.

The average velocity magnitude of the calculated wind-wave-driven currents is compared to the average magnitude of the pre-existing regional circulation for each wind event and drifter type in Fig. 10. The magnitude of the regional circulation is plotted as a percentage of the combined wind- and wave-driven velocity magnitude. This percentage decreases as the wind- and wave-driven effects become increasingly large during each high wind event. During the analysis periods over which we deconstruct the total surface current (shown by vertical lines in Fig. 10), the pre-existing circulation is 30-45 % as large as the combined wind-wave-driven velocity calculated using drogued drifters, and 25-30 % as large as that measured by undrogued drifters.

The wind-wave-driven, wind-driven, and wave-driven (Stokes drift) velocities are binned by wind magnitude on 0.5 m s<sup>-1</sup> intervals. The total number of drifter positions, per wind bin, where the surface velocity deconstruction is performed, are plotted in Fig. 11, which shows that the most robust results exist over wind bins from 14.5-18 m s<sup>-1</sup> for both drogued and undrogued drifters. It should be noted that although the sample size varies considerably between drifter types and over the assigned wind bins, both drifter types have substantial sample sizes over most wind bins presented, given the relatively short time periods of analysis. The sample size of drifter measurements is also listed for each high wind event in Fig. 8. Averages and standard deviations of the velocity components were computed within each bin. The average deflection angle from the wind direction of the Stokes velocity, wave-wind-driven velocity and wind-driven velocity for each respective drifter draft depth are shown in Fig. 12. The magnitudes of the same velocity components are plotted as a percentage of the wind magnitude in Fig. 13. Figures 12c and 13c are obtained by subtracting the given Stokes drift velocity (Figs. 12a, 13a) from the estimated wind-wave-driven velocities (Figs. 12b, 13b). Bins lower than 11.5 m s<sup>-1</sup> have been omitted in Figs. 12 and 13, due to lack of data points and large variation of deflection angle in the given bins. Error bars indicate one standard deviation about the mean for each bin (Figs. 12, 13).

In the upper 5 cm, the average wind-wave-driven component of the flow varies with increasing wind speed, traveling between ~4° and 40°, to the right of the wind, as winds increase from 11.5-20 m s<sup>-1</sup> (Fig. 12b). On average, the magnitude of this flow varies from 4.5-7.1 % of the wind speed (Fig. 13b). Over the deeper surface layer (0-60 cm), the deflection angle of the wind-wave-driven current varies from ~26°-60°, as winds increase over the same range, traveling at 2.8-4.6 % of the wind speed, on average (Figs. 12b and 13b). The total wind-wave-driven flow in both layers exhibit larger

Deleted: . 4

Deleted: 5

Deleted: 6

Deleted: 6

Deleted: 7

Deleted: 7

Deleted: 8

Deleted: 5

Deleted: 9

Deleted: 1

Deleted: 0

Deleted: 9

Deleted: 10

Deleted: 9

Deleted: 10

Deleted: 9

Deleted: 10

Deleted: 9

Deleted: and

Deleted: 10

deflection angles as wind speeds increase, with the 0-60 cm layer travelling at a slower velocity, and being deflected  $\sim 5^{\circ}$ - $28^{\circ}$  further to the right than the 0-5 cm layer.

Our estimates for purely wind-driven surface currents over the two layers measured (Figs. 12c and 13c) show the upper 5cm layer traveling  $\sim 5^{\circ}$  to the right of the wind, at 6.0 % of the wind speed during  $12 \text{ m s}^{-1}$  winds. The deflection angle gradually increases to  $\sim 55^{\circ}$  to the right of the wind as wind speeds increase to  $20 \text{ m s}^{-1}$ . The average velocity magnitude varies between 3.4-6.0 % of the wind speed over this wind interval. The deflection angle of the wind-driven surface current residing in the upper 60 cm ranges from  $\sim 30^{\circ}$ - $85^{\circ}$ , again with higher deflection angles occurring at higher wind speeds. The velocity magnitude of this wind-driven layer varies from 2.3-4.1 % of the wind speed over the given wind speed interval. The difference in deflection angle between layers varies between  $\sim 8^{\circ}$  and  $30^{\circ}$ , with the deeper layer traveling further to the right, at a slower velocity. In both cases there seems to exist an increase in deflection angle with increasing wind speed.

## 5. Discussion

Comparison of scatter plots in Fig. 9 indicate that the pre-existing regional circulation still influences the surface currents over the depths measured by both drifter types during a large wind-driven event. The scatter of deflection angles between different drifter types also suggests that the relatively deeper layer measured by the drogued drifter exhibits larger variation in velocity due to the regional circulation component of the flow. The shallow layer, observed with undrogued drifters, seems to be more dominantly driven by the wind and wave components, as removing the influence of the regional circulation results in a less drastic compression of the scatter. In both the drogued and undrogued cases, the removal of the estimated regional circulation results in a decrease in the standard deviation of the surface current deflection angle for all wind bins from  $11.5$ - $20 \text{ m s}^{-1}$ .

Comparison of the relative magnitudes of the combined wind-wave-driven currents and the pre-existing circulation estimates confirms that the surface velocities are dominantly wind- and wave-driven during the high wind periods (Fig. 10). Analysis of the plots in Fig. 10, led the authors a-posteriori to determine the optimal windows for the velocity deconstruction results during the high wind events. With respect to the subtraction of the pre-existing regional circulation and the improvement of the scatter in deflection angles (seen Fig. 9), the most robust results, for both drifter types, occur when the relative strength of the wind-wave-driven flow to the pre-existing regional circulation reaches a plateau (seen in Fig. 10). This is also when the wind, and therefore the wind-wave-driven component, is the strongest, which suggests that any error introduced during the velocity deconstruction makes up a smaller percentage of the calculated velocities. Extending the velocity deconstruction analysis windows, by 2 hours before and 2 hours after, does not significantly change the averages and trends shown in Figs. 12 and 13, but does however, slightly disorganize the scatter of the deflection angles seen in Fig. 9c,d. This investigation of sensitivity also aided in determining the optimal time periods for analysis.

Formatted: Indent: First line: 0.5"

Formatted: Font color: Text 1

Deleted: 6

Deleted: Figure 7 shows that on average, during the high wind analysis windows (shown by vertical dashed lines), the pre-existing circulation is only  $\sim 25$ - $30$  % as strong as the combined wind-wave-driven flow measured by the undrogued drifters. Drogued drifter measurements during the same periods also show that the pre-existing circulation is relatively weaker ( $\sim 30$ - $45$  % of the combined wind-wave-driven velocity magnitude over the drogued drifter depth).

Deleted: 7

Deleted: 6

Deleted: 7

Deleted: 9

Deleted: 10

Deleted: 6

Figure 12b shows that the estimated deflection angle of the combined wind- and wave-driven currents in both surface layers measured, vary significantly with increasing wind velocity. Since the deflection angle of the Stokes drift velocity (Fig. 12a) is almost constant with wind speed, the increase in deflection angles seen in Figs. 12b, is most likely due to a change in the wind-driven momentum input. The increased deflection angle observed between the 0-5 cm and 0-60 cm layers also seems to be predominately wind-driven based on the relative magnitudes of Stokes drift and estimated wind-driven currents (Fig 13). Classical Ekman theory, is based on the balance between Coriolis and vertical viscosity in the water column, which given the parameterization for wind stress and viscosity assigned by Ekman (1905), results in a wind-driven surface current deflected 45° to the right of the wind in the Northern Hemisphere, which spirals to the right and decreases in magnitude with depth. In contrast to Ekman, the “Slab” solution, based on enhanced surface mixing due to breaking waves and shear-induced turbulence, prescribes a linear decrease of wind stress with depth, resulting in a surface current which travels 90° to the right of the wind, uniformly with depth (Pollard and Millard, 1970).

The findings presented here, seem to support aspects of both the Ekman and Slab solutions, as there does appear to be a rotation of the surface current with depth, however, both layers display a larger deflection than predicted by Ekman at larger wind speeds. This can possibly be explained by enhanced vertical mixing under high wind and wave conditions, which acts to diminish the effects of stratification and distribute wind-driven momentum into the water column. This theory motivates the assignment of a linearly decreasing wind stress with depth used in the slab model solution by Pollard (1970) which results in deflection angles of 90 degrees over all depths of the mixed layer. The observed increase in deflection angle with wind speed may suggest a gradual change in wind-driven flow regimes, from surface Ekman dynamics to more Slab-like dynamics, as increasing wind velocity and subsequent turbulence from vertical shear and breaking waves, mix momentum vertically in the wind-driven layer. However, there still exists a rotation of the wind-driven current with depth which cannot be explained using slab-like dynamics alone.

