Universiteit Utrecht

Opleiding Natuur- en Sterrenkunde

Analysis of surface drifter trajectories in the tropical Atlantic to track Sargassum

Bachelor Thesis

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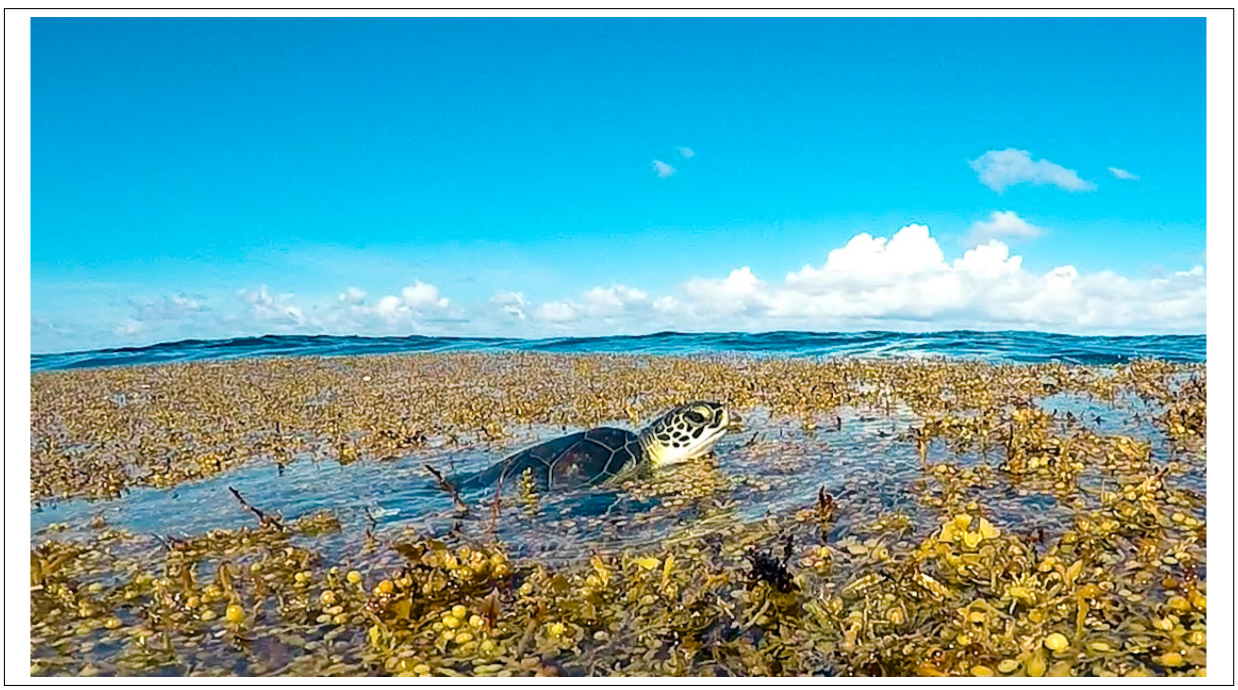

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Abstract

The Great Atlantic Sargassum Belt is growing in density and areal extent with an unexplained annual cycle. Large quantities of Sargassum have recently been reported in the central Atlantic Ocean and the Caribbean Sea, accompanied by frequent beaching events that have caused serious environmental, ecological, and economic problems. Sargassum consists of leafs that look like berries, these berries are filled with oxygen, allowing Sargassum to float on the surface. Using data collected in the summer of 2019 from undrogued Stokes and drogued SVP drifters, we investigate how the depth of the drifters impacts their trajectories and dispersion. We analyse for similarities and differences by comparing the difference in distance between drifters that are part of a pair, examining drifter trajectories, comparing their velocities and checking if there is a relation with the wind, waves or currents. We compare the trajectories of the drifters going eastward and we find that the undrogued Stokes drifters vary little in latitude while the drogued SVP drifters veer more south. By using multi linear regression, we find that this is possibly due to the wind. For the drifters going westward, we see that some of the drogued SVP drifters follow a different trajectory due to the presence of inertial oscillations. By comparing the velocities for the drifters, we find that the undrogued Stokes drifters drift faster than the drogued SVP drifters. This is expected because the wind has more effect on the surface than on the deeper layers in the ocean. We can conclude that if there will be any further research done into Sargassum, it matters if they use drogued or undrogued drifters. Sargassum floats at the surface thus the undrogued drifters are a better choice.

Contents

1 Introduction

Sargassum is an open-ocean seaweed species that floats freely in the ocean [1]. The two most frequent spieces present are the Sargassum fluitans and the Sargassum natans. The difference between the fluitans and the natans is that the natans are tipped with a spike and have leaves that are long-stalked and narrow [2]. But both kinds of Sargassum consist of leafs that look like berries [3], these berries are filled with oxygen, called pneumatocysts [4]. The oxygen causes the plant structure to be buoyant and allows it to float on the surface, where it is influenced by the wind and surface currents, forming large, dense mats. These mats of Sargassum can provide for protection of many life forms and can be used to reproduce and feed [5].

Figure 1: Sargassum consists of leafs that look like berries, the berries are filled with oxygen making it float on the surface of the ocean. Lines on the paper in the back show 1 cm squares. Photo taken by Erik Zettler [6].

Mats of Sargassum form a good habitat and can be used as a nursery for multiple marine species, making it an important part of the ecosystem near coasts [2]. The Sargassum drifts along coastlines near the Caribbean islands and almost every winter, the trade winds drive great amounts onto the beaches. But in the past few years, there has been a significant increase in the amount of Sargassum. This could have a negative impact on the marine ecosystems and could disrupt local communities. When Sargassum washes up on beaches, it starts to rot and release toxic chemicals, driving away tourists [6]. The rotting Sargassum also turns the water brown. While this is another reason for tourists to stay away, it also has a negative impact on the health of the ecosystems.

A place where a lot of this Sargassum can be found is called the Sargasso Sea, see figure 2. This area is also known as the Great Atlantic Sargassum Belt (GASB). In 2011, Sargassum in the Caribbean region reached a new high [2]. And in the same year, Sargassum started washing up on the shores of Africa. Up until this point, it was assumed that the Sargassum originated from the Sargasso Sea but recent studies point to the Small Sargasso Sea, see figure 2. This area is sometimes also referred to as the North-Equatorial Recirculation Region (NERR) [6].

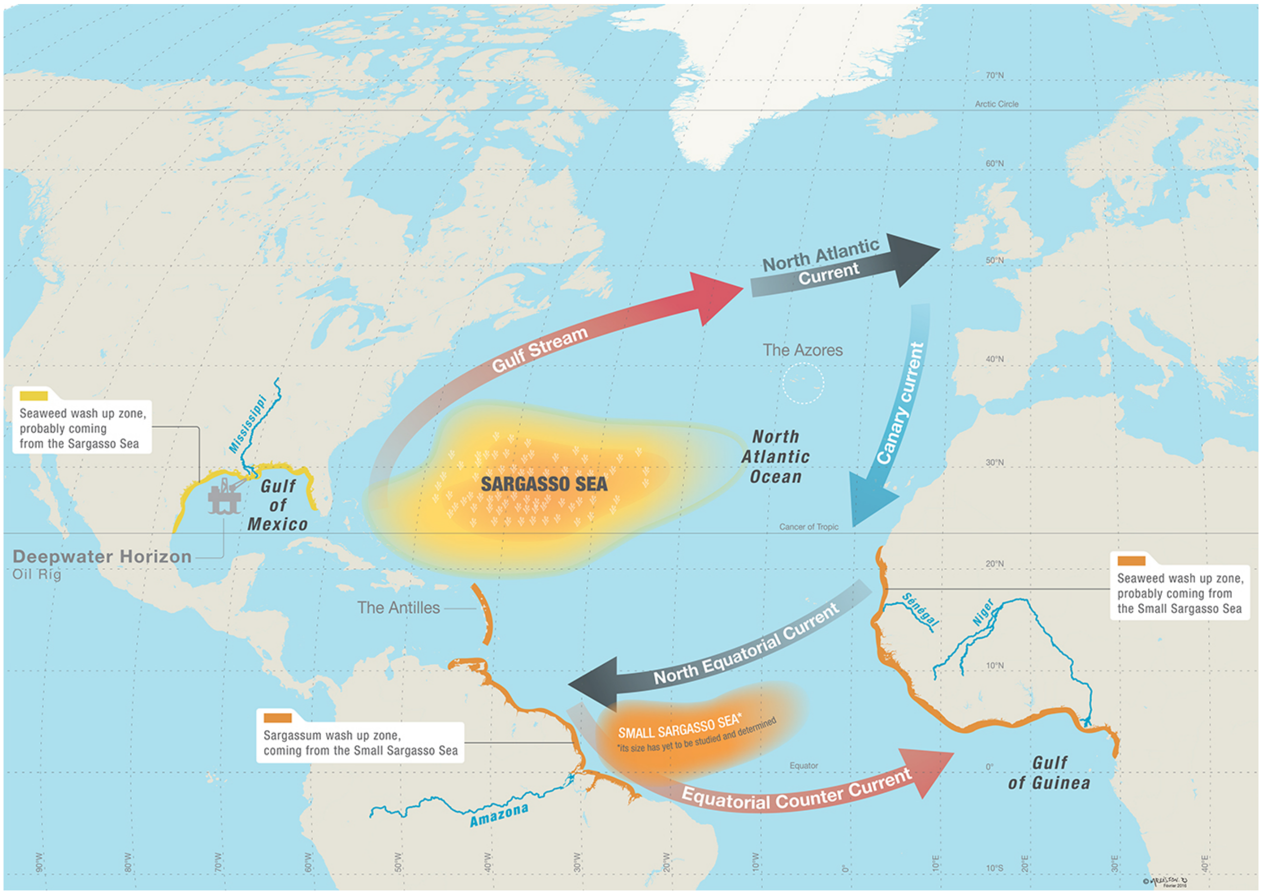


Figure 2: Map showing ocean currents that make up the limits for the Sargasso Sea. It also shows where the Small Sargasso sea is, bound between the North Equatorial current and the Equatorial Counter current. [5]

There are many unanswered questions about the beached Sargassum, like what is the origin and which route does it take to get to the beaches? To search for answers, a NIOZ (Nederlands Instituut voor Onderzoek der Zee) flagship, called Research Vessel Pelagia, sailed the Northern Atlantic Ocean to study Sargassum. The RV Pelagia was built in 1991 and with a length of 66 meters, it is completely designed to do research on while sailing. On the back of the ship and in the cargo hold are sea containers with changing laboratories. The “Sargassum” cruise (PE-455), along with a team of scientists, sailed from July 11th till August 11th.

