Modeling drifter trajectories and ensemble dispersion from the Ocean Training Course 2025

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1 Introduction

This project aims to reconstruct the trajectory of drifters deployed during the expedition and to better understand how physical processes govern their motion. We thus need to take into account the satellite measurements of sea surface deformation, wave induced currents and wind speed. We employ a two folded approach: (i) in first approximation a linear combination of the surface currents, Stokes drift and direct wind-force, and (ii) the full equations describing the dynamics of floating intertial particles in the ocean -the Maxey-Riley set. These two methods will allow us to decompose and analyze the individual forces governing the drifter's motion, providing deeper insights into the underlying dynamics.

We focus here on deterministic modellings of the drift. However, given the inherent chaotic nature of the problem and the uncertainties carried by our observations of oceanic and atmospheric variables, stochastic approaches might be relevant to simulate ensemble of probable and realistic trajectories, rather than one *incorrect* estimate. One challenge is to control the dispersion of simulated ensembles to accurately cover the distribution of possible trajectories. To address this question we study the relative dispersion over time of several ensembles of drifters deployed at the same space-time position.

2 Instruments, data and methods

This section describes the two types of drifters deployed during OTC25, as well as the data and trajectory reconstruction methods used in our analysis. We first present the design of the MELODI and SPOT drifters. Next, we introduce the different satellite-derived and drifter datasets (including the preprocessing steps applied when relevant). Finally, we detail the Lagrangian statistics used to characterize the drift dynamics, the trajectory reconstruction methods implemented, and the metrics employed to evaluate them.

2.1 Drifters deployed during the campaign

At the time of writing only eOdyn MELODI and IGE SPOT data are available. We therefore focus on these two types of drifters; however, it should be mentioned that 16 OpenMetBuoy, 4 CLS MARGE-T II, and 1 Sofar Spotter buoys were also deployed during the campaign. Including these additional drifters would help strengthen our analysis, as described in Section 4.