Comparison to more recent observational studies is nontrivial due to differences in instrumentation, measurement depth, and time resolution of measurements. Many previous studies have performed spectral analysis on years of HF radar or drifter data with time resolutions varying from 0.5-6 hours, and calculated correlations between wind and surface currents in order to isolate the wind-driven component of the flow. Results from these studies find a range of deflection angles from 17-90 degrees to the right of the wind, with current magnitudes varying from 0.4-5 % of the wind speed (Ardhuin et al., 2009; Poulain et al., 2009; Kim et al., 2010; Röhrs and Christensen 2015;). Sentchev et al. (2017) used instantaneous vertical ADCP measurements to calculate the wind-driven effect on surface currents (0.5-75m depth) during sea breeze conditions (wind speeds of ~3-6 m s<sup>-1</sup>), finding wind-driven deflection angles of 12°-25° and current magnitudes of 2-4 % of wind speed. The study also found a rotation to the right was present between wind-driven velocities of increasing measurement depth. Berta et al. (2018) used hourly HF radar measurements to observe the influence of large wind events lasting 1-3 days. After subtracting the geostrophic component of the flow to isolate the wind-driven current, they found surface velocity deflection angles and magnitudes of 25-30° and ~2 % of the wind speed, respectively. More details of these previous studies on wind-driven dynamics can be found in Table 1.

**Deleted:** In the upper 5 cm, the average wind-wave-driven component of the flow varies with increasing wind speed, traveling between ~4° and 40°, to the right of the wind, as winds increase from 11.5-20 m (Fig. 9b). On average, the magnitude of this flow varies from 4.5-7.1 % of the wind speed (Fig. 10b). Over the deeper surface layer (0-60 cm), the deflection angle of the wind-wave-driven current varies from ~26°-60°, as winds increase over the same range, traveling at 2.8-4.6 % of the wind speed, on average (Figs. 9b and 10b). The total wind-wave-driven flow in both layers exhibit larger deflection angles as wind speeds increase, with the 0-60 cm layer travelling at a slower velocity, and being deflected ~5°-28° further to the right than the 0-5 cm layer. Since the deflection angle of the Stokes drift velocity (Fig. 9a) is almost constant with wind speed, the increase in deflection angle seen in Figs. 9b and 10b, is most likely due to a change in the wind-driven momentum input.

**Deleted:** is

**Deleted:** Both of these theories are formed under idealized situations, which under represent other ocean processes associated with wind-driven dynamics, possibly the most significant being Stokes drift. We can however, make a reasonable comparison to these theoretical results after the wind-driven component is isolated from the other components that make up the total drifter velocities.

**Deleted:** Our estimates for purely wind-driven surface currents over the two layers measured (Figs. 9c and 10c) show the upper 5cm layer traveling ~5° to the right of the wind, at 6.0 % of the wind speed during 12 m winds. The deflection angle gradually increases to ~55° to the right of the wind as wind speeds increase to 20 m. The average velocity magnitude varies between 3.4-6.0 % of the wind speed over this wind interval. The deflection angle of the wind-driven surface current residing in the upper 60 cm ranges from ~30°-85°, again with higher deflection angles occurring at higher wind speeds. The velocity magnitude of this wind-driven layer varies from 2.3-4.1 % of the wind speed over the given wind speed interval. The difference in deflection angle between layers varies between ~8° and 30°, with the deeper layer traveling further to the right, at a slower velocity. In both cases there seems to exist an increase in deflection to the right with increasing wind speed.

**Deleted:** se

**Deleted:** is thought to

**Deleted:**

**Deleted:**

**Deleted:** 1

**Deleted:** .

The findings portrayed in this paper seem to be within the range of previously reported results for wind-driven surface flows with discrepancies likely resulting from the differences in the depth of the measurement, range of wind magnitudes, upper ocean stratification, or methodology in isolating the wind-driven component. Several of these previous studies also utilized data sets with a portion of surface current measurements occurring close to the coast, were topography  
 5 could've added noise to the measurements (Poulain et al., 2009; Kim et al., 2010; Röhrs and Christensen, 2015; Berta et al., 2018). With the exception of Arduin et al. (2009), these past studies have not accounted for Stokes drift in their measurements, sometimes due to negligible wave influence under low wind conditons, possibly resulting in smaller deflection angles due to the near alignment of winds and wave direction (Poulain et al., 2009; Kim et al., 2010; Röhrs and Christensen 2015; Sentchev et al., 2017; Berta et al., 2018). The UWIN-CM modeled Stokes velocity used for this study,  
 10 seems to be in good agreement with the full Stokes velocity magnitude and deflection angle, with respect to the wind, presented by the previous literature (Arduin et al., 2009).

One source of error in the wind-driven measurements reported here is the possible evolution of the regional circulation during the time gap between the observation of the pre-existing regional circulation and the velocity deconstruction during the high wind period. Although difficult to quantify given the available data, the regional circulation is  
 15 evolving, to a certain extent, during the time gap between the observation of the regional circulation and the analysis periods of high winds. In addition, the regional circulation could begin to be modified through interactions with the large wind- and wave-induced currents. The extent to which this is occurring can be seen qualitatively in Figs. 6 and 7 by comparing the change of the SST fields in time. One example of which is evident in the South-eastward progression of the front seen in the SST fields associated with the January high wind event. The movement of this front seems to generally mimic the movement  
 20 of the drifters during this high wind event shown in the top panels of Fig. 8. The overall timescales on which these flow features evolve or are altered by each high wind event is beyond the scope of this paper, given the available data set. However, the relatively short time scales of these periods of high winds and the overall agreement between the pre-existing circulation estimates and the SST fields (shown in Figs. 6 and 7) suggest that the method of velocity deconstruction used here is adequate. In addition, the decreased variability seen in the deflection angles after the subtraction of the pre-existing regional circulation (Fig. 9) suggests, a-posteriori, that the regional circulation does maintain its structure to a reasonable  
 25 extent during the periods of increasing winds being analyzed.

Another possible source of error comes from the velocity slip characteristics of the drifters mentioned above, mostly relevant in the undrogued case. The magnitude of the wind-wave-driven and purely wind-driven velocities calculated using undrogued drifters are among the higher estimates previously reported (Arduin et al., 2009; Poulain et al., 2009; Kim et al.,  
 30 2010; Sentchev et al., 2017; Berta et al., 2018). The effect on the velocity slip of these drifters due to windage and wave steepening has been tested in the lab by Novelli et al. (2017). Although there exists a large difference in scales between the lab and the real ocean, the differences between the combined wind-wave-driven velocity magnitudes of drogued and undrogued drifters (~2 % of the wind speed on average) in the current study, are in good agreement to that of laboratory studies using half scale drifters and a past field experiment using full size drifters (Laxague et al., 2017; Novelli et al., 2017).

Deleted: none of

Deleted:

Deleted:

Deleted: it is

Deleted:

Deleted: should limit the errors introduced by the evolution of the pre-existing circulation

Deleted: T

Deleted: 6

Deleted: documented

As mentioned above, laboratory testing of undrogued drifters showed that the total velocity slip could be as high as 14 cm s<sup>-1</sup>, but was shown to decrease to only 1 cm s<sup>-1</sup> with increasing wind speeds (over a range of 15-23 m s<sup>-1</sup> in the lab) due to the sheltering of drifters from the wind by increasing wave heights (Novelli et al., 2017). This could partly explain the gradual decrease in wind-driven velocities for both drifter types from wind bins 11.5-18 m s<sup>-1</sup>, especially given the relatively high wind-driven velocities seen at lower wind bins. Exactly how much wind-slip is occurring during specific wind velocities and wave heights in the real ocean is difficult to determine, but the average magnitude of the observed vertical shear seems to be in relatively good agreement with past experiments and laboratory testing performed with these drifters (Laxague et al., 2017; Novelli et al., 2017).

The momentum input from large breaking waves into the surface currents at the very high wind speeds studied here, could also cause an increase in velocities observed in the wind-driven surface currents estimated from either drifter type. In addition, the surfing behavior of the undrogued drifters could amplify this increase in observed velocities further. Velocity slip due to wind and breaking waves could also account for some of difference seen in deflection angles between the 0-5 cm and 0-60 cm layers, as the influence of wind and waves would keep the undrogued drifters more in-line with the wind. Ardhuin et al. (2009) attributes larger deflection angles of wind-driven currents to enhanced mixing due to wave breaking, which could be a congruous theory to our observation of increasing deflection angles at higher wind speeds. Enhanced mixing caused by breaking waves, acts to mix the vertical momentum of surface currents, likely resulting in larger deflection angles at shallower depths (Rascle et al., 2006).

The results presented here, to the authors' knowledge, are among the few studies able to reported estimates of the vertical shear of wind-and wave-driven currents in the upper 1 meter of the ocean under this regime of high winds (11.5-20 m s<sup>-1</sup>). The combined wind-wave-driven velocity in the upper 5 cm calculated here is, on average, ~1.6 times greater than that measured over 0-60 cm for the wind magnitudes presented. These results support the finding of Laxague et al. (2017), which showed that, in the presence of negligible stratification in the upper layer, total surface currents in the upper 1 cm are twice as fast as the average current over the first 1 m (measured to be 0.57 m s<sup>-1</sup> and 0.3 m s<sup>-1</sup>, respectively) due to wind- and wave-driven vertical velocity shear. It should also be noted, however, that vertical shear in the presence of strong mixing (i.e. wave breaking) acts to diminish vertical velocity gradients, which could suggest some of the shear observed is due to the velocity slip of the undrogued drifters (Sutherland et al. 2016). The true novelty of the results presented here lies in the instantaneous estimates for the vertical shear of the purely wind-driven surface current over the 0-5 cm and 0-60 cm layers, made possible through the method of velocity deconstruction used here. The deconstruction of the total velocity measured from drogued and undrogued drifters gives us an estimate, directly related to the wind velocity, of the wind-driven vertical shear at the very surface of the ocean, which has proved difficult to measure by previous studies and has significant implications for surface transport problems in the real ocean.