The researchers on this ship kept up a journal from this cruise [6]. Erik Zettler, a guest researcher from NIOZ, writes in an entry from July 23rd about Satellite Oceanography. He writes about the big question concerning Sargassum, “Where does it come from?”. At first it was thought that the source was the Sargasso sea. But recent predictions suggest it originates more south and east, in the Small Sargasso Sea between Africa and Southern America, as mentioned before and shown in figure 2. One of the main reasons of this research cruise is to investigate this hypothesis [6].

While sailing through this belt, there were multiple drifters released during a span of 17 days. All drifters are being tracked by a GPS satellite system called Spot [7] and their location is collected every hour apart from 4 drifters, their location is collected every half hour. There are two types of drifters launched, undrogued and drogued. The researchers released 20 undrogued drifters that are 10 cm tall and stick only 1 cm above the surface [6]. The undrogued drifters are designed to move with the surface layer of the ocean, exposed to the Stokes drift and thus, from now on, they are referred to as undrogued Stokes drifters. The Stokes drifters were designed and built by Erik van Sebille at Utrecht University and are based on a design from Nicolas Wienders at Florida State University [6]. Furthermore, they also deployed 18 more traditional 'SVPstyle' drifters that are drogued at nominally 15 meters depth [e.g. Van Sebille et al., 2015]. The SVP (Surface Velocity Program) drifters have the aim to travel with the upper mixed layer and are provided by Shaun Dolk at NOAA/AOML/PhOD, Miami, FL, USA.

Figure 3: During the span of 17 days in the summer of 2019, 20 undrogued Stokes and 18 drogued SVP drifters are released in the North Atlantic sea to track Sargassum. On the left we see a drogued SVP drifter and on the right we see an undrogued Stokes drifter. Photo taken by Erik Zettler [6].

The reason for launching two types of drifters is to understand the mechanisms and pathways of Sargassum (and other small floating object, like plastic). This is crucial to prevent it from washing ashore, where it can cause problems.

2 Theory

The difference between undrogued Stokes drifters and drogued SVP drifters, is that the SVP drifters have a 15 meter drogue making sure it follows the currents at a depth of 15 meters and minimises the wind slippage [8]. There are multiple reasons as to why the undrogued Stokes drifters would behave differently than the drogued SVP drifters. Here, we discuss some of these reasons, like Stokes drift, surface ocean currents, the Ekman spiral and inertial oscillations.

2.1 Wind and waves

Along the sea surface, wind creates stress and this is the driving force of basin-wide circulations in the top layer of the water column [9]. The waters in the ocean respond to the wind stress because it has a low resistance to shear stress and the winds blow over the surface in a consistent matter. Multiple papers have written about the wind effects on drogued and undrogued drifters, for example Poulain et al. (2009) in the Eastern Mediterranean. One of the conclusions from this paper is that the motion of drogued drifters (15m drogue, like our SVP drifters), are less related to the surface winds than the undrogued drifters.

Wind is the primary source of waves, wind-driven waves are created by the friction between wind and surface water [10]. The gravitational pull of the sun and moon on the Earth also causes waves, called tidal waves. Another kind of wave is the surface gravity wave, these waves are created because of a restoring force due to gravity. They travel with the wave propagation and induce a net drift also called the Stokes drift [11]. Stokes drift follows the motion of particles underneath a wave. The linearised trajectories of Lagrangian particles are formed by closed ellipses. During the phase cycle of the Lagrangian particle, the fluid particle oscillates back and forth because of the linear wave motion. This makes for a net forward drift and the fluid particle moves forward. The net forward drift is used to calculate the net velocity of the Stokes drift. Stokes drift is important to explain the formation of vortices near the surface of the ocean with bands of, for example, seaweed like Sargassum. The Sargassum is accumulating in the convergence zones between the vortices, at scales between 2 meters and 1 kilometer.

2.2 Surface ocean currents

Wind is also the main component of the movements in the water on the oceans surface [12]. The wind creates patterns called surface ocean currents. These surface ocean currents form, in the large scale, gyres. These gyres flow clockwise in the Northern hemisphere and counterclockwise in the Southern hemisphere because of the Coriolis effect. The Coriolis effect is one of the two acceleration terms in the equation of motion as a result of the Earth spinning on its axis. In other words, the Coriolis effect is the deflection of the water as a result of the rotation of the Earth, which is why the surface ocean currents flow in curved paths [13].

In figure 2 we see some of these surface ocean currents. As mentioned before, we are looking into the area where the North Equatorial current and the Equatorial Counter current are present, between the west coast of Africa and the Caribbean called the Small Sargasso Sea.

2.3 Ekman spiral

The Ekman spiral is a result of balance between friction of the wind at the surface of the ocean and the Coriolis effect. The wind drags deeper layers of water below the surface layer [13]. Every layer is moved by friction from the shallower layer and each deeper layer will move slower until there is no more movement. The deflection in the deeper layers is due to the Coriolis force and is determined by the velocity. Since the velocity varies in depth in the ocean, the deflection in the different layers does as well, resulting in a spiral effect, see figure 4.

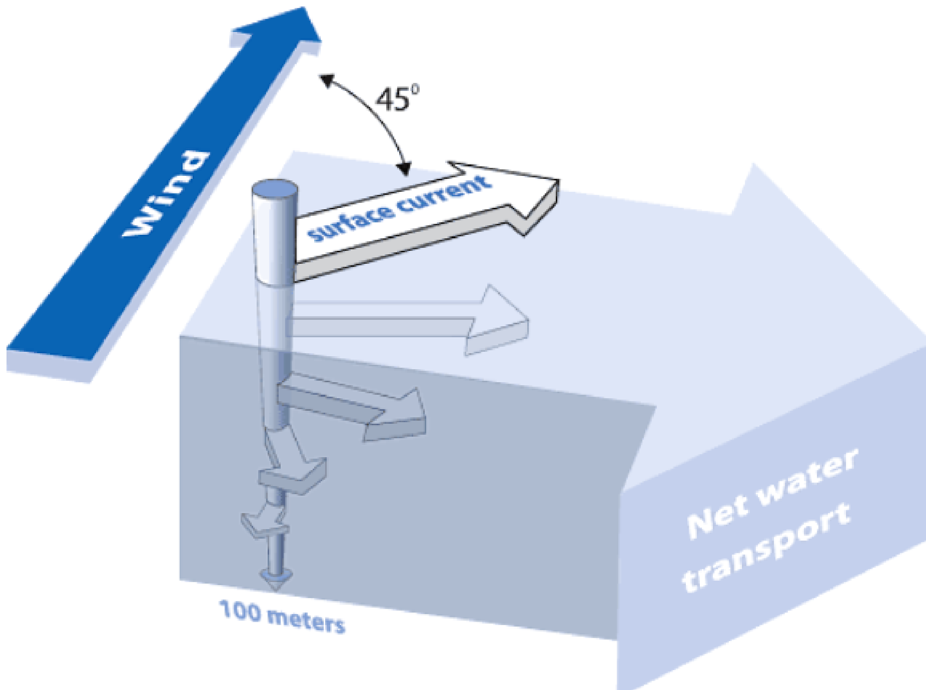


Figure 4: Ekman spiral [14].

The transport is orientated perpendicular to the wind stress.

2.4 Inertial oscillations

The Coriolis effect can deflect a drifters trajectory to the left or to the right, depending on the hemisphere. To show this, we can take a drifter that only has velocity in the y-direction. Because the drifter has a velocity, the Coriolis force deflects the particle to the left (or to the right). This deflection also gives the drifter a velocity in the x-direction. This process gives the particle a spontaneous circling trajectory as a result of the initial velocity in a rotating environment, which we call inertial oscillations [9].

To show this using formulas, we start with describing horizontal, unforced motions

$$\frac{du}{dt} - fv = 0 \tag{1a}$$

$$\frac{dv}{dt} + fu = 0 \tag{1b}$$

Where u and v are the velocities of a particle in the zonal and meridional directions. The general solution to this system of linear equations is

$$u = V \sin(ft + \phi) \tag{2a}$$

$$v = V \cos(ft + \phi) \tag{2b}$$

where f is called the Coriolis parameter given by $f = 2\Omega \sin\varphi$, Ω is the rotation rate of the Earth ($7.29 \cdot 10^{-5}$ rad/sec) and φ is the latitude. V is the amplitude and ϕ is the phase.

The inertial oscillations on Earth have a period equal to

$$T = \frac{2\pi}{f} = \frac{2\pi}{2\Omega sin(\varphi)} \tag{3}$$

The period of the inertial oscillations can be ranging from 11h 58 min at the poles to infinity along the equator.

The oscillations are not be circles at a constant position but become cycloides, this is because of steady ocean currents, caused by the wind [15].