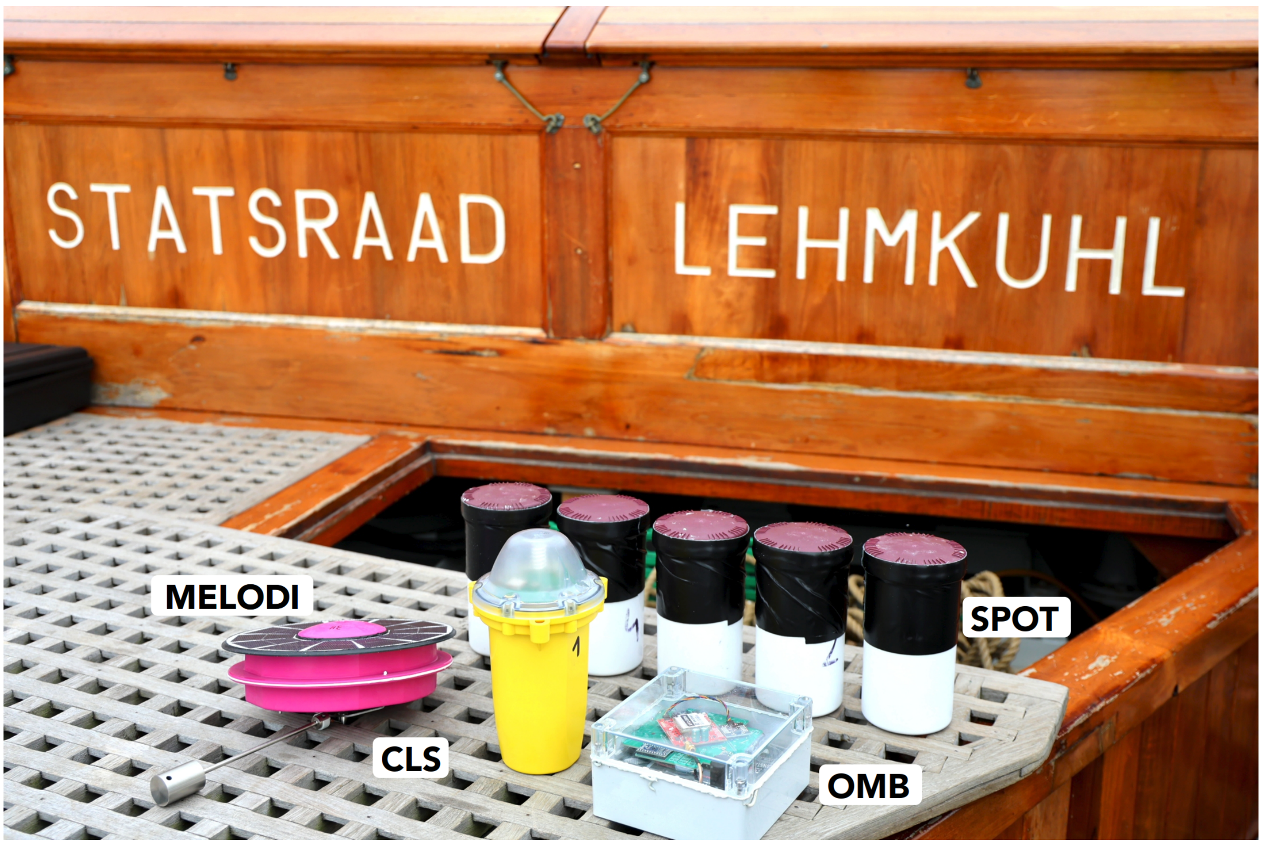

Figure 1: Types of drifters deployed during the OTC25 campaign between Tromsø and Nice. There was also a Sofar drifter not shown in the picture. Photo taken by Joël Marc.

2.1.1 MELODI

The MELODI ("MELODI" 2024) is a surface drifter developed by the company eOdyn. Although we are only interested in the drifter's position, it also measures surface currents, surface temperature and wave parameters. The position is determined using several satellite constellations, with a sampling frequency of 1 hour. The drifter uses the Iridium satellite network to transmit its data. It is powered by four Li-ion 3500 mAh, 3.7 V batteries and a 6 W solar panel, which allows it to operate for at least several months. Thanks to its low-profile, see Figure 2, the MELODI drifter is expected to be only weakly affected by wind drift.

From Tromsø to Nice, 18 MELODI drifters were deployed in various locations: in the North Sea and its

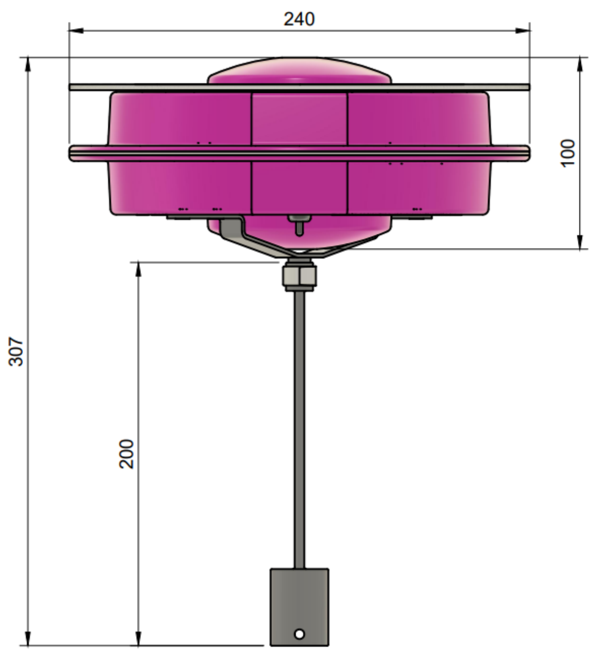

Figure 2: Design of the MELODI drifter

Lofoten eddy, in the North Atlantic (including during a storm event), before and after the Strait of Gibraltar (within the Alboran eddy), and in the western Mediterranean Sea. This can be seen in Figure 3.