The high wind events focused on here only occurred for a small number of days during the LASER campaign, which is typical for the Northern Gulf of Mexico in the winter. Since the velocity profile within upper meter has been shown

Deleted:

Deleted: the first

Deleted:

Deleted: .

Deleted:

Deleted: directly

Deleted: 's surface

to be very dynamic, being affected by the general oceanic circulation as well as local wind-wave-driven mechanisms, it is important to observe near surface currents under different environmental conditions and at greater vertical resolution. Attention also needs to be given to the transport of Lagrangian particles by breaking waves which induce vertical motion and mixing which can alter wind-driven currents.

## 5 6. Conclusion

We use a combination of stored output data from the UWIN-CM fully coupled atmospheric-wave-ocean model and observational trajectory data from both drogued and undrogued CARTHE drifters to calculate an estimate for purely wind-driven currents during periods of strong, increasing winds. The use of co-located drogued and undrogued drifters provides measurements for the vertical shear between the upper 5 cm and upper 60 cm surface layers. Using the Lagrangian Variation Analysis, we are able to create velocity fields in the hours leading up to the high wind events studied, that serve as an estimate for the pre-existing regional circulation which is found to still affect the surface velocities during periods of high winds. After subtracting the regional circulation from our measured drifter velocities we analyze the relationship between wind velocity, Stokes drift, and wind-driven current over the draft depth of the drifters. On average, we find the wind-driven current to decrease in magnitude and rotate to the right of the wind with depth, with the upper 5 cm (60 cm) traveling  $\sim 5^\circ$ - $55^\circ$  ( $\sim 30^\circ$ - $85^\circ$ ) at 3.4-6.0 % (2.3-4.1 %) of the wind speed over the range of 12-20 m s<sup>-1</sup>. Both surface layers display an increase in deflection angle with increasing wind speed, sustaining an average difference of  $8^\circ$ - $30^\circ$  between flow directions.

This study is among the few (Sentchev et al., 2017; Berta et al., 2018) that have investigated the real-time response of very near surface currents to increasing wind. We are able to observe characteristics of the vertical shear present between the upper 60 cm and 5 cm of wind driven surface currents. Observations of vertical shear this close to the surface in the real ocean, especially during high wind events of this nature, are very scarce due to the limitations of present day instrumentation. The vertical velocity profile within the upper meter has been shown to exhibit a large amount of shear, with velocities at the surface (upper few centimeters) being largely dominated by wind and waves (Laxague et al., 2017; Morey et al., 2018). This highlights the importance of very near surface observations, such as those presented in this paper, as this vertical shear can have large impacts on the transport of pollutants of varying size and buoyancy, like plastics and oil. Incorporating vertical shear due to wind and waves within the upper meter, could have important implications for fate prediction of pollutants transported at the ocean surface.

**Data Availability.** Raw, processed drifter trajectory data, and drogue classification are publicly available through the Gulf of Mexico Research Initiative Information & Data Cooperative (GRIIDC) at <https://data.gulfresearchinitiative.org> under <https://doi.org/10.7266/N7MS3R6V>, <https://doi.org/10.7266/N7W0940J>, and <https://doi.org/10.7266/N7QN656H>, respectively. The UWIN-CM data can also be obtained from GRIIDC under <https://doi.org/10.7266/N7KW5DH7>, where the moving vessel profiler CTD data can also be found under <https://doi.org/10.7266/N7H130FC>. AVIOS SST products, produced by Collecte Localisation Satellites (CLS), are available upon request.

Deleted:

Formatted: Default Paragraph Font, Font color: Text 1

Deleted: .



**Competing interests.** The authors declare that they have no conflict of interest.

**Author Contribution.** The formal analysis was carried out by JL as a PhD candidate under the supervision of TO. All authors contributed in the conceptualization of the work. MB educated JL on the necessary algorithm (LAVA) used to performed the formal analysis.

**Acknowledgements.** This research was made possible by a grant from The Gulf of Mexico Research Initiative. The authors would like to thank all those involved in planning and executing LASER, as well as the scientists involved with the data processing and drogued detection that made this analysis possible. [The authors would like to express gratitude to Dr. Milan Curcic for sharing his expertise of the UWIN-CM.](#)

## References

- Ardhuin, F., Marié, L., Rasclé, N., Forget, P. and Roland, A.: Observation and estimation of Lagrangian, Stokes, and Eulerian currents induced by wind and waves at the sea surface, *J. Phys. Oceanogr.*, 39, 2820-2838, <http://doi:10.1175/2009JPO4169.1>, 2009.
- 15 Berta, M., Bellomo, L., Magaldi, M.G., Griffa, A., Molcard, A., Marmain, J., Borghini, M. and Taillandier, V.: Estimating Lagrangian transport blending drifters with HF radar data and models: results from the TOSCA experiment in the Ligurian Current (North Western Mediterranean Sea). *Prog. Oceanogr.*, 128, 15-29, <https://doi.org/10.1016/j.pocean.2014.08.004>, 2014.
- 20 Berta, M., Griffa, A., Magaldi, M.G., Özgökmen, T.M., Poje, A.C., Haza, A.C. and Olascoaga, M.J.: Improved surface velocity and trajectory estimates in the Gulf of Mexico from blended satellite altimetry and drifter data, *J. Atmos. Ocean. Tech.*, 32, 1880-1901, <https://doi.org/10.1175/JTECH-D-14-00226.1>, 2015.
- Berta, M., Bellomo, L., Griffa, A., Magaldi, M.G., Molcard, A., Mantovani, C., Gasparini, G.P., Marmain, J., Vetrano, A., Béguery, L. and Borghini, M.: Wind-induced variability in the Northern Current (northwestern Mediterranean Sea) as depicted by a multi-platform observing system. *Ocean Sci.*, 14, 689-710, <https://doi.org/10.5194/os-14-689-2018>, 2018.
- 25 Buckley, M.P. and Veron, F.: The turbulent airflow over wind generated surface waves, *Eur. J. Mech. B. Fluids*, 73, 132-143, <https://doi.org/10.1016/j.euromechflu.2018.04.003>, 2019.
- Chang, Y., Hammond, D., Haza, A.C., Hogan, P., Huntley, H.S., Kirwan Jr, A.D., Lipphardt Jr, B.L., Taillandier, V., Griffa, A. and Özgökmen, T.M.: Enhanced estimation of sonobuoy trajectories by velocity reconstruction with near-surface drifters, *Ocean Modell.*, 36, 179-197, <https://doi.org/10.1016/j.ocemod.2010.11.002>, 2011.
- 30 Chassignet, E.P., Smith, L.T., Halliwell, G.R. and Bleck, R.: North Atlantic simulations with the Hybrid Coordinate Ocean Model (HYCOM): Impact of the vertical coordinate choice, reference pressure, and thermobaricity, *J. Phys. Oceanogr.*, 33, 2504-2526, 2003.