3 Drifter data

The 20 undrogued Stokes drifters and the 18 drogued SVP drifters were deployed in groups of 2 Stokes and 2 SVP drifters between July 20th and August 6th 2019 as seen in table 1. Stokes 13 has been deployed as a single and Stokes 20 has been deployed alongside Stokes 18 and 19. The most recent data was retrieved on november 10th 2019 for the drogued SVP drifters and on november 15th for the undrogued Stokes drifters.

2019-07-20 18:46	Stokes 1 and 2	SVP 5 and 10
2019-07-22 10:28	Stokes 3 and 4	SVP 6 and 14
2019-07-23 21:36	Stokes 5 and 6	SVP 4 and 18
2019-07-25 11:14	Stokes 7 and 8	SVP 8 and 9
2019-07-26 11:13	Stokes 9 and 10	SVP 7 and 16
2019-07-28 21:48	Stokes 11 and 12	SVP 2 and 13
2019-07-30 17:09	Stokes 13	
2019-08-04 10:48	Stokes 14 and 15	SVP 3 and 11
2019-08-06 13:27	Stokes 16 and 17	SVP 1 and 17
2019-08-08 12:05	Stokes 18, 19 and 20	SVP 15 and 12

Table 1: Deployment moments of all 20 undrogued Stokes and 18 drogued SVP drifters. The times are in UTC.

Shown in figures 5 and 6 are the trajectories of the undrogued Stokes and the drogued SVP drifters. We were able to collect more data from the drogued SVP drifters than from the undrogued Stokes drifters, because of premature failure of the undrogued Stokes drifters.

From the figures, we see that if the drifters were deployed between -30 and -40 degrees longitude and 6 and 7 degrees latitude, they drift eastward. We also see that if they were deployed between -53 and -57 longitude and 10 and 12 degrees latitude the drifters move westward. This is because of the surface ocean currents, more specifically, the Equatorial counter current and the North Equatorial current, see figure 2. The drifters deployed between -45 and -50 longitude and 7 and 9 degrees latitude are harder to analyse, for now we say that they stay in the centre.

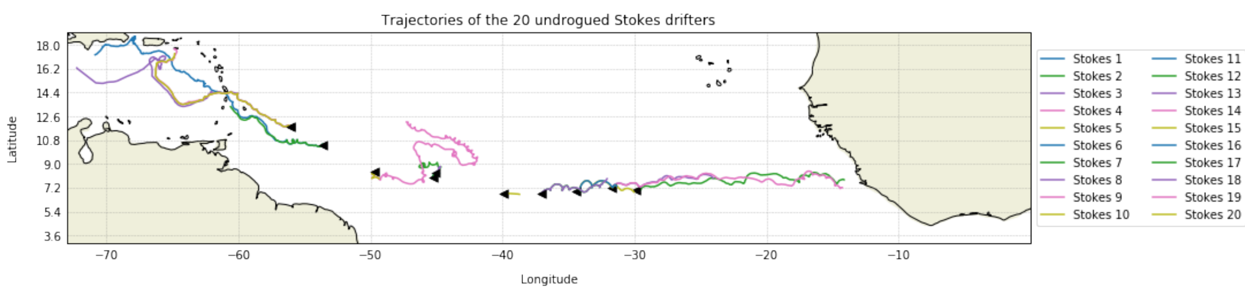


Figure 5: Trajectories of 20 undrogued Stokes drifters. Triangles represent their starting position.

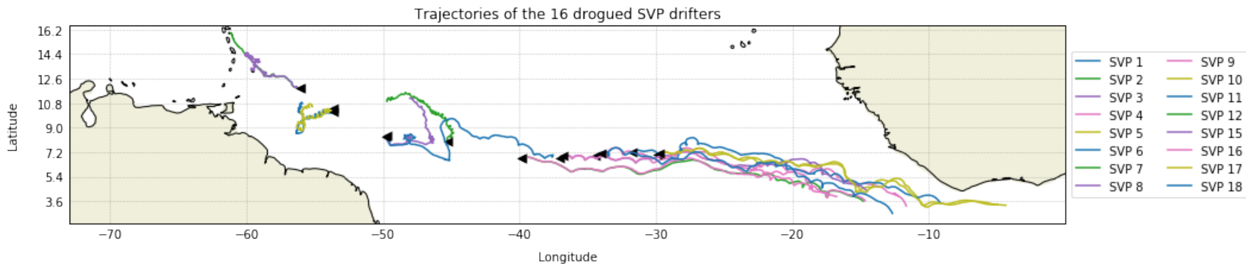


Figure 6: Trajectories of 16 drogued SVP drifters. Triangles represent their starting position.

3.1 Incomplete data

3.1.1 Undrogued Stokes drifters

Figure 7 shows the amount of data points in time for every Stokes drifter. If there is a large gap between the dots, it means the drifter did not sent its data for a while. If the line of dots ends, it means the drifter has 'died'. There are drifters that have been sending in their data consistently, for example Stokes 14 and 16. But others have many gaps, like Stokes 18. And unfortunately, there are drifters, like Stokes 9, 10 and 13, that have sent in barely any of their data. The reason behind the incomplete data is still unknown. It could be because they were flipped during a storm [16] and when they are flipped, their satellite antenna points downward and thus intermittently reduce the frequency of GPS fixes. This seems unlikely since there weren't any big storms in this area at the time, additionally the failing of the drifters seems to be happening at random. A better reason for the early drifter failure is that the drifters weren't sealed good enough and have come in contact with too much water due to the roughness of the ocean. But, as seen in figure 7, some drifters stop and then continue sending their data, meaning that not all of them failed because of water damage right away.

On December 28th, Stokes drifter 10 has been found by someone on Mes-Meheux, part of the Banana islands in Sierra Leone, West Africa. This particular drifter stopped transmitting information very quickly. So, knowing it has arrived on a beach, we know that it did not sink. The person that found and emailed us about the found drifter, has placed it back in the ocean as described on the drifter so we were unable to investigate the drifter itself to find out why the drifters fail.

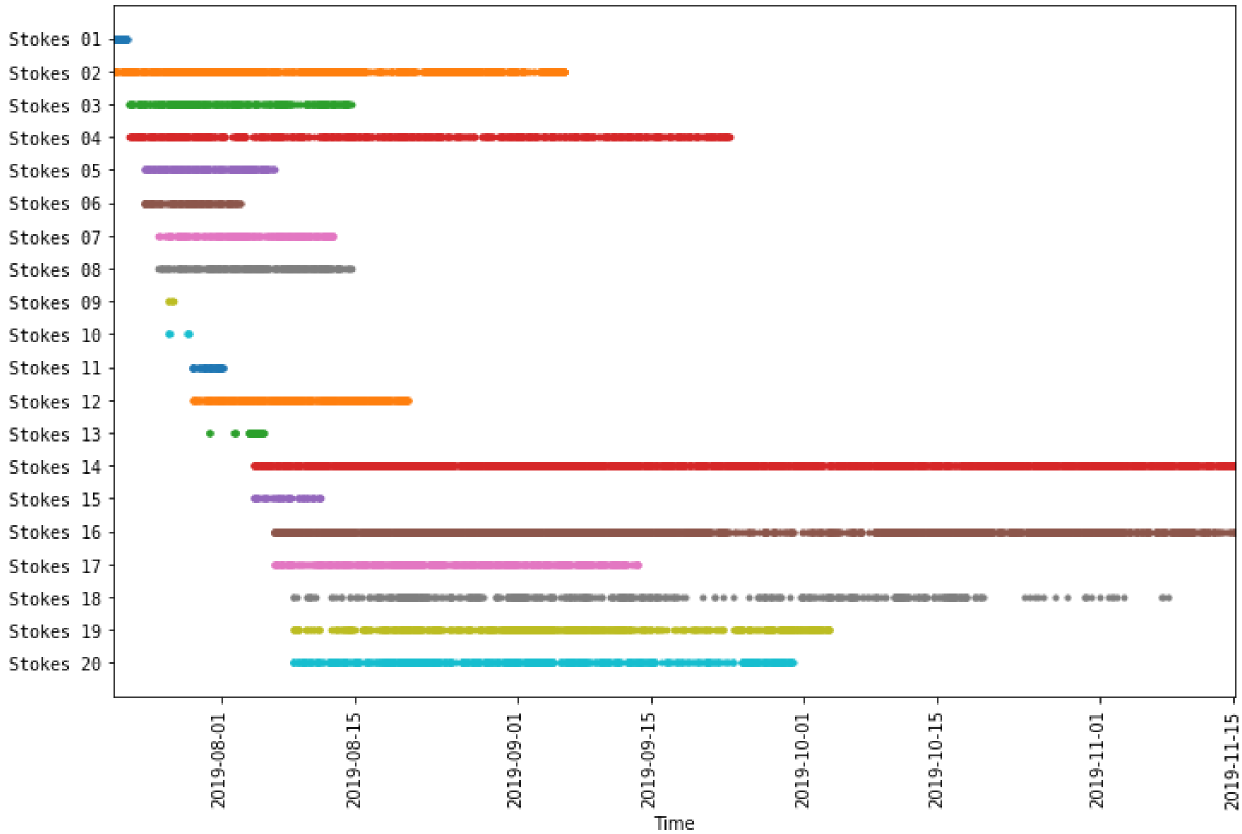


Figure 7: Data received from each undrogued Stokes drifter. The drifters are deployed between July 20th and August 6th 2019 and only two drifters were still active on November 15th 2019.

3.1.2 Drogued SVP drifters

There were 18 SVP drifters deployed in pairs, thus 9 pairs. Something unknown has gone wrong with SVP 13 because the data file was empty and could thus not be analysed. Something unknown has also gone wrong with the data from SVP 14, the data is not physically possible. For example, making enormous jumps in an hour, with jumps as high as 138 degrees in latitude or 182 in longitude. The data in SVP 14 ranges between -64 and 76 degrees in latitude and between -177 and 154 in longitude during a period of 90 days.