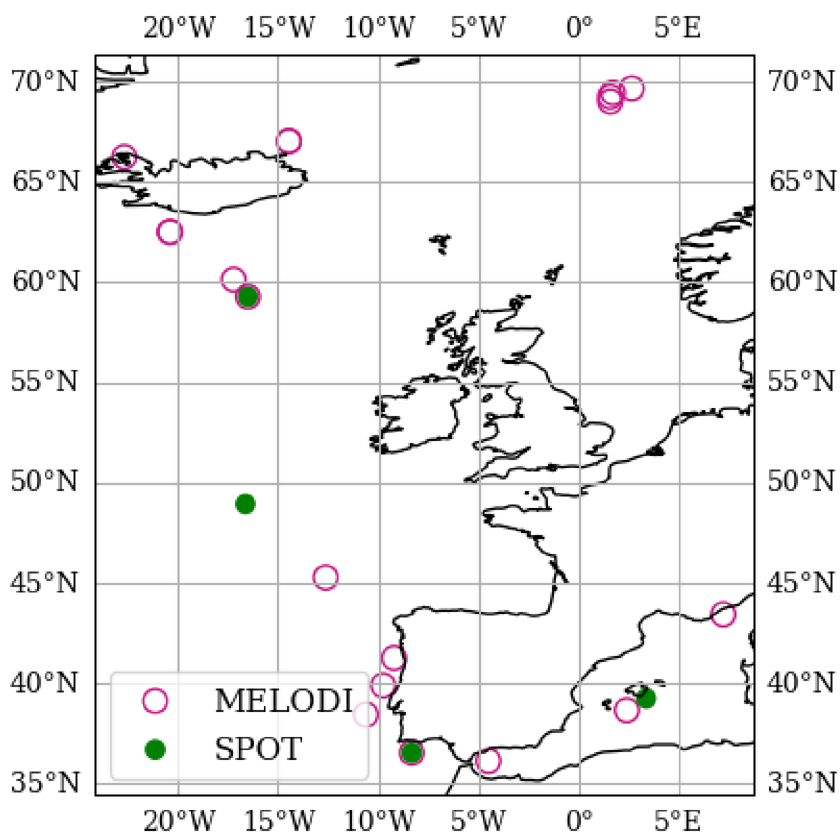

Figure 3: MELODI and SPOT drifter deployments during the OTC25 campaign.

2.1.2 SPOT

The SPOT ("SPOT" 2024) is a home-made surface drifter designed and developed at Institut des Géosciences de l'Environnement (IGE). Its design is very simple, see Figure 4: a weighted waterproof jar containing a GPS tracer powered by external batteries. The GPS tracer is a SPOT Trace, which uses the Globalstar satellite network to transmit its position every 30 minutes. External batteries (4 LR20 alkaline 1.5V 13Ah) allow the drifter to operate for up to 6 months and counting at the time of writing.

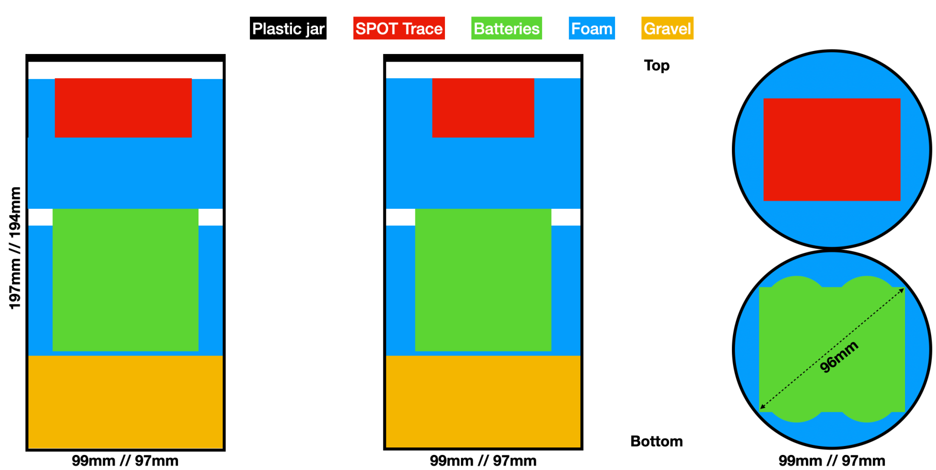

Figure 4: Design of the SPOT drifter

During the first deployments we noticed that the SPOT drifters exhibited an orbital motion around their vertical axis and we suspected that it was the cause for the observed effective sampling frequency being larger than the nominal 30 minutes (see Figure 6). To mitigate this motion we designed a dynamic anchor attached to the bottom of the drifter. Being at sea we had to reuse material available aboard the ship: old sails and steel wire ropes, as visible in Figure 5.

Figure 5: SPOT drifter with a dynamic anchor

The last 5 drifters deployed in the Mediterranean Sea were equipped with this anchor. Using the drifter data presented in Section 2.2.2 it seems that the anchor was effective in improving the effective sampling frequency, as shown in Figure 6. Further analysis would be required to confirm this is due to the dynamic anchor and not because of an overall quieter sea state in the Mediterranean Sea.