- Chassignet, E.P., Hurlburt, H.E., Smedstad, O.M., Halliwell, G.R., Hogan, P.J., Wallcraft, A.J., Baraille, R. and Bleck, R.: The HYCOM (hybrid coordinate ocean model) data assimilative system, *J. Mar. Syst.*, 65, 60-83, <https://doi.org/10.1016/j.jmarsys.2005.09.016>, 2007.
- Chen, S.S., Zhao, W., Donelan, M.A. and Tolman, H.L.: Directional wind-wave coupling in fully coupled atmosphere-wave-ocean models: Results from CBLAST-Hurricane, *J. Atmos. Sci.*, 70, 3198-3215, <https://doi.org/10.1175/JAS-D-12-0157.1>, 2013.
- Chen, S.S. and Curcic, M.: Ocean surface waves in Hurricane Ike (2008) and Superstorm Sandy (2012): Coupled model predictions and observations, *Ocean Modell.*, 103, 161-176, <https://doi.org/10.1016/j.ocemod.2015.08.005>, 2016.
- Cole, R., & Symonds, D.: A 25 year collaboration using ADCPs. In 2015 IEEE/OES 11th Current, Waves and Turbulence Measurement Workshop, St. Petersburg, FL, USA, March 2015, 1-10, 2015.
- Curcic, M., Chen, S.S. and Özgökmen, T.M.: Hurricane-induced ocean waves and stokes drift and their impacts on surface transport and dispersion in the Gulf of Mexico, *Geophys. Res. Lett.*, 43, 2773-2781, <http://doi.org/10.1002/2015GL067619>, 2016.
- Davis, R.E.: Drifter observations of coastal surface currents during CODE: The method and descriptive view, *J. Geophys. Res. C: Oceans*, 90, 4741-4755, 1985
- Donelan, M.A., Curcic, M., Chen, S.S. and Magnusson, A.K.: Modeling waves and wind stress, *J. Geophys. Res. C: Oceans*, 117, <http://doi.org/10.1029/2011JC007787>, 2012.
- Ekman, V.W.: On the influence of the Earth's rotation on ocean-currents, *Arkiv for Matematik, Astronomi, och Fysik*, 2, 1-52, 1905.
- Gonçalves, R.C., Iskandarani, M., Özgökmen, T. and Thacker, W.C.: Reconstruction of submesoscale velocity field from surface drifters. *J. Phys. Oceanogr.*, in press, <http://doi.org/10.1175/JPO-D-18-0025.1>, 2019.
- Haza, A.C., D'Asaro, E., Chang, H., Chen, S., Curcic, M., Guigand, C., Huntley, H.S., Jacobs, G., Novelli, G., Özgökmen, T.M. and Poje, A.C.: Drogue-loss detection for surface drifters during the Lagrangian submesoscale experiment (LASER), *J. Atmos. Ocean. Tech.*, 35, 705-725, <http://doi.org/10.1175/JTECH-D-17-0143.1>, 2018.
- Hill, C., DeLuca, C., Suarez, M. and Da Silva, A.: The architecture of the earth system modeling framework, *Comput. Sci. Eng.*, 6, 18-28, <https://doi.org/10.1109/MCISE.2004.1255817>, 2004.
- Isobe, A., Kubo, K., Tamura, Y., Nakashima, E. and Fujii, N.: Selective transport of microplastics and mesoplastics by drifting in coastal waters, *Mar. pollut. Bull.*, 89, 324-330, <https://doi.org/10.1016/j.marpolbul.2014.09.041>, 2014.
- Kim, S.Y., Cornuelle, B.D. and Terrill, E.J.: Decomposing observations of high-frequency radar-derived surface currents by their forcing mechanisms: Locally wind-driven surface currents, *J. Geophys. Res. C: Oceans*, 115, C12046 <https://doi.org/10.1029/2010JC006223>, 2010.

Kudryavtsev, V.N. and Soloviev, A.V.: Slippery near-surface layer of the ocean arising due to daytime solar heating, *J. of Phys. Oceanogr.*, 20(5), 617-628, [https://doi.org/10.1175/1520-0485\(1990\)020<0617:SNSLOT>2.0.CO;2](https://doi.org/10.1175/1520-0485(1990)020<0617:SNSLOT>2.0.CO;2), 1990.

Formatted: Font color: R,G,B (26,26,26)

- Laxague, N.J., Özgökmen, T.M., Haus, B.K., Novelli, G., Shcherbina, A., Sutherland, P., Guigand, C.M., Lund, B., Mehta, S., Alday, M. and Molemaker, J.: Observations of Near-Surface Current Shear Help Describe Oceanic Oil and Plastic Transport, *Geophys. Res. Lett.*, 45, 245-249, <https://doi.org/10.1002/2017GL075891>, 2018.
- 5 Le Hénaff, M., Kourafalou, V.H., Paris, C.B., Helgers, J., Aman, Z.M., Hogan, P.J. and Srinivasan, A.: Surface evolution of the Deepwater Horizon oil spill patch: combined effects of circulation and wind-induced drift, *Environ. Sci. Technol.*, 46, 7267-7273, <https://doi.org/10.1021/es301570w>, 2012.
- Lumpkin, R., and Pazos, M.: Measuring surface currents with Surface Velocity Program drifters: the instrument, its data, and some recent results, In: *Lagrangian Analysis and Prediction of Coastal and Ocean Dynamics*, edited by: Griffà, A., Kirwan, A. D., Mariano, A., Özgökmen, T. M., and Rossby, T. Cambridge University Press, Cambridge, 39–67, 2007.
- 10 Lumpkin, R., Özgökmen, T. and Centurioni, L.: Advances in the application of surface drifters, *Annual Review of Marine Science*, 9, 59-81, <https://doi.org/10.1146/annurev-marine-010816-060641>, 2017.
- Morey, S., Wienders, N., Dukhovskoy, D. and Bourassa, M.: Measurement characteristics of near-surface currents from ultra-thin drifters, drogued drifters, and HF radar, *Remote Sens.* 10(10), 1633, <https://doi.org/10.3390/rs10101633>, 2018.
- 15 Novelli, G., Guigand, C.M., Cousin, C., Ryan, E.H., Laxague, N.J., Dai, H., Haus, B.K. and Özgökmen, T.M.: A biodegradable surface drifter for ocean sampling on a massive scale, *J. of Atmos. Ocean. Tech.* 34, 2509-2532, <https://doi.org/10.1175/JTECH-D-17-0055.1>, 2017.
- Ohlmann, J.C. and Niiler, P.P.: Circulation over the continental shelf in the northern Gulf of Mexico, *Prog. Oceanogr.*, 64, 45-81, <https://doi.org/10.1016/j.pocean.2005.02.001>, 2005.
- 20 Özgökmen, T.M., Chassignet, E.P., Dawson, C.N., Dukhovskoy, D., Jacobs, G., Ledwell, J., Garcia-Pineda, O., MacDonald, I.R., Morey, S.L., Olascoaga, M.J. and Poje, A.C.: Over what area did the oil and gas spread during the 2010 Deepwater Horizon oil spill?, *Oceanography*, 29, 96-107, <http://dx.doi.org/10.5670/oceanog.2016.74>, 2016.
- Phillips, O. M.: *Dynamics of the Upper Ocean*. Cambridge University Press, Cambridge. 1977.
- Pollard, R.T.: On the generation by winds of inertial waves in the ocean, *Deep Sea Research and Oceanographic Abstracts*, 17, 795-812, [https://doi.org/10.1016/0011-7471\(70\)90042-2](https://doi.org/10.1016/0011-7471(70)90042-2), 1970.
- 25 Pollard, R.T. and Millard Jr, R.C.: Comparison between observed and simulated wind-generated inertial oscillations, *Deep Sea Research and Oceanographic Abstracts*, 17, 813-821, [https://doi.org/10.1016/0011-7471\(70\)90043-4](https://doi.org/10.1016/0011-7471(70)90043-4), 1970.
- Poulain, P.M., Gerin, R., Mauri, E. and Pennel, R.: Wind effects on drogued and undrogued drifters in the Eastern Mediterranean, *J. Atmos. Ocean. Techn.*, 26, 1144-1156, <https://doi.org/10.1175/2008JTECHO618.1>, 2009.
- 30 Rascle, N., Ardhuin, F. and Terray, E.A.: Drift and mixing under the ocean surface: A coherent one-dimensional description with application to unstratified conditions, *J. Geophys. Res. C: Oceans*, 111, C03016, <https://doi.org/10.1029/2005JC003004>, 2006.

**Formatted:** Default Paragraph Font, Font:(Default) Times New Roman, 12 pt, Font color: R,G,B (26,26,26), English (UK)  
**Deleted:** .

- Raschke, N., and Arduini, F.: Drift and mixing under the ocean surface revisited: Stratified conditions and model-data comparisons, *J. Geophys. Res.*, 114, C02016, <http://doi.org/10.1029/2007JC004466>, 2009.
- Röhrs, J., Sperrevik, A.K., Christensen, K.H., Broström, G. and Breivik, Ø.: Comparison of HF radar measurements with Eulerian and Lagrangian surface currents, *Ocean Dyn.*, 65, 679-690, <https://doi.org/10.1007/s10236-015-0828-8>, 2015.
- 5 Röhrs, J., and Christensen, K. H.: Drift in the uppermost part of the ocean, *Geophys. Res. Lett.*, 42, 10349-10355, <https://doi.org/10.1002/2015GL066733>, 2015.
- Santala, M. J., & Terray, E. A.: A technique for making unbiased estimates of current shear from a wave-follower, *Deep Sea Res. Part A*, 39(3-4), 607-622, [https://doi.org/10.1016/0198-0149\(92\)90091-7](https://doi.org/10.1016/0198-0149(92)90091-7), 1992.
- Sentchev, A., Forget, P. and Fraunié, P.: Surface current dynamics under sea breeze conditions observed by simultaneous HF radar, ADCP and drifter measurements, *Ocean Dyn.*, 67, 499-512, <https://doi.org/10.1007/s10236-017-1035-6>, 2017.
- 10 Skamarock, W.C., Klemp, J.B., Dudhia, J., Gill, D.O., Barker, D.M., Duda, M.G., Huang, X.Y., Wang, W. and Powers, J.G.: A description of the advanced research WRF version 3, NCAR Technical Note NCAR/TN-475+STR, National Center for Atmospheric Research, <http://dx.doi.org/10.5065/D68S4MVH>, 2008.
- Stewart, R.H. and Joy, J.W.: HF radio measurements of surface currents, *Deep Sea Research and Oceanographic Abstracts*, 15, 21, 1039-1049, [https://doi.org/10.1016/0011-7471\(74\)90066-7](https://doi.org/10.1016/0011-7471(74)90066-7), 1974.
- Stokes, G. G.: On the theory of oscillatory waves, *Transactions of the Cambridge Philosophical Society*, 8, 441-473, 1847.
- Sutherland, G., Marié, L., Reverdin, G., Christensen, K.H., Broström, G. and Ward, B.: Enhanced turbulence associated with the diurnal jet in the ocean surface boundary layer, *J. Phys. Oceanogr.*, 46(10), 3051-3067, <https://doi.org/10.1175/JPO-D-15-0172.1>, 2016.
- 20 Taillandier, V., Griffa, A. and Molcard, A.: A variational approach for the reconstruction of regional scale Eulerian velocity fields from Lagrangian data, *Ocean Modell.*, 13, 1-24, <https://doi.org/10.1016/j.ocemod.2005.09.002>, 2006.
- Wallcraft, A.J., Metzger, E.J. and Carroll, S.N.: Software design description for the Hybrid Coordinate Ocean Model (HYCOM) version 2.2, Naval Research Laboratory Tech. Rep. NRL/MR/7320-09-9166, NRL, 2009.
- Wu, J.: Sea-surface drift currents induced by wind and waves, *J. Phys. Oceanogr.*, 13, 1441-145, [https://doi.org/10.1175/1520-0485\(1983\)013<1441:SSDCIB>2.0.CO;2](https://doi.org/10.1175/1520-0485(1983)013<1441:SSDCIB>2.0.CO;2), 1983.
- 25