SVP 12 has arrived at a beach in Guadelupe, we discard the data after it arrived on the beach on day 44.

The data that was sent by several of the SVP drifters had very strong spikes in terms of position. We defined it as a spike if it would travel over 0.1 degree within one hour and travel the same distance back to almost the same position previous to the spike. In figure 8 we see this for SVP 1, we only show 15 data points spread out over part of a day to show a spike. Spikes like these are discarded.

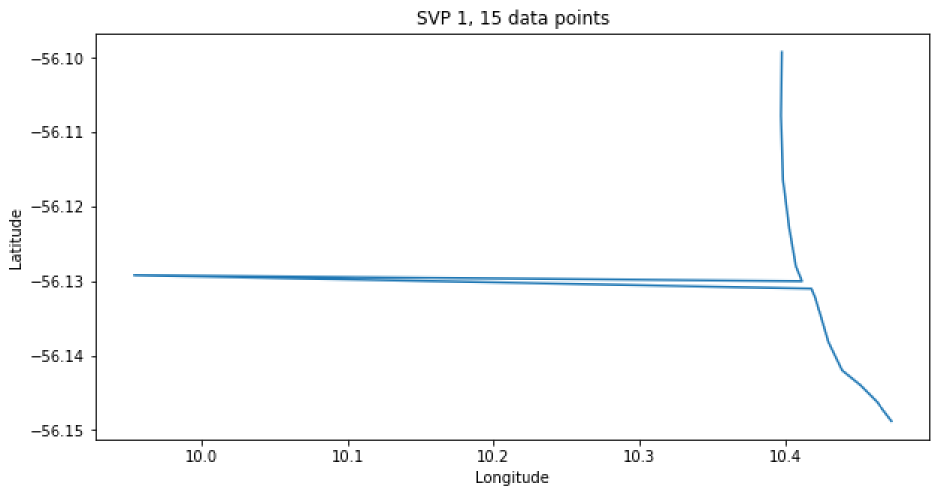


Figure 8: SVP 1, 15 data points to show a spike travelling more than 0.1 degree and immediately returning.

3.1.3 MeteoFrance

SVP drifters 1-8 are from the Global Drifter Programm, while 9-18 are from MeteoFrance. MeteoFrance didn't start collecting their data until the second day of release, while the rest of our data does start at the moment of release. As can be seen in figure 15, where one of the red lines starts below the other. The reason that there isn't a second black triangle (representing the starting position) visible is because we do know its starting position, we know when and where it was released.

3.1.4 Possible drogue failure

Sometimes drogued drifters, like our SVP drifters, lose their drogue [16]. Since drogued drifters drift differently from undrogued drifters, we needed to check that our drogued drifters are drogued throughout the period of observation. We were unable to confirm that all our drogued SVP drifters had not lost their drogue. After analysing the velocities of our drogued drifters, we did not see a bump in velocity. Since we cannot tell when and which drifter lost its drogue, we are going to assume all of them have their drogue throughout the entire period.

3.1.5 Conclusion

Upon analysing the distance between drifters and calculating the average velocities, certain data is discarded. When analysing the pairs, we discard the pairs Stokes 9-10, SVP 13-2 and SVP 14-6, and individual Stokes 13. Upon calculating the average velocities we discard Stokes 1, 9, 10, 11, 12 and 13 and SVP 13 and 14.

4 Methods

We analyse the drifters in four different ways. We start by looking at the pair separation between the drifters part of a pair. Then we are going to compare their trajectories and we look at the average velocities. After that we are also going to use multi linear regression to find a relation between our drifters and the wind, waves and currents in the ocean.

4.1 Pair separation

Before looking at the pairs, we focus on selecting only the data of the pairs that sent their location within 30 minutes of each other. We choose 30 minutes because the drifters sent their location once every hour. By doing this selective process, we eliminate data from a drifter if its pair drifter has big gaps, see section 3.1. If the pair does not have gaps, we take the data that was sent in the shortest amount of time. Some drifters (Stokes 1, 2, 14 and 16) have sent their data every 30 minutes, in these cases we use the data that is within 15 minutes of each other.

Using this selected data, we want to see what the separation within the pairs looks like. The data that we have from our drifters, is longitudes and latitudes. We find the arc length, d, by multiplying the central angle with the radius of the Earth: 6371 km.

$$d = r \arccos\Big(\sin(lat_1)\sin(lat_2) + \cos(lat_1)\cos(lat_2)\cos(lon_1 - lon_2)\Big) \tag{4}$$

where lon and lat are the longitudes and latitudes of the two drifters in a pair and r is the radius of the Earth.

This arc length 'd' is the distance between the two drifters in a pair, in kilometres. We show this separation distance in a figure and compare the undrogued Stokes with the drogued SVP drifter pairs.

To compare the undrogued Stokes drifters with the drogued SVP drifters, we check how long it takes for the drifter pairs to separate over 10 km from each other.

4.2 Trajectory comparison

In figure 9 we show the trajectory of all the undrogued Stokes and the drogued SVP drifters. Just like in figure 5 and 6 we see drifters going eastward, westward and a few that stay in the centre. We discuss them separately which is why they are colour coded.

The black triangles represent their deployment location, see table 1 for the drifters' release times.

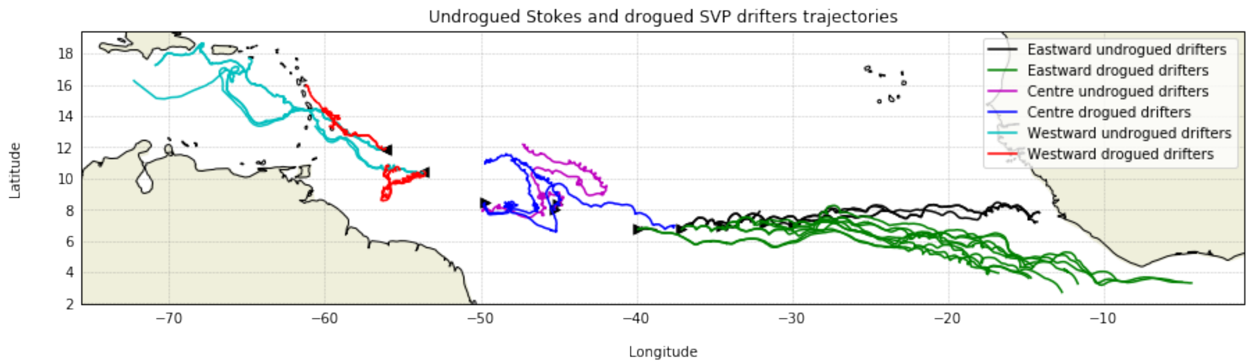


Figure 9: Undrogued Stokers drifters and drogued SVP drifters trajectories, divided into three areas; travelling east towards Africa (black and green), staying in the centre of the ocean (purple and dark blue) and travelling west towards the Caribbean (light blue and red).

4.3 Average velocities

We compare the average velocities between the undrogued Stokes and the drogued SVP drifters. We start by finding the total distance travelled, using the distance between data points that we collected, dx. By adding all the intermediate distance differences, $\sum dx$, and dividing by the total time that the drifter was active, t, we find the average velocity of the drifter.

$$v_{avg} = \frac{\sum dx}{t}. \tag{5}$$

4.4 Multi linear regression

Multi linear regression is used to find a relation between an input of independent variables, like wind, waves and currents, and an outcome, like our drifter trajectories. The data that we use in the multi linear regression is provided by Copernicus Marine Environment Monitoring Service (CMEMS) [17].

WIND_GLO_WIND_L4_NRT_OBSERVATIONS_012_004 provides a forecast of a 6-hourly-mean for the wind. GLOBAL_ANALYSIS_FORECAST_WAV_001_027 provides a forecast of a 3-hourly-instantaneous data for the waves. GLOBAL_ANALYSIS_FORECAST_PHY_001_02 provides a forecast of an hourly mean for the currents.

The wind data retrieved is the velocity of the wind just above the surface of the ocean. This is not the information we want to use for our multi linear regression, we want to know the impact that the wind has on the surface of the ocean. Poulain [2008] states that “Undrogued SVP drifters have a general downwind slippage of about 1% of the wind speed”, which is why the wind data used in the multi linear regression is 1% of the wind velocity from CMEMS.

The data retrieved from CMEMS was measured at different moments in time than our drifter data. We linearly interpolate the data from the wind, waves and currents to find the correct position and the correct time.

For the multi linear regression we select daily data to make sure we filter out small oscillations in the ocean. The daily data consists of data points closest to midnight, we do so to maximise our data set while still having approximately 24 hours between data points.

Using figures, we show the velocity of the drifter in the x-direction on the x-axis and the velocity of the wind, waves and currents in the x-direction on the y-axis in three different colours. In a second figure, we again show the velocities of the drifter on the x-axis and the velocities of the wind, waves and currents on the y-axis but in the y-direction. We show the data from the undrogued Stokes drifter separate from the drogued SVP drifters.

$$f(x_1, x_2, x_3) = b_0 + b_1x_1 + b_2x_2 + b_3x_3 \tag{6}$$

Formula 6 is the estimated regression function. The function finds coefficients that define the slope (b_1, b_2, b_3). For this we give a predicted response, $f(x_1, x_2, x_3)$, and the three independent variables, (x_1, x_2, x_3). In our case, the predicted response is the velocity of the drifter and the three independent variables is the velocity of the wind (x_1), waves (x_2) and the currents (x_3). Using the Linearregression().fit(X,Y) command in Python, we calculate the optimal values for the intercept b_0 and the coefficients b_1, b_2 and b_3. The intercept tells us where the line crosses the y-axis and the coefficients determine the slope.