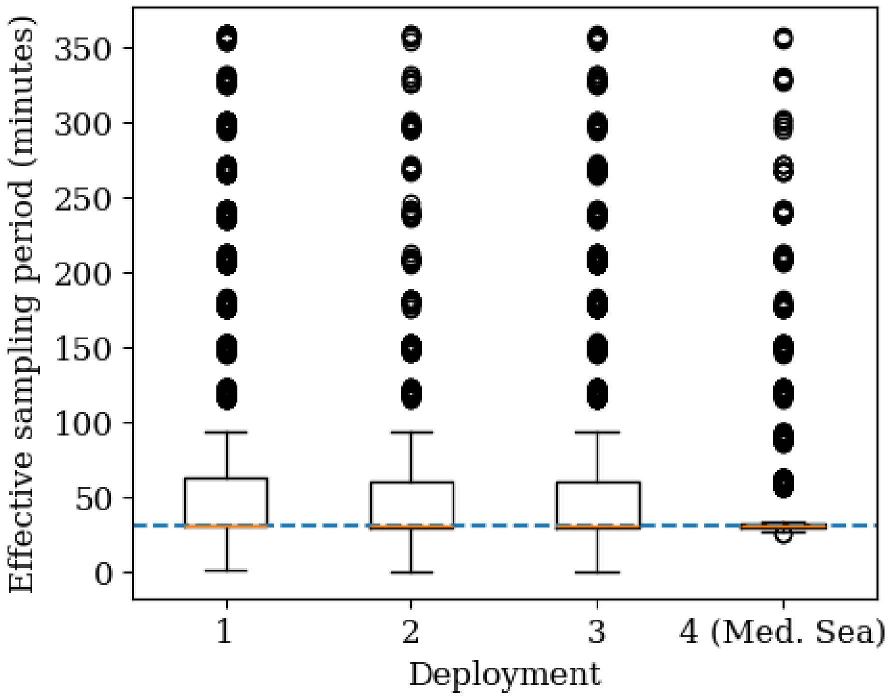

Figure 6: SPOT drifters effective sampling period. The dashed blue line indicates the nominal sampling period of 30 minutes.

2.2 Satellite and drifter data

Our analysis requires both maps of geophysical quantities (surface currents, waves, winds) and lagrangian drifter trajectories.

2.2.1 Satellite-derived gridded products

Geophysical quantities of interest are derived from satellite observations, assimilated in physical models of varying complexity.

2.2.1.1 Sea Surface Height

VarDyn is a variational mapping method jointly reconstructing Sea Surface Height (SSH) and Sea Surface Temperature (SST) (Le Guillou, Chapron, and Rio 2025). The version used in our analysis assimilates both SWOT KaRin and Nadir altimeters data and produces daily $0.05° \times 0.05°$ maps. This dataset provides both SSH and sea surface currents, derived from the SSH field using the cyclogeostrophic inversion method proposed by Bertrand, Le Sommer, et al. (2025) and implemented in the Python package `jaxparrow` (Bertrand, Vianna Zaia De Almeida, et al. 2025).

2.2.1.2 Sea Surface Wind

Wind acts both directly on the drifter (the leeway) and indirectly through its effect on waves and currents. We use the wind velocity at 10 meters above the surface from the $0.125° \times 0.125°$ hourly ECMWF bias corrected product (WIND_GLO_PHY_L4_NRT_012_004 2024) developed by the Royal Netherlands Meteorological Institute.

2.2.1.3 Sea State

Waves also affect drifter trajectories through the Stokes drift. We employ the Stokes drift obtained by assimilating significant wave height in the wave model MFWAM, available in the 0.083° × 0.083° hourly Global Ocean Waves Analysis and Forecast product (GLOBAL_ANALYSISFORECAST_WAV_001_027 2023) developed by Mercator Ocean International.

2.2.2 Drifter data

Starting from the raw GPS positions transmitted by the drifters, we perform several preprocessing steps before using them in our analysis.

2.2.2.1 L0 version

The L0 version of the data consists of datasets containing the original timestamps and positions (latitude and longitude) for each drifter, complemented by its deployment date and time. Each record also includes the time interval between successive measurements.

2.2.2.2 L1 version

The L1 version of the data is produced by applying the following Quality Control (QC) steps to the L0 dataset:

1. Spurious GPS locations were removed following the procedure described by Elipot et al. (2016),
2. Curated trajectories were divided into segments whenever the time gap between two consecutive timestamps exceeded 6 hours,
3. Segments shorter than 1 day are discarded.

As shown in Table 1, these QC steps result in only a small reduction in the number of MELODI drifter observations. In contrast, about 20% of the SPOT observations were discarded, primarily due to transmission issues that caused large gaps in the original trajectories and consequently led to many short segments being removed.

Table 1: Number of observations and segments in L0 and L1 versions for SPOT and MELODI datasets.

Dataset	# Observations		# Segments	
	L0	L1	L0	L1
SPOT	24503	19846	20	189
MELODI	47399	46837	19	39

2.2.2.3 L2 version

Trajectories are resampled at a regular time interval of 1 hour using a linear interpolation for the positions and the velocities are then computed using central differences.

An example of L0, L1 and L2 trajectories for a SPOT drifter is shown in Figure 7. It can be seen that the L0 trajectory contains some spurious points, which are removed in the L1 and L2 versions. Holes in the L1 and L2 trajectories correspond to gaps larger than 6 hours in the original data. Holes are not filled by interpolation in the L2 version as those trajectories are then considered as distinct segments.