**Deleted:**

**Formatted:** Font:Not Italic

**Formatted:** Font:Not Italic

**Formatted:** Font:Not Italic

**Formatted:** Font:Not Italic

**Formatted:** Font:Not Italic

**Formatted:** Default Paragraph Font, Font:(Default) Times New Roman, 12 pt, Font color: R,G,B (26,26,26), English (UK)

**Formatted:** Font:Not Italic

**Formatted:** Font:Not Italic

**Formatted:** Font:Not Italic

**Formatted:** Font:Not Italic

5

Literature	Instrument Used	Measurement Depth	Wind Magnitude	Avg. Velocity of Wind-Driven Current (% of Wind)	Avg. Deflection Angle to the Right of Wind
Ardhuin et al. 2009	HF radar	0-1 m	1-19 m s <sup>-1</sup>	0.4 – 0.8 %	45° - 70°
Kim et al. 2010	HF radar	0-1 m	1-5 m s <sup>-1</sup>	2 – 5 %	50° - 90°
Berta et al. 2018	HF radar	0-0.75 m	10-20 m s <sup>-1</sup>	2 %	25° - 30°
Sentchev et al. 2017	ADCP	0.5-0.75 m	1-6 m s <sup>-1</sup>	2 – 4 %	12° - 25°
Poulain et al. 2009	Undrogued SVP drifter	0-0.25 m	0-15 m s <sup>-1</sup>	2 %	17° - 20°
	CODE drifter	0-1 m		1 %	28° - 30°
Röhrs and Christensen, 2015	iSphere	0-0.15m	0-20 m s <sup>-1</sup>	3-5%	64°
	CODE drifter	0.3-1 m		2.4%	84°
Current Work	CARTHE Undrogued	0-0.05 m	11-20 m s <sup>-1</sup>	3.6-6 %	5° - 55°
	CARTHE Drogued	0-0.60 m		2.3-4.1 %	30° - 85°

Table 1: Review of literature on wind-driven surface currents using real ocean, observational data.

10

15

5

10

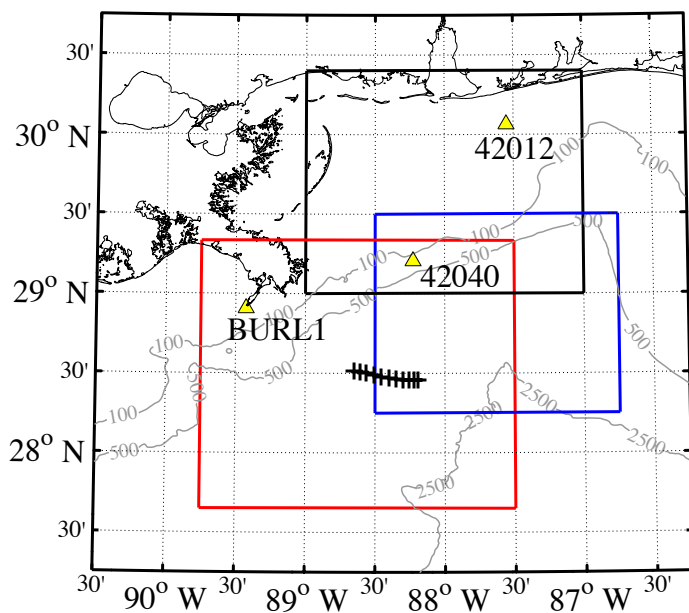
15

20

25

30

35



Deleted: <sp>

Formatted: Font:9 pt, Bold, Font color: Text 1

Formatted: Font:9 pt, Bold, Font color: Text 1

Deleted: U10

Figure 1: Research area in the Northern Gulf of Mexico, ESE of the Mississippi River delta. NDBC buoy locations used for validation of UWIN-CM, wind and wave data are shown by yellow triangles. Domains corresponding to each high wind event analyzed are shown in the red (February 24<sup>th</sup>), blue (January 22<sup>nd</sup>), and black (March 20<sup>th</sup>) boxes. Black hash marks show the ship track where data in Fig. 2 were collected. Grey contours show the bathymetry at 100, 500 and 2500 meters.

5

10

15

20

25

30

35

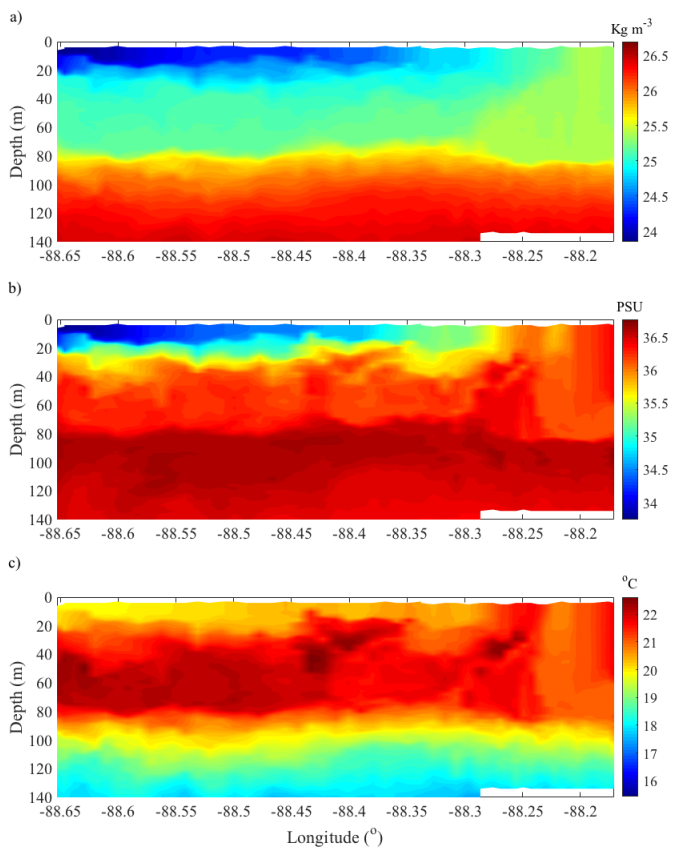


Figure 2: Potential density (a), salinity (b) and temperature (c) data along the eastward traveling transect shown in Fig. 1, measured by moving vessel profiler (MVP) CTD casts taken on January 28<sup>th</sup> from 16:48 – 21:00 UTC.