To interpret the results, we look at the p-value of the intercept and the coefficients, which tells us if we can reject our null hypothesis. The null hypothesis says that the variable is not significant to our outcome. We consider the p-value to be low if it is smaller than 0.05 and, in this case, the null hypothesis must be rejected, in other words, there is a significant relationship for this variable. If the p-value is above 0.05, it indicates that the evidence against the null hypothesis is weak and you do not have to reject the null hypothesis.

5 Results

5.1 Pair separation

In figure 10 we see the difference in distance for the undrogued Stokes drifters in a pair as described in section 4.1, using formula 4 and the selected data.

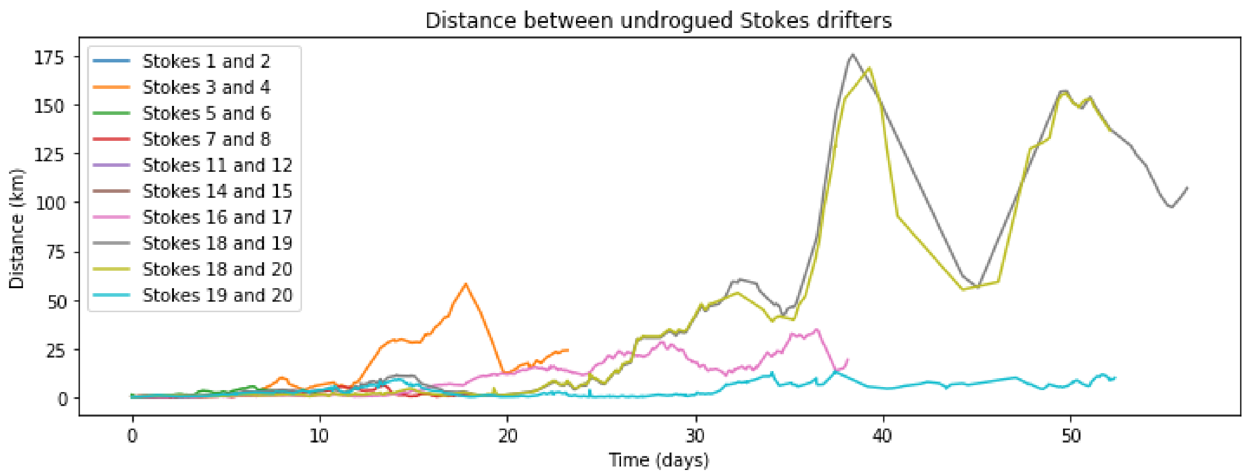


Figure 10: Distance between undrogued Stokes drifters in a drifter pair.

The first drifter pair to separate over 10 km, is Stokes 3 and 4 and it takes 12 days. On day 25, more than half (four out of five) pairs have separated over 10 km. The last pair, Stokes 19 and 20, reaches a separation of 10 km on day 33.

In figure 11 we see the difference in distance for the drogued SVP drifters in a pair.

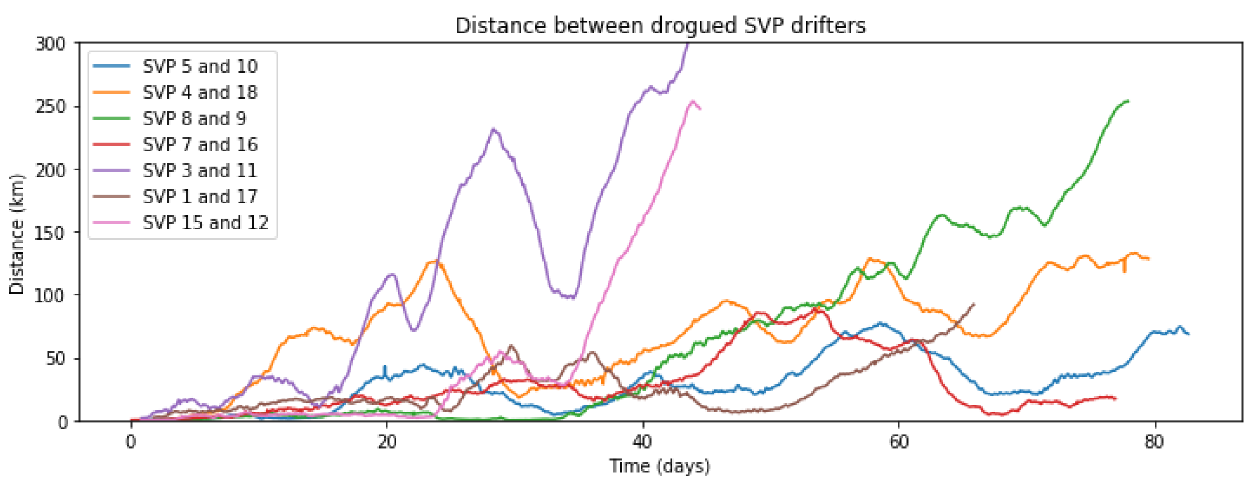


Figure 11: Distance between drogued SVP drifters in a drifter pair.

One of the drifter pairs, SVP 3 and 11, has reached a separation over 800 km within 80 days, a much larger separation than the other pairs.

SVP 12 has beached on an island of Guadelupe and we stop showing its data after day 44.

The first drifter pair to reach over 10 km in separation is SVP 3 and 11 on day 3. On day 14 more than half (four out of seven) of the pairs have separated over 10 km, on day 24 most (six out of seven) pairs separated over 10 km. The last pair, SVP 8 and 9, separated over 10 km on day 35.

In figure 12 we see both the undrogued Stokes and the drogued SVP drifter separation.

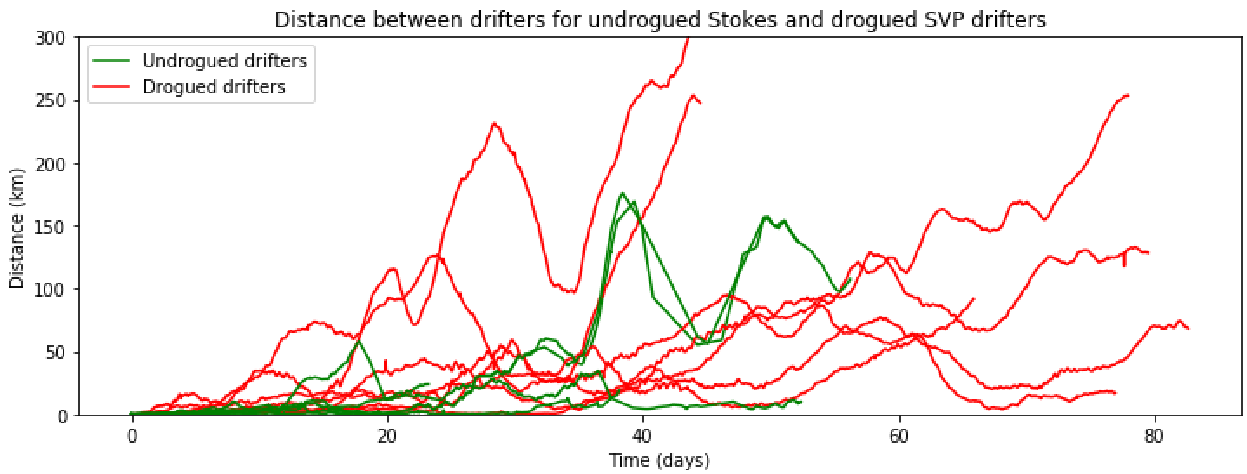


Figure 12: Difference in distance, plotted for both the undrogued and the drogued drifters.

The first undrogued Stokes drifter pair to have separated over 10 km accomplishes this on day 12, while the first drogued SVP drifter pair to accomplishes this already on day 3. Most of the undrogued Stokes drifters separated over 10 km on day 25 and the drogued SVP drifters on day 24. All the undrogued Stokes drifters reached a separation over 10 km on day 33 and the drogued SVP drifters on day 35. For further comparison, we look at their separation distance on day 25. In both the undrogued Stokes as in the drogued SVP pairs, the smallest separation is between 0 and 2 km. But the undrogued Stokes drifter pair most separated is at 24 km while there are two drogued SVP pairs separated at 107 and 162 km.

5.2 Trajectory comparison

As explained in section 4.2, we compare the trajectories of the drifters. We have divided the drifters into three regions and will do the comparison per region.

5.2.1 Eastward

The first area looked at, is the comparison between all the undrogued drifters and the drogued drifters going eastward, see the black and green trajectories in figure 9. One can clearly see that the drogued data is veering south, unlike the undrogued data which vary little in latitude.

We know that this difference in trajectory can be due to an influence of a mixture between wind, waves and currents. To find out if our data is indeed influenced by these factors, we use multi linear regression in the region where the drifters are going eastward. The results is discussed in section 5.4.

5.2.2 Centre

Figure 13 shows us the trajectory of Stokes 14 and SVP 2, 3 and 11. The figure shows a clear dispersion for the drogued SVP drifter pair 3 and 11. The best explanation for this is that SVP 11 has drifted into the Equatorial counter current while SVP 3 is in the North Equatorial current. SVP 3 started to drift with the Equatorial counter current, but it has changed direction and seems to be back in the North Equatorial current, going west. Stokes 14 seems to be switching between the two currents, while SVP 2 has stayed in the North Equatorial current.

Analysing drifters released into this area is complicated since it appears to be between two surface ocean currents.