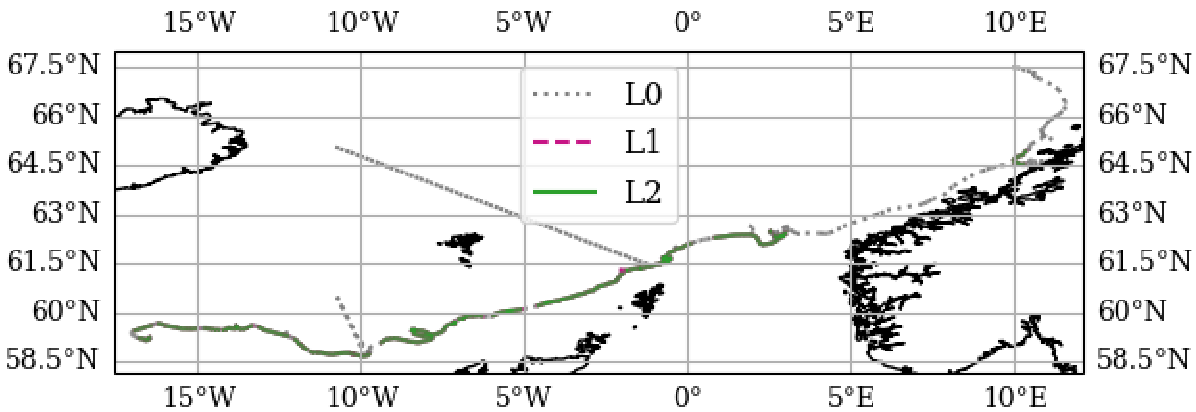

Figure 7: SPOT drifter 0-4498291 data (2025-05-12 – 2025-09-16) at different pre-processing levels.

Figure 8 presents the L2 trajectories of both SPOT and MELODI drifters deployed between Tromsø and Nice during OTC25.

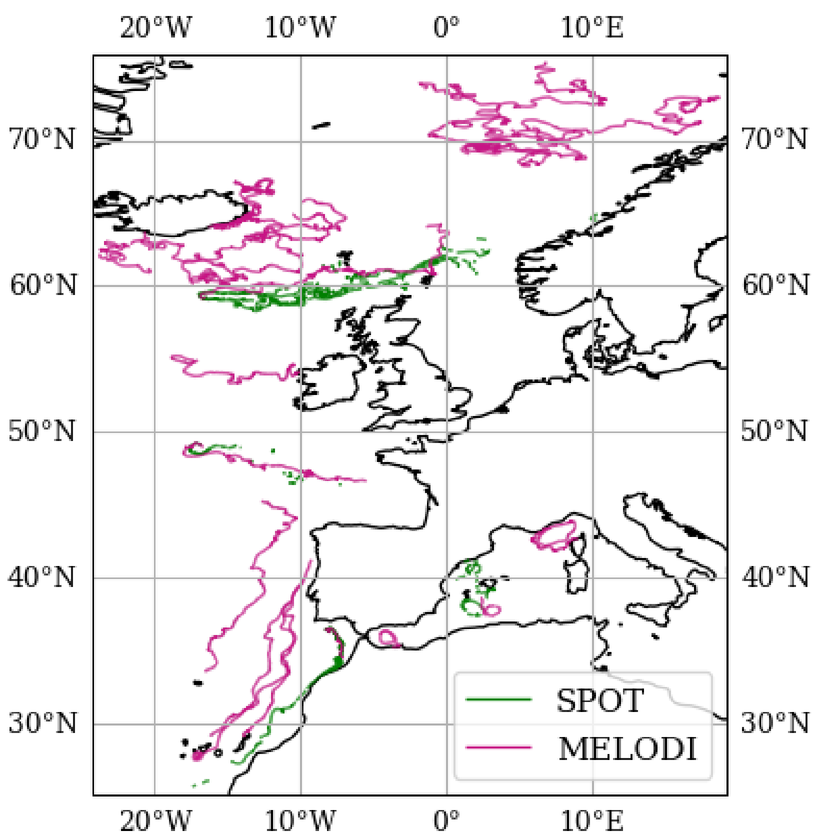

Figure 8: L2 drifters data from the OTC 25 (2025-04-25 – 2025-09-16).

2.3 Modeling of drifter trajectories

2.3.1 Linear combination

2.3.2 Maxey-Riley equation

2.4 Pair dispersion

Spreading of a group of surface drifters can be characterized by the distance D between a pair of drifters and the relative diffusivity K, defined as:

$$K(D) = \frac{1}{2}\frac{\partial D^2}{\partial t}, \tag{1}$$

where t stands for the time (Van Sebille et al. 2015). Since we study the motion of floaters at the sea surface, we will use the 2-D Quasi-Geostrophic turbulence theory. add citations In this context, the dynamics of the pair separation can be classified in three regimes, depending on the scale of the underlying currents. There are two important length scales: the Rossby deformation radius, that is the distance at which rotational effecs become important, and the scale of the eddies present in the flow.