Formatted: Font:9 pt, Bold

Deleted:

Deleted:

... [3]

Formatted: Font color: Auto, English (US)

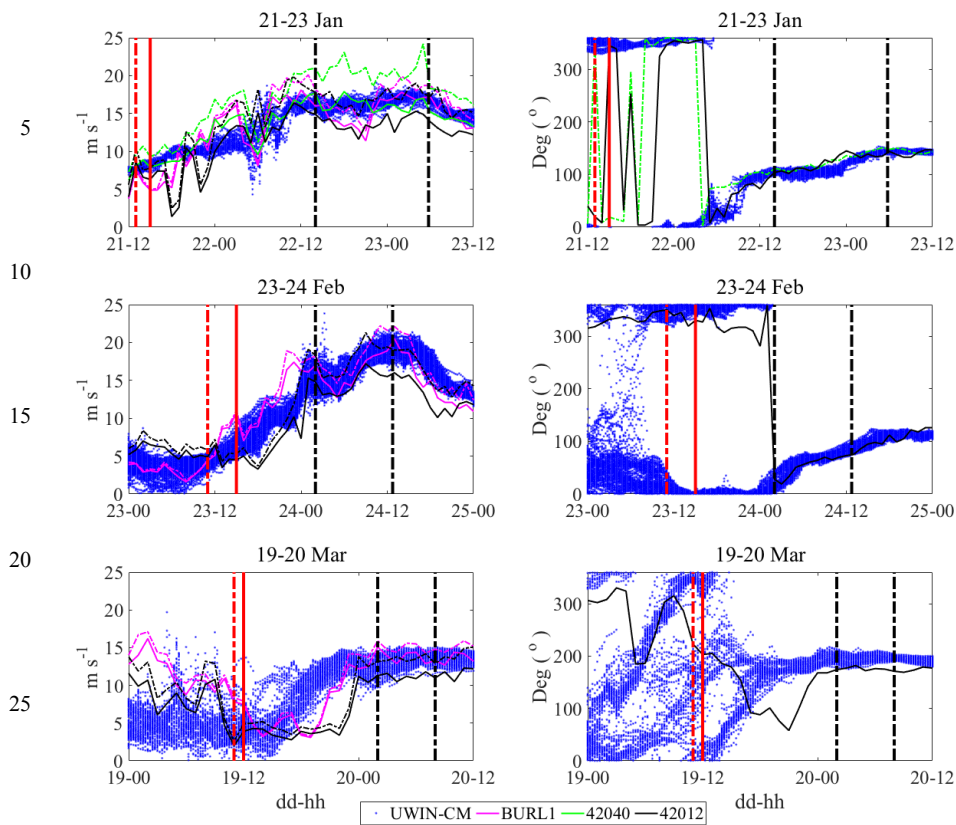


Figure 3: Wind velocity magnitudes (left) and directions (right) during the hours preceding, and including, each high wind event. Black dashed vertical lines show the beginning and end of the high wind analysis periods. Red dashed(solid) red lines indicate beginning of the hour over which the pre-existing regional circulation was estimated with undrogued(drogued) drifters. U10 wind data from the UWIN-CM are plotted at the nearest point to every drifter location. Wind observations from NDBC buoys BURL1, 42040, and 42012 are plotted as well. Solid lines show sustained winds, while dashed lines show wind gusts. All wind directions are plotted as the direction in which the wind is traveling. Buoy 42040 was only operational during the first wind event and BURL1 did not record any wind direction data during the experiment.



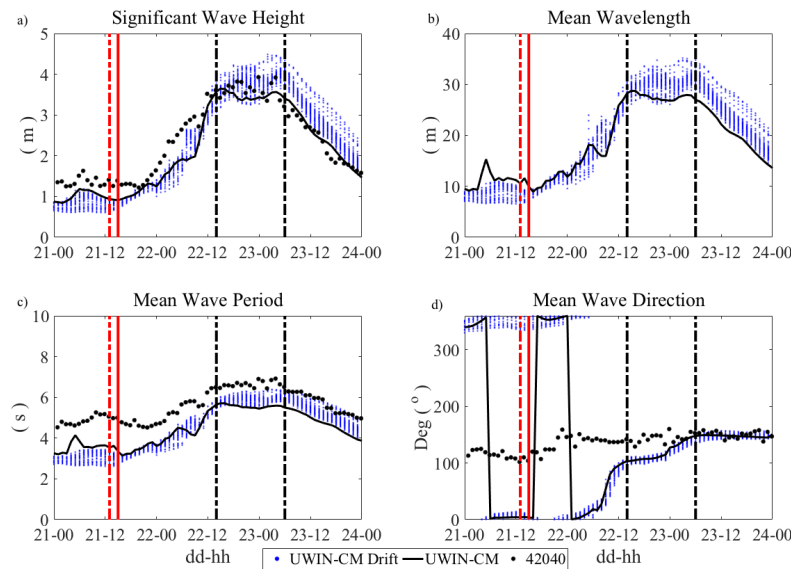
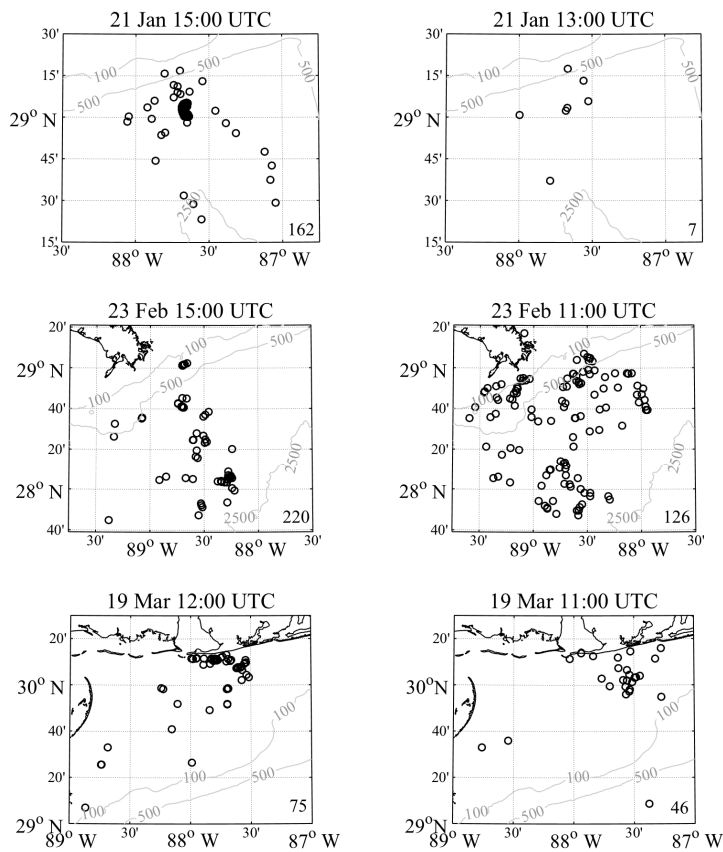


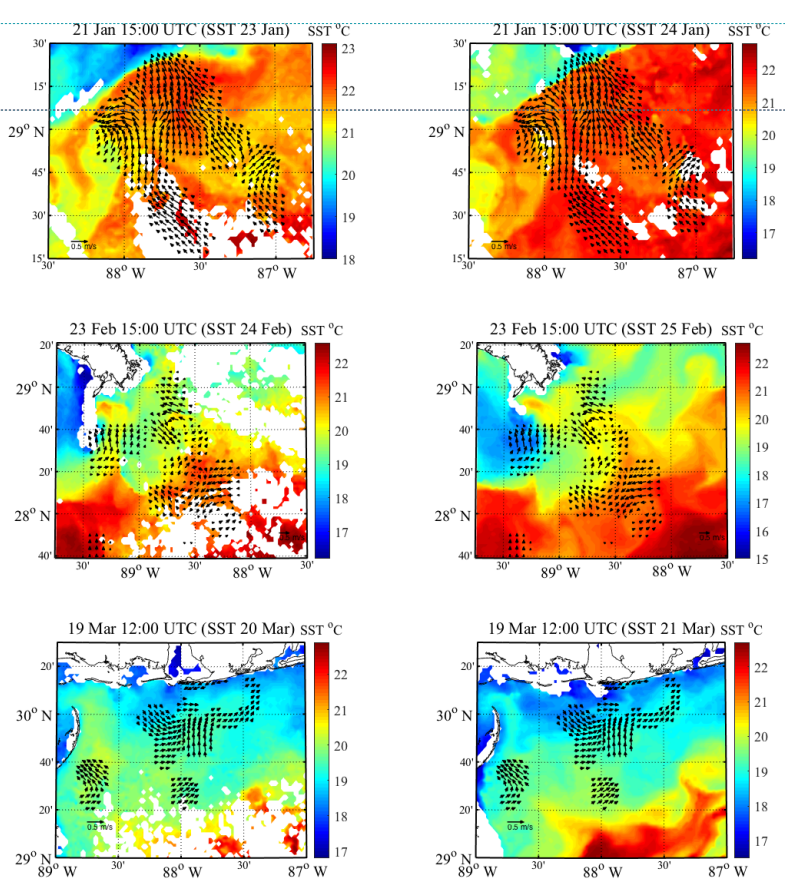
Figure 4: Significant wave height (a), mean wavelength (b), mean wave period (c) and mean wave direction (d) from the UWIN-CM and NDBC buoy 42040 during the January high wind event. Black dashed vertical lines show the beginning and end of the high wind analysis periods. Red dashed(solid) red lines indicate beginning of the hour over which the pre-existing regional circulation was estimated with undrogued(drogued) drifters. Wave data from the UWIN-CM, plotted at the nearest point to every drifter location, are shown in blue. The solid black lines show the UWIN-CM output data closest to the coordinates of buoy 42040, while observations from buoy 42040 are shown black dots. Wavelength data was not collected by this NDBC station.



**Figure 5:** Drogued (left) and undrogued (right) drifters used to create Eulerian velocity fields of the pre-wind event regional circulation estimates using the LAgrangian Variational Analysis (LAVA). Raw drifter locations are plotted at the end of the hour over which the velocity fields are created. Numbers in bottom right corner of plots display the number of drifters used for each velocity field construction. Panels correspond to sub-domains shown in Figure 1.