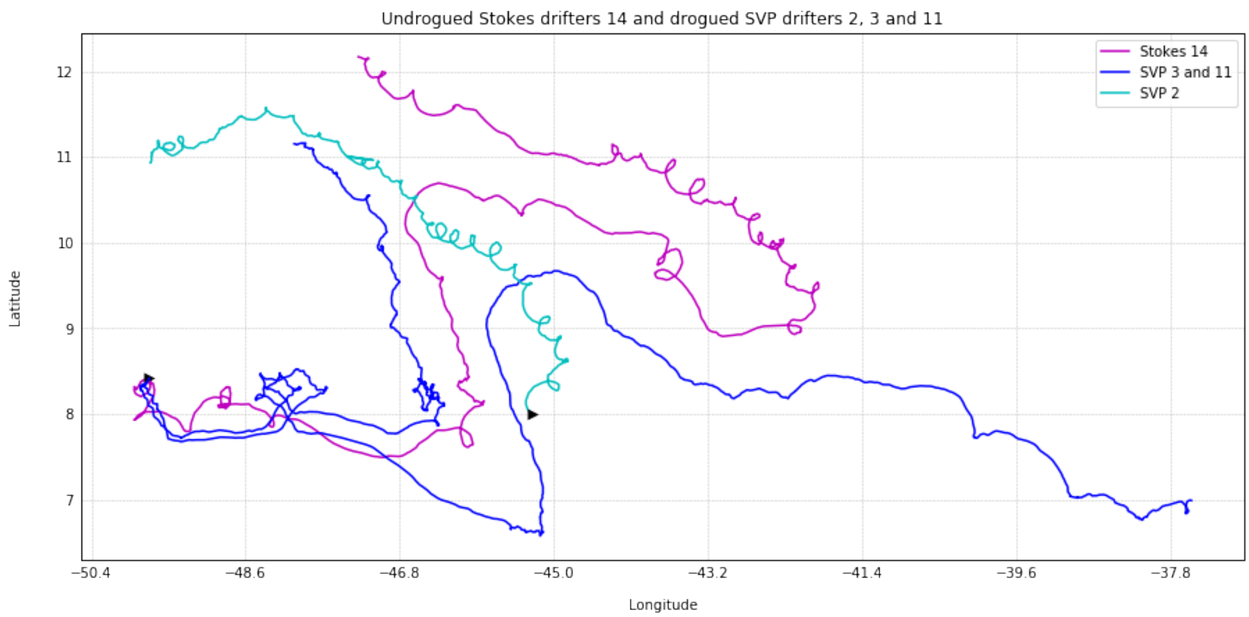


Figure 13: Trajectories of the undrogued Stokes drifter 14 and drogued SVP drifters 2, 3 and 11.

5.2.3 Westward

There are 2 sets moving in the westward direction. We notice that the Stokes drifters, independently of their release location, drift past the Caribbean between the same islands. This could be because of the currents and/or the depth around the islands. One set contains 5 drifters that are moving westward towards the Caribbean islands, see figure 14. One of the five drifters, SVP 12, has arrived on one of the islands near Guadelupe. The other set contains the undrogued Stokes drifters 16 and 17 and drogued SVP drifters 1 and 17. In this set we see there is a clear difference; the drogued SVP drifters drift in circles.

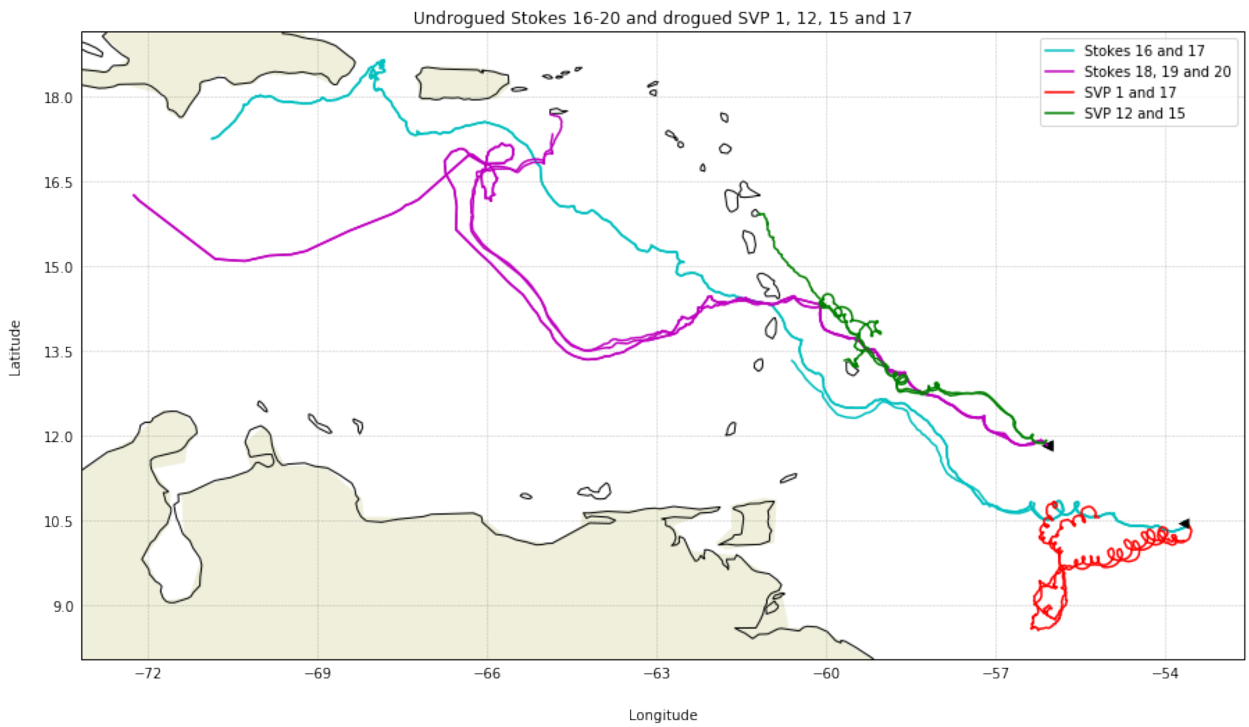


Figure 14: Trajectory of the undrogued Stokes trio 18, 19 and 20 and drogued SVP pair 12 and 15. And the trajectories of the undrogued Stokes drifters 16 and 17 and drogued SVP drifters 1 and 17.

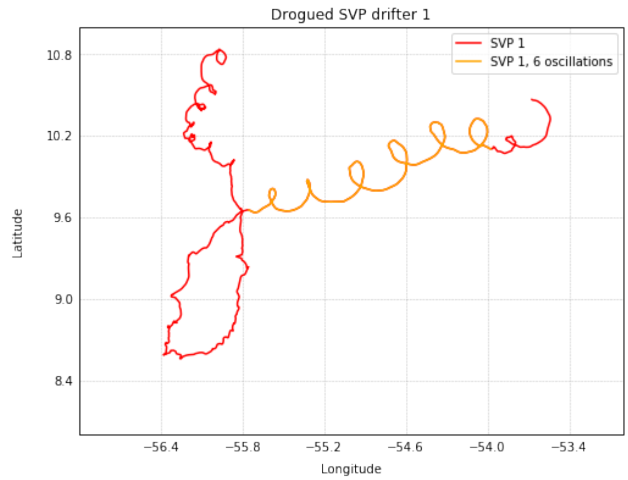


Figure 15: Trajectory of the drogued SVP drifter 1 in red. Showing a period of 6 oscillations in orange.

The circles, highlighted in figure 15, look a lot like the inertial oscillations of the ocean (section 2.4). We test if they really are inertial oscillations, using equation 3.

$$t = \frac{2\pi}{2 \cdot 7.29 \cdot 10^{-5} \cdot \sin\left(10 \cdot \pi/180 \text{ rad}\right)} = 2.9 \text{ days}$$

An oscillation at a latitude of 10 degrees has a period of 2.9 days. If we look in the figure, we find 6 oscillations in the time span of 16.3 days. This is equal to an oscillation period of 2.7 days, which is close to the Coriolis frequency of 2.9 days.

5.3 Average velocities

See table 2 for the average velocities of the individual drifters going eastward, westward or staying in the centre, calculated using formula 5.

Eastward				Westward			
Stokes 2	0.512 m/s	SVP 4	0.475 m/s	Stokes 16	0.320 m/s	SVP 1	0.232 m/s
Stokes 3	0.490 m/s	SVP 5	0.455 m/s	Stokes 17	0.316 m/s	SVP 12	0.259 m/s
Stokes 4	0.500 m/s	SVP 6	0.433 m/s	Stokes 18	0.361 m/s	SVP 15	0.242 m/s
Stokes 5	0.602 m/s	SVP 7	0.477 m/s	Stokes 19	0.370 m/s	SVP 17	0.236 m/s
Stokes 6	0.619 m/s	SVP 8	0.427 m/s	Stokes 20	0.371 m/s		
Stokes 7	0.469 m/s	SVP 9	0.388 m/s				
Stokes 8	0.454 m/s	SVP 10	0.461 m/s				
		SVP 16	0.479 m/s				
		SVP 18	0.430 m/s				
Centre							
Stokes 12	0.334 m/s	SVP 2	0.268 m/s				
Stokes 14	0.384 m/s	SVP 3	0.246 m/s				
Stokes 15	0.340 m/s	SVP 11	0.415 m/s				

Table 2: Average velocities of drifters drifting eastward, westward or staying in the centre.

We confirm here what we found in section 5.2.2, Stokes 14 and SVP 2 and 3 seem to agree with the drifters going west while SVP 11 seems to agree with the drifters going east if we compare their average velocities to the same drifters in these regions.