For separations smaller than the Rossby deformation radius, we expect the pair dispersion D^2 to increase exponentially with time and the pair diffusivity to be proportional to the pair dispersion D^2. This is known as the "exponential regime". If the separation is bigger than the Rossby deformation radius but smaller than the biggest eddies in the flow, the dynamics is known as "Richardson regime" and is expected to scale as $D^2 \propto t^3$. The pair diffusivity is expected to be $K \propto D^{4/3}$. These two regimes are *local*, meaning that their dynamics is governed by eddies of $(O)(D)$. For scales larger than the eddies, i.e., for non-local dynamics, we expect a diffusive random walk regime with dispersion scaling linearly with time and K keeping a constant value. In this case, the diffusive character of the dynamics arises because each drifter of the pair is influenced by different, uncorrelated eddies.

We performed four deployments of five SPOT drifters each dedicated to study pair dispersion, as shown in Figure 3. The first deployment was performed on the 12th May on the Atlantic Sea, the second on the 18th May, the third on the 24th May just before crossing Gibraltar straight, and one last deployment on May 30th at the mediterranean sea.

2.5 Drone measurements

Source: Instruments, data and methods

3 Results

3.1 Pair dispersion

We used the home-made SPOT drifters to study pair dispersion. They are designed to transmit their position every 30 minutes. However, this is not always the case. In order to calculate the distance betwen a pair of drifters, they should have transmitted in the same time interval. Figure 9 shows in black when each drifter transmitted its position, using a time interval of 30 minutes. This trajectories have already been interpolated in time (L2 version). For each deployment of $N = 5$ drifters, there are $N(N-1)/2 = 10$ pairs. For each pair, we will consider their positions if they transmitted at the same time interval.

Considering the variability of the conditions for making *in-situ* measurements, each group of drifters behave differently. We can observe that there are several pairs for the first and third depoyments, but less simultaneous transmissions for the second and fourth. For example, on the last deployment one drifter stop transmitting almost inmediately, so we have only 6 pairs. But if we take a closer look at Figure 9 (d) we see that in practice we have only one pair of drifters that transmitted for more than a month.

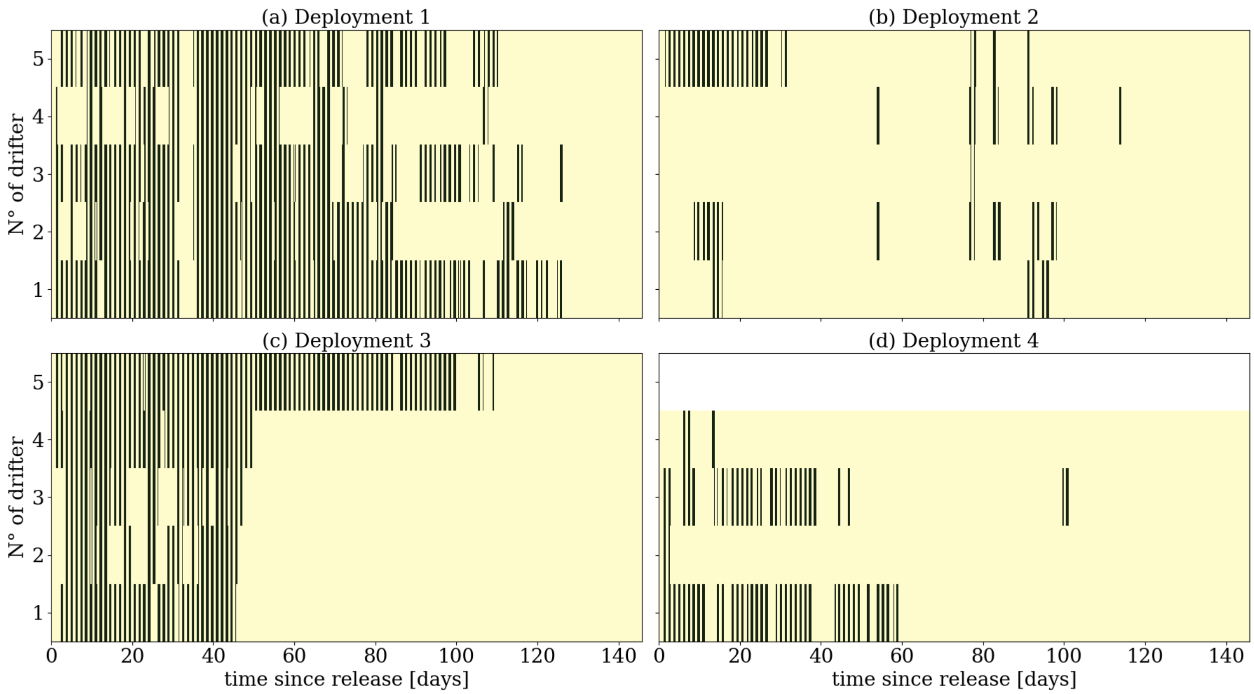

Figure 9: Mask showing if the drifters transmitted their position. The black rectangles indicate that the transmission was successful, yellow rectangles indicate that they did not transmit. L2 trajectories are used for the analysis.