Deleted:	.	...	[4]
Deleted:	.	...	[5]
Deleted:	3		

5  
10  
15  
20  
25  
30  
35



Formatted: Font:9 pt, Bold, Font color: Text 1

Deleted: <sp>

Formatted: Font:9 pt, Bold, Font color: Text 1

Deleted: .

Deleted: .

Deleted: 4

Deleted: (left) and undrogued (right)

Deleted: .

Formatted: Superscript

Figure 6: Eulerian velocity fields of the regional circulation that preceded each high wind event, created using LAVA for drogued drifters in the area. 24-hour averages of AVISO SST data during (left) and after (right) each high wind event are also plotted. Titles of each plot list the beginning of each hour over which the velocity field was created from drifter trajectories and the day corresponding to the AVISO SST data. 24-hour averages, produced by AVISO, are centered on the 0<sup>th</sup> hour of the day listed. In each velocity field, every third vector is plotted for visibility. Velocity fields on the left and right side panels are identical.

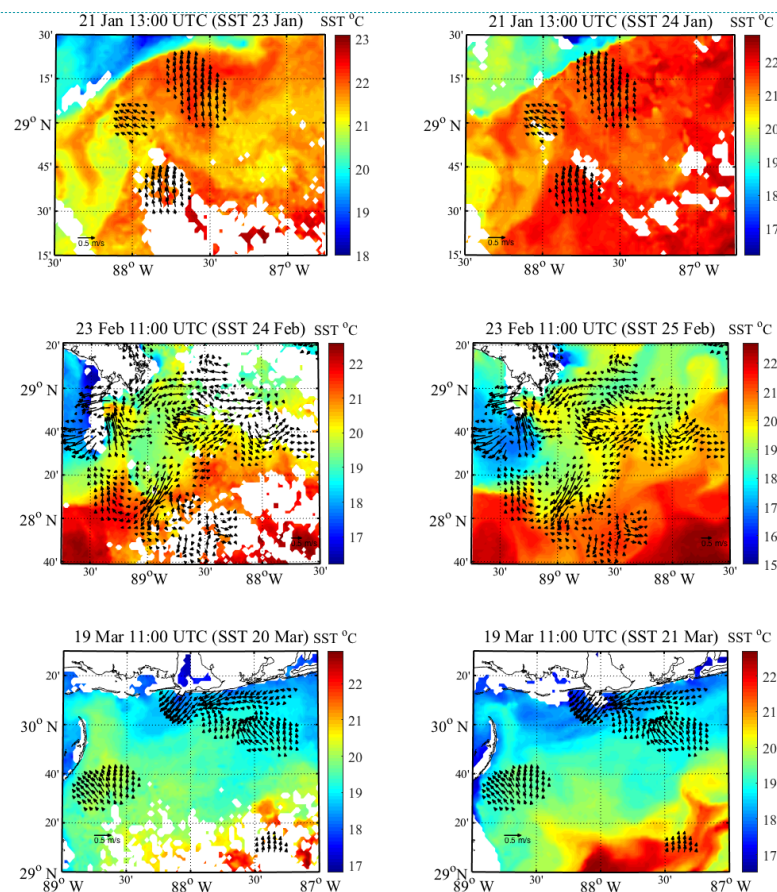
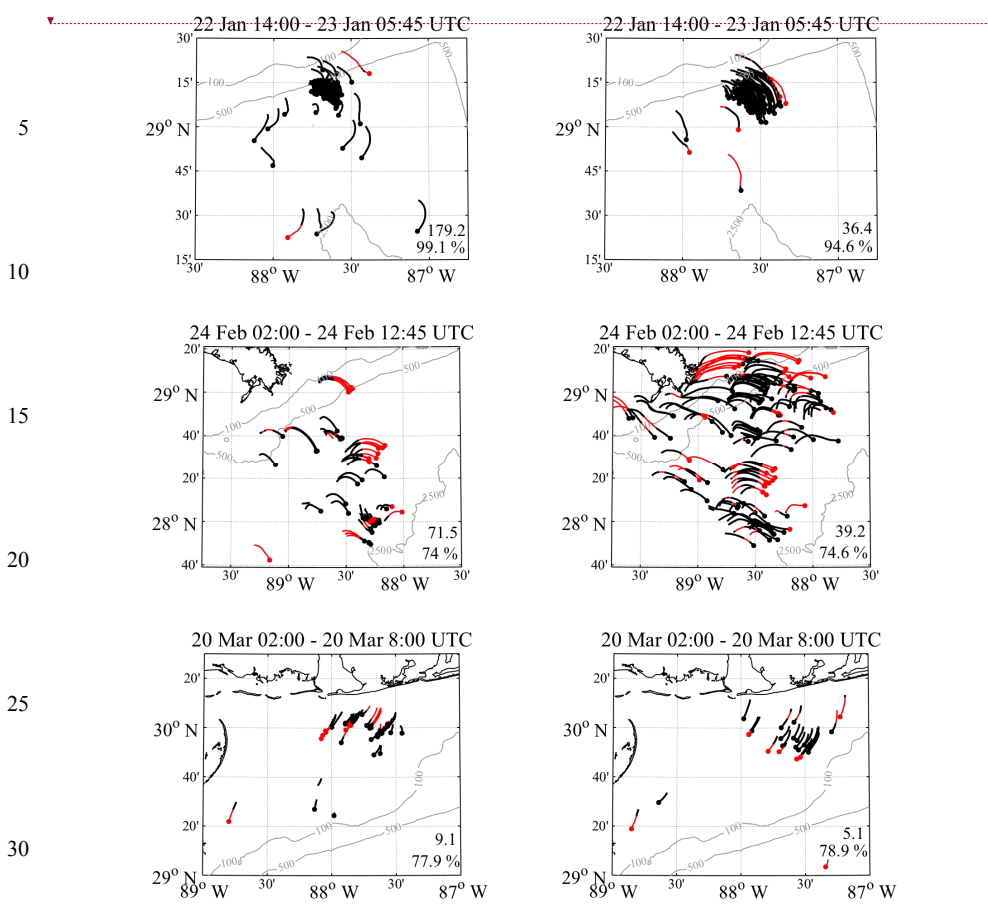


Figure 7: Eulerian velocity fields of the regional circulation that preceded each high wind event, created using LAVA for undrogued drifters in the area, plotted on top of the same 24-hour averages of SST data shown in Fig. 6. Titles and data are plotted in the same manner as Fig. 6.



**Figure 8:** Drogued (left) and undrogued (right) drifter trajectories during the hours of analysis for each high wind event. Time periods over which the total velocity deconstructions were calculated are shown in each title. Portions of the trajectories shown in black (red) depict segments which overlap (do not overlap) spatially with each respective Eulerian velocity field in Fig 4. (Top) the total number of retained trajectory data points, defined as number of drifter days given 15-minute time steps, and (bottom) the percentage of coverage between trajectories and each respective Eulerian velocity field in Fig.4 are listed within each plot. Trajectories missing head markers are a result of either drogue loss or lost GPS transmission during the experiment.

Deleted: .

Deleted: 5

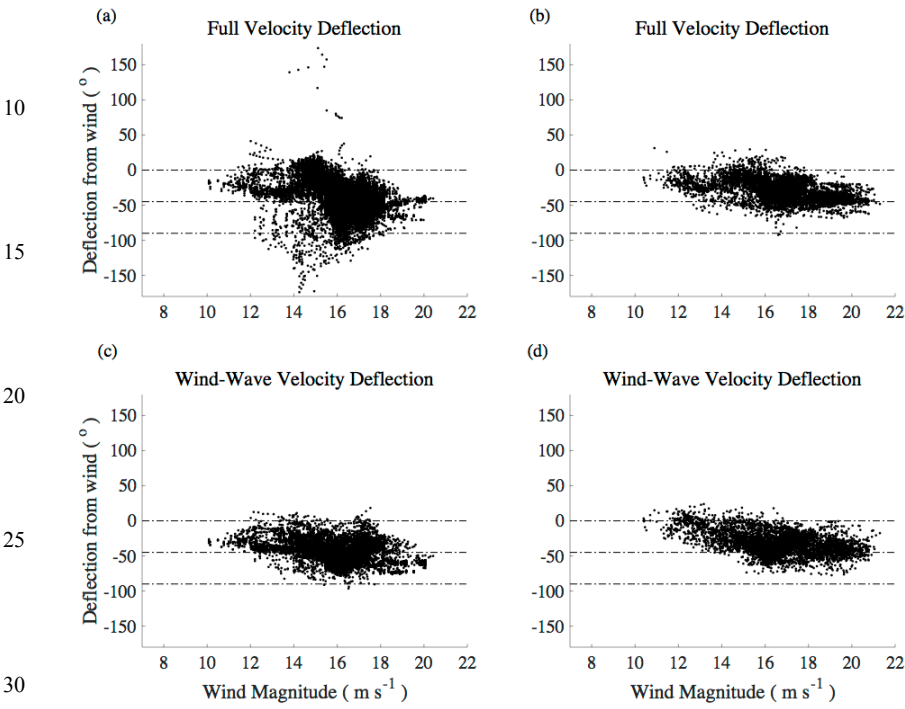


Figure 9: Scatter plots of deflection angles of drogued (a,c) and undrogued (b,d) drifter velocities before (a,b) and after (c,d) subtracting the pre-existing regional circulation velocity fields during the high wind periods analyzed. Data points that do not have both individual drifter velocity measurements and coinciding data in the Eulerian velocity fields of the pre-existing circulation during the high wind event are not included. Deflection angles are plotted against the U10 wind magnitude from the UWIN-CM model at the nearest point to the drifter locations in the domain.