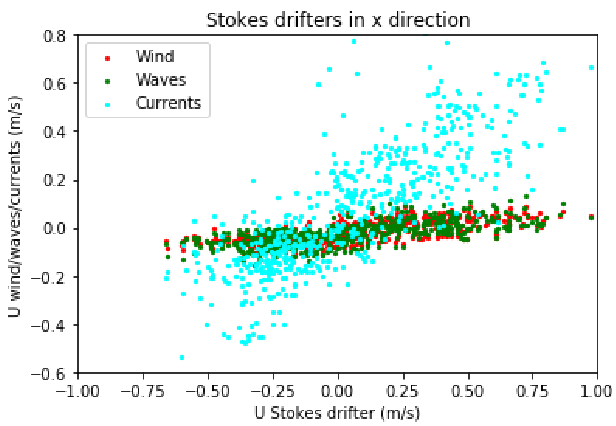
From table 2 we find an average velocity of 0.521 m/s for the undrogued Stokes drifters and 0.444 m/s for the drogued SVP drifters going eastward. And an average velocity of 0.350 m/s for the undrogued Stokes drifters and 0.247 m/s for the drogued SVP drifters going westward. From this we can conclude that on average the undrogued Stokes drifters drift faster than the drogued SVP drifters. This is to be expected because the surface layer has an extra wind component, moving it faster than lower layers.

We assume that this difference in velocity is due to an influence of wind, waves and currents. We try to verify this using multi linear regression on all the drifters, see section 5.4 for the results.

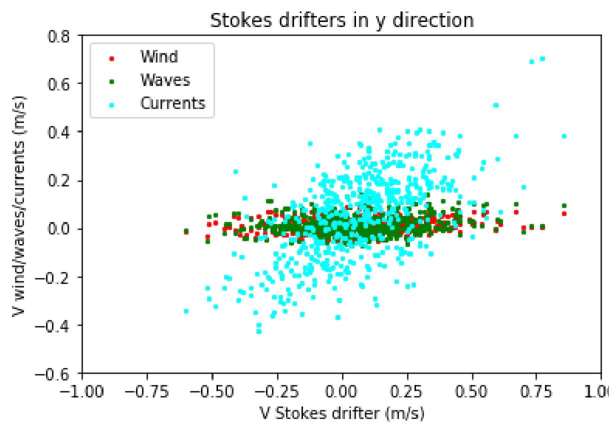
5.4 Multi linear regression

In figure 9 we saw that the undrogued Stokes drifters portray a different trajectory than the drogued SVP drifters. We talk about this observation in section 5.2.1 as well but we have not yet been able to confirm why this is happening.

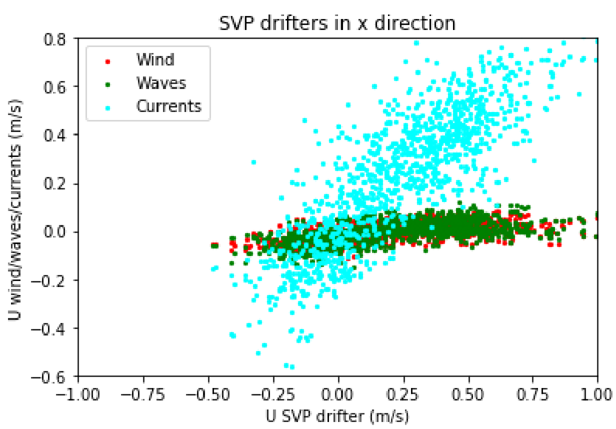
To investigate if the difference in the trajectories between the undrogued and drogued drifters is due to the wind, waves or currents, we use multi linear regression. We do a multi linear regression for the undrogued Stokes drifters in the x and y direction and for the drogued SVP drifters in the x and y direction. In figure 16 we see the data from the wind, waves and currents against the drifters.



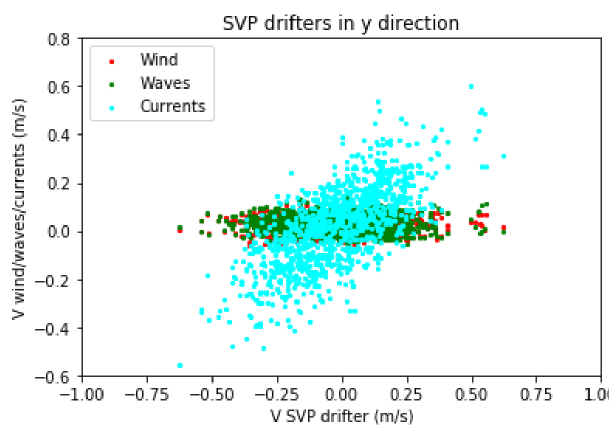
(a) Undrogued Stokes drifters in the x direction



(b) Undrogued Stokes drifters in the y direction



(c) Drogued SVP drifters in the x direction



(d) Drogued SVP drifters in the y direction

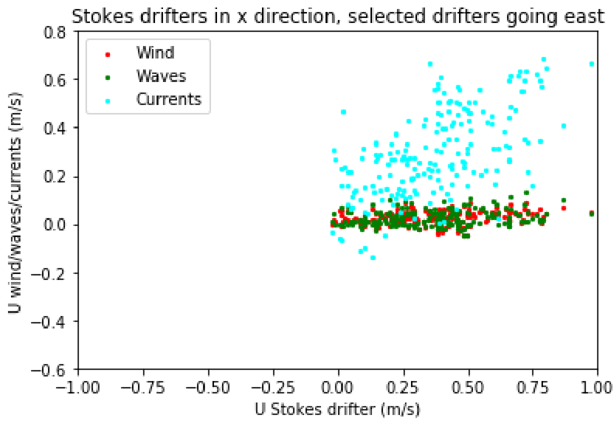
Figure 16: Data from the undrogued Stokes and drogued SVP drifters, with the corresponding wind, waves and currents velocities, using daily data.

The fit function we find from this, contains an intercept and coefficients which are shown in table 3, along with the corresponding p-values.

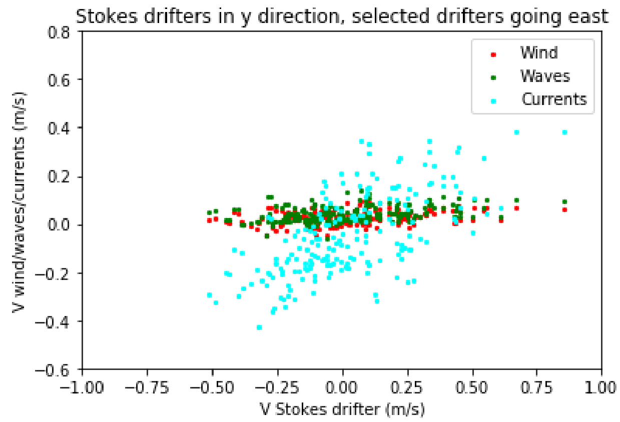
	Intercept	P-value	Coefficients	Intercept	P-value	Coefficients
	Stokes x direction			Stokes y direction		
	0.048	0.06		0.019	0.067	
Wind		0.000	4.02		0.076	1.31
Waves		0.067	-1.07		0.462	0.20
Currents		0.000	0.85		0.000	0.77
	SVP x direction			SVP y direction		
	0.057	0.000		-0.036	0.000	
Wind		0.027	-0.79		0.000	-0.56
Waves		0.008	1.39		0.140	0.46
Currents		0.000	0.79		0.000	0.76

Table 3: Intercepts, coefficients and corresponding p-values for the multi linear regression from the data shown in figure 16. Grey coefficients indicate weak evidence against the null hypothesis due to their high p-value ($p > 0.05$).

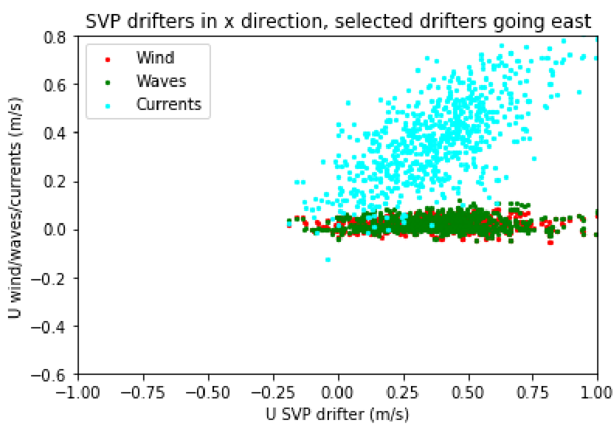
We did a second multi linear regression where we selected only the drifters going in the eastward direction and we show the intercepts, coefficients and corresponding p-values in table 4.



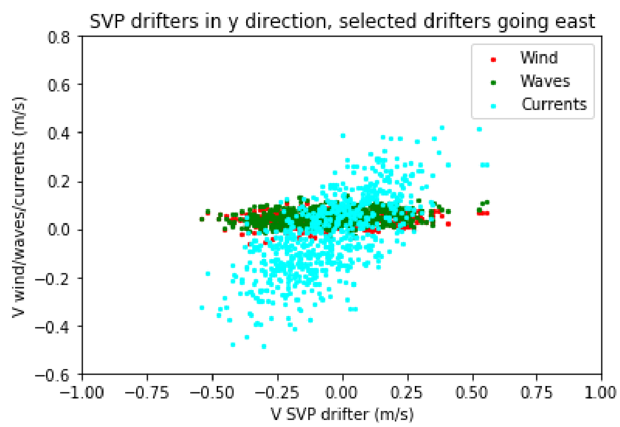
(a) Undrogued Stokes drifters in the x direction



(b) Undrogued Stokes drifters in the y direction



(c) Drogued SVP drifters in the x direction



(d) Drogued SVP drifters in the y direction

Figure 17: Data from the undrogued Stokes and drogued SVP drifters, with the corresponding wind, waves and currents velocities, using daily data. Showing only the data going eastward.

	Intercept	P-value	Coefficients	Intercept	P-value	Coefficients
	Stokes x direction			Stokes y direction		
	0.092	0.182		0.060	0.021	
Wind		0.031	2.77		0.820	0.64
Waves		0.193	-1.71		0.238	-0.30
Currents		0.000	0.95		0.000	0.89
	SVP x direction			SVP y direction		
	0.054	0.000		-0.026	0.019	
Wind		0.013	-1.41		0.000	-1.22
Waves		0.000	1.68		0.050	0.84
Currents		0.000	0.85		0.000	0.77

Table 4: Intercepts, coefficients and corresponding p-values for the multi linear regression from the data shown in figure 17, using only the data going eastward. Grey coefficients indicate weak evidence against the null hypothesis due to their high p-value ($p > 0.05$).