Figure 10 shows the pair dispersion D^2 as a function of time for each deployment. As discussed before, for the first and third deployments we have several pairs while we do not have enough data for the second and fourth. In Figure 10 (a) we can clearly observe two different behaviors: an exponential growth for the first two weeks after release, and a different regime after. Pink lines indicate the exponential and the richardson regimes, showing a good agreement with the measured data. The third deployment, however, seems to show only an exponential behavior. It follows a scaling law $D^2 \propto e^{\alpha t}$, with $\alpha = 5$. comment on that

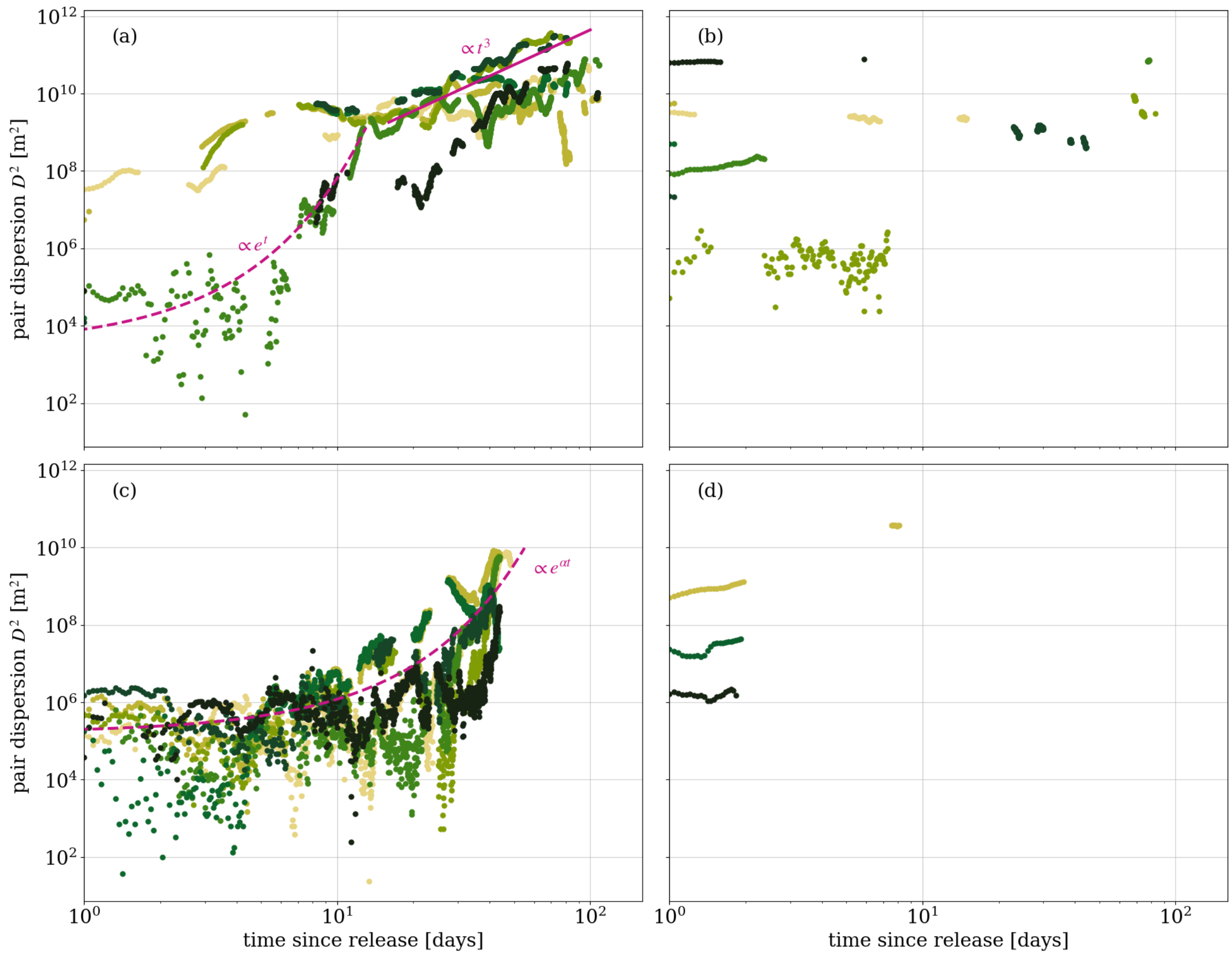

Figure 10: Pair dispersion for each deployment as a function of the time since release. The colors represent the different pairs. The pink dashed line shows the scaling corresponding to the exponential regime and the solid pink line represents the scaling of the richardson regime.

The rate of change of separation, or pair diffusivity, has been calculated using Equation 1 and is shown in Figure 11. Both regimes are shown for all deployments. For the first one, it does not seem to be so clear that there are two regimes, as it was in Figure 10 (a). The third one, however, shows one clear tendency where $K \propto D^2$. The second and fourth deployment do not have enough data to determine the regime that governs its dynamics.

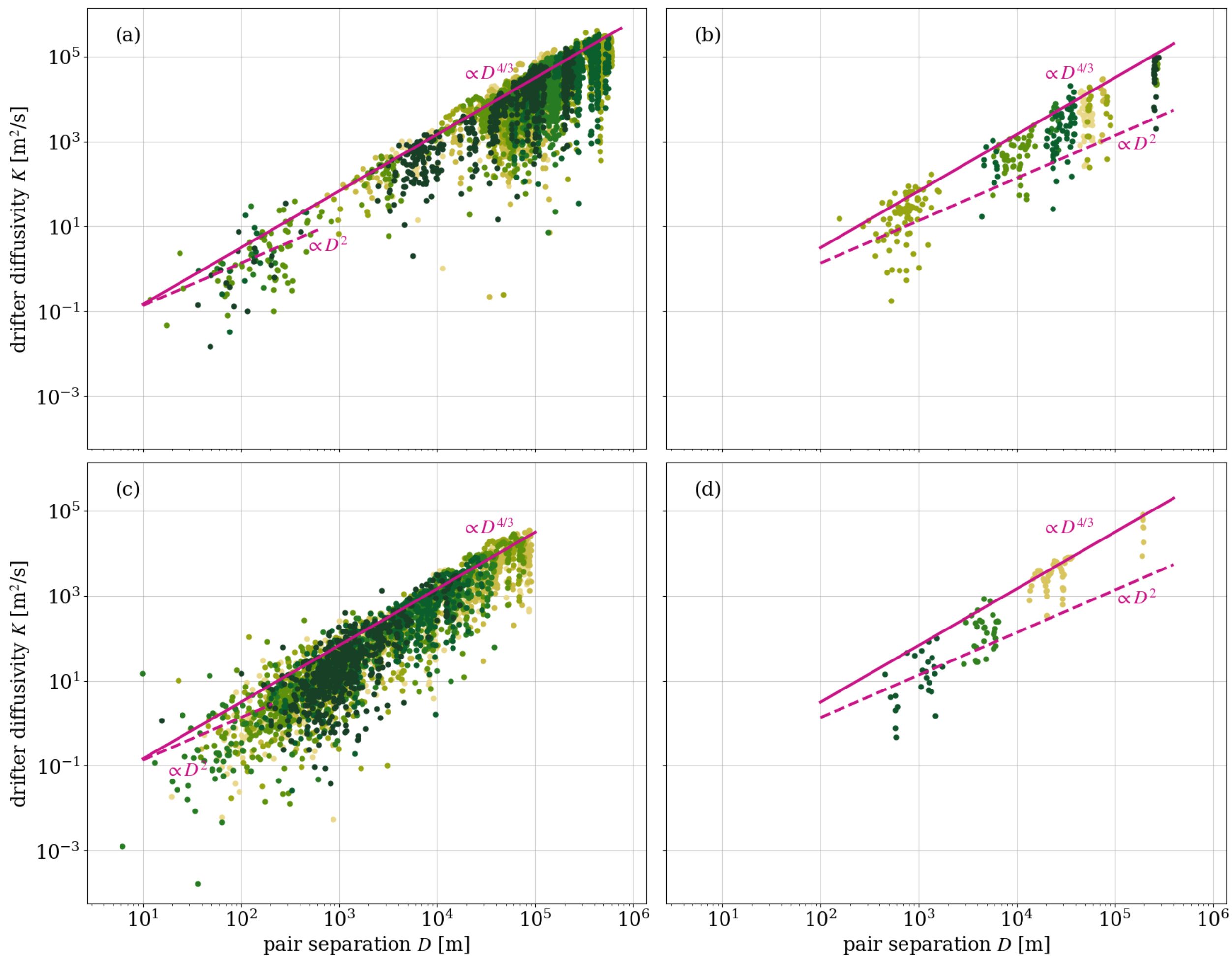

Figure 11: Pair diffusivity as a function of the distance between pairs. The colors represent the different pairs. The pink dashed line shows the scaling corresponding to the exponential regime and the solid pink line represents the scaling of the richardson regime.

Source: Results

4 Discussion

4.1 Pair dispersion

From the data from the first deployment, we could distinguish two different regimes (see Figure 10). However, the separation between them was not clear on the pair diffusivity (Figure 11). The change of regime arrives at aptoximately two weeks after the deployment, when the distance between pairs is around 70 km. Figure