Deleted: 6

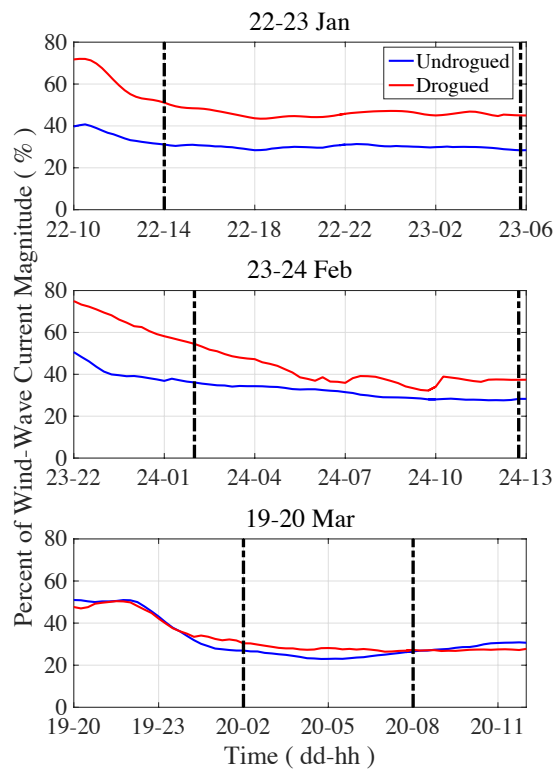
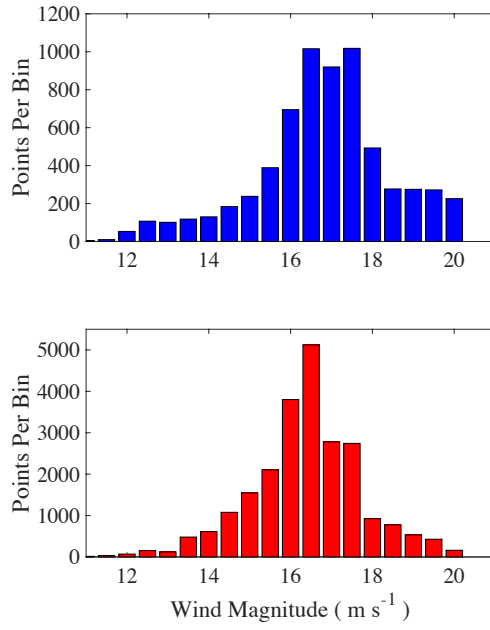


Figure 10: Average of the Eulerian velocity field estimates of the pre-wind regional circulation plotted as a percentage in time of the average combined wind- and wave-driven flow for drogued and undrogued drifters. Vertical dashed lines depict the analysis period for the total velocity deconstruction.

Deleted: 7

Deleted: .

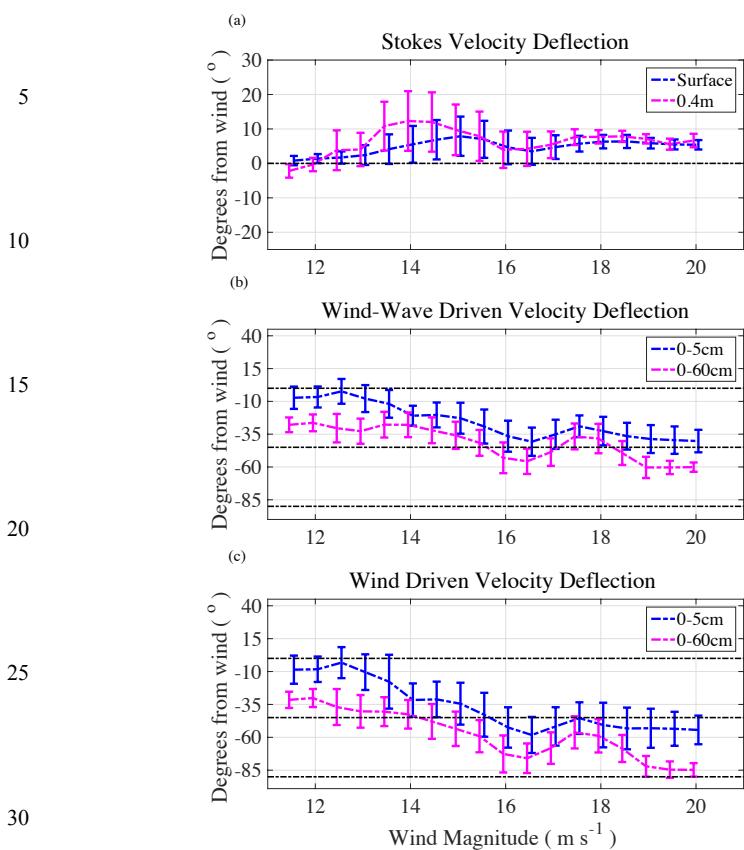
... [6]



**Figure 11:** Number of undrogued (top) and drogued (bottom) drifter positions where the velocity deconstruction was performed, binned by wind velocity magnitude on  $0.5 \text{ m s}^{-1}$  intervals. Point velocity measurements calculated from drifter trajectories that do not coincide spatially with available data in the pre-existing circulation velocity fields are not included.

Deleted: 8





**Figure 12:** Average deflection angles at drifter locations during periods of high wind binned by UWIN-CM wind magnitudes on  $0.5 \text{ m s}^{-1}$  intervals. Horizontal dotted lines denote  $0^\circ$ ,  $45^\circ$ , and  $90^\circ$  to the right of the wind. (a) UWIN-CM Stokes drift velocity direction at the surface ( $0 \text{ m}$ ) and at  $0.4 \text{ m}$  depth. (b) Velocity direction of drogued and undrogued drifters after the subtraction of the pre-existing circulation estimate. (c) Velocity direction of the purely wind-driven component of the drifter velocities. All error bars show  $\pm$  one standard deviation within each bin. Data in wind bins lower than  $11.5 \text{ m s}^{-1}$  were omitted due to lack of data points and large standard deviations.

Deleted: 9

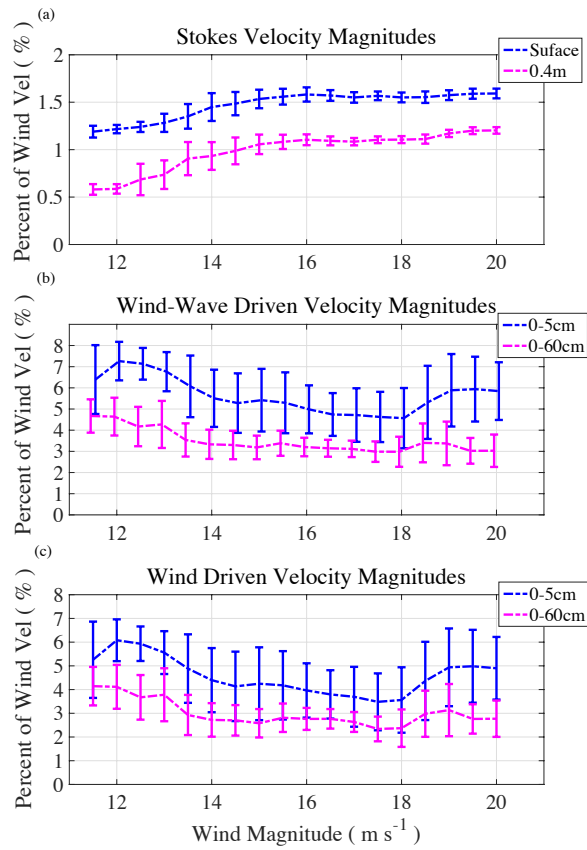


Figure 13: Average velocity magnitudes at drifter locations during periods of high wind binned by UWIN-CM wind magnitude on 0.5 m s<sup>-1</sup> intervals. (a) UWIN-CM Stokes drift velocity magnitude at the surface (0 m) and at 0.4 m depth. (b) Velocity magnitude of drogued and undrogued drifters after the subtraction of the pre-existing circulation estimate. (c) Velocity magnitude of the purely wind-driven component of the drifter velocities. All error bars show +/- one standard deviation within each bin. Data bins omitted in Figure 9 are also excluded.

Deleted: 0