From the figures and tables above, we see that the currents explain a large fraction of the drifter velocities, both in the figures of all the data and the figures with the selected data. We also see that for a lot of the data from the wind and waves, the p-values are high ($p > 0.05$). These high p-values indicate that our evidence is not strong enough to suggest an effect exists. The p-values are lower for the drifters going eastward, suggesting that they have a more significant relationship than the rest of the analysed drifters.

We concluded, in section 5.2.1, that the undrogued Stokes drifters had a different trajectory than the SVP drifters when drifting eastward. We saw that the undrogued Stokes drifters vary little in latitude while the drogued SVP drifters are veering south. If we look for the SVP drifters in the y direction in table 4, we see that this could be because of wind, pushing the SVP drifters in the negative y direction. This could also be because of the Ekman spiral, but we didn't check for this and this could be done if there will be further research into this dataset. For the Stokes drifters in the y direction, we find a positive coefficient but since this coefficient has a high p-value, we can't reject the null hypothesis. We can thus not draw the conclusion that this difference in trajectory is due to the wind, waves or currents in this area.

In section 5.3 we find that the undrogued Stokes drifters drift consistently faster than the drogued SVP drifters. This is likely due to the wind because it has more effect on the surface than on deeper layers in the ocean [18]. In table 3 we see that the coefficients for the wind are larger for the undrogued Stokes drifters (4.02 in the x direction) than for the drogued SVP drifters, also suggesting that the drifters move in the opposite direction of the wind (-0.79 in the x direction and -0.56 in the y direction), possibly confirming Ekmans theorem where wind stress in the y direction causes flow in the x direction and vice versa. We also find that the slope coefficients for the currents for the undrogued Stokes drifters (0.84 in the x direction and 0.77 in the y direction) are larger than the drogued SVP drifters (0.78 in the x direction and 0.75 in the y direction). But we have to keep in mind that this is a very small difference.

6 Discussion and conclusion

6.1 Limited data

We analysed data for 20 undrogued Stokes drifters and 18 drogued SVP drifters, this is very limited compared to other papers like Poulain et al. (2008) who did research in the Eastern Mediterranean or Brugge and Dengg (1991) who did research in the North Atlantic. Poulain et al. uses 173 undrogued drifters in a span of 5 years and has data for a total of 32 drifter years. He compared these undrogued drifters with drogued drifters, of which he had data of 100 drifters in a span of 2 years meaning 30 drifter years. For the comparison in the paper from Brugge and Dengg, the data that forms his base contains 116 undrogued buoys that have 12 buoy years, he compared these buoys with 164 drogued buoys that had 19 buoy years. Our collected data consisted of 1.9 years in undrogued Stokes drifter data and 3.2 years in drogued SVP drifter data, which is indeed, after comparing to other papers, very limited.

Our drifters were released in pairs of 2 undrogued Stokes and 2 drogued SVP drifters. This was done so that we could also statistically analyse the drifters as pairs, like Essink (2019) did using Relative dispersion, FSLE (Finite Size Lyapunov Exponents) or Pair Separation PDF. But since many of our drifters prematurely died, there weren't many pairs left with enough data to do these kinds of statistics. Papers like LaCasce (2008) also talk about single particle statistics. But to do these methods properly, one would need more data. If researchers want to do more research into pair dispersion, they could consider releasing drifters in groups of 3 or 4 instead of 2 of the same type of drifters at a time. This way, if one drifter would stop working for some reason, they would still have 'backup' drifters. And if the drifters would all work, you could even attempt multiple particle statistics as described by LaCasce.

Not only do we have less drifters in our data set than other papers, our drifters also stopped working prematurely or had unusable data. From the data that we have collected, we cannot draw a conclusion with accuracy, we can only suggest certain things. Like, from our data we can clearly see a difference between the undrogued and drogued drifters, this agrees with other papers. If there is any more research done in the future to track Sargassum, or other floating objects in the ocean (like plastic), they need to decide if they want to use undrogued or drogued drifters, since they are clearly behaving in different ways. In my opinion, they should use the undrogued drifters since the Sargassum is not drogued. If they use the undrogued drifters, they should consider making them more waterproof and making sure they can't tip over easily. Before they start doing a large drifter release, they should test them thoroughly since they are clearly more fragile than the drogued drifters.

6.2 Assumptions

When looking at the data and analysing it, we have made certain assumption and neglected certain forces or boundaries. We have looked at the wind, waves and currents at the top layer, but we don't know what kind of impact these wind, waves and currents have for lower layers, like at a depth of 15 meters, where our SVP drifters drift. We expect, for example, that the wind has a smaller effect at a depth than at the surface of the ocean. This is explained in the Ekman spiral but not applied in our results.

All the data that we analysed, was analysed in the deep ocean, but not once do we take in account shallower waters, like near islands and coasts. In these shallower areas, other forces start to work, like tidal forces. Luckily, we know of only one drifter that has come near these shallow waters, SVP 12 which has beached on Guadelupe. Some of the drifters going westward had a trajectory that went in between the Caribbean islands, where currents could flow differently.

We also made assumptions during the multi linear regression, for example that the relation was linear. We did not talk about it possibly not being linear but, for example, polynomial. Trying a polynomial regression is an option but because we did not see a clear polynomial regression in our fits, we decided against it since we would probably be overfitting the figure. We also neglect rotations during our multi linear regression even though rotations play a significant role as we can see in the Ekman spiral. This would be very interesting for further research into this data set.

6.3 Accuracy

Whenever we do a measurement, we want to find the best estimate of the true value but there is always uncertainty. Our instruments have finite precision, thus our data (time, longitudes and latitudes) also has a finite precision. The time has a precision up to seconds and the longitudes and latitudes have a five decimal place accuracy, meaning 5 numbers after the decimal. We know that 0.00001 degree latitude is about 1.1 km, changing slightly depending on where you are on the globe. This is quite accurate considering we are talking about a large scale. The waves and currents data retrieved from CMEMS has a spatial resolution of 0.083 degree x 0.083 degree and the wind has a spatial resolution of 0.25 degree x 0.25 degree.

In section 5.3, we calculate average velocities. Since our distances and times have small errors, so will the velocities. These errors should be taken into account as well, when calculating the average velocity. For this we can use the standard deviation, which grows smaller if you have more data points.

In section 3.1, we talked about rejecting measurements if they were not physically possible and were thus considered noise. We did this for SVP 14, which had data that was clearly unusable and we neglected this entire data set. We also discarded certain data from, for example, SVP 1 and 2, that had only one or two data spikes and thus only those spikes were discarded. It is always dangerous to manipulate data but in our case, we knew they weren't physically possible and that is why they were discarded.

6.4 Conclusion

The main goal of this experiment was to investigate how the depth of the drifters impacts their trajectories and dispersion. To do this, we analysed data from 20 undrogued Stokes drifters and 16 drogued SVP drifters. We were looking for similarities and differences by looking at the difference in distance between drifters that are part of a pair, examining their trajectories, finding the velocities of these pairs and checking if there was a relation with the wind, waves or currents.

From the pair dispersion we concluded that the first undrogued Stokes drifter pair to have separated over 10 km accomplishes this on day 12, while the first drogued SVP drifter pair to accomplishes this already on day 3. We know that most of the undrogued Stokes drifters separated over 10 km on day 25 and the drogued SVP drifters on day 24. All the undrogued Stokes drifters reached a separation over 10 km on day 33 and the drogued SVP drifters on day 35. We also looked at their separation distance on day 25. In both the undrogued Stokes as in the drogued SVP pairs, the smallest separation is between 0 and 2 km. But the undrogued Stokes drifter pair most separated is at 24 km while there are two drogued SVP pairs separated at 107 and 162 km.

After comparing the trajectories for the drifters going eastward, we saw that the undrogued Stokes drifters varied little in latitude while the drogued SVP drifters in the same region, veered south. Using multi linear regression for the drifters in this area, we can conclude that this can be due to the negative coefficient of the wind velocity in the y direction for the SVP drifters. We compared the drifters that stayed in the centre and concluded that this was a tricky area to do research in since it is between two surface ocean currents, the North Equatorial current and the Equatorial Counter current. In the area of the drifters going westward, we saw that the drogued SVP drifters follow a different trajectory due to the presence of inertial oscillations.

From the data available, we were also able to compute average velocities of the drifters so we could compare the undrogued Stokes drifters with the drogued SVP drifters. We found that the velocities were different depending on the current they were in. For the drifters in the Equatorial Counter current, the undrogued Stokes drifters (0.521 m/s) drifted faster than the drogued SVP drifters (0.444 m/s). We saw the same result in the North Equatorial current we saw that the undrogued Stokes drifters (0.350 m/s) drifted faster than the drogued SVP drifters (0.247 m/s). This is to be expected because the wind has more effect on the surface than on the deeper layers in the ocean. We tried to confirm this by using multi linear regression on all the drifters for the wind, waves and the currents. We can conclude that for the wind and for the currents, the slope coefficients are larger for the Stokes drifters than for the SVP drifters, this would suggest that the undrogued Stokes drifters are more affected by the wind and the currents than the drogued SVP drifters. We are unable to say more about the waves due to high p-values, meaning that there could be a relation, but it is just not very strong or measurable with our drifters.

We can conclude that if there will be any further research done into Sargassum, it matters if they use drogued or undrogued drifters. Sargassum floats on the surface thus the undrogued drifters are a better choice. But the undrogued drifters would have to be made stronger and more waterproof.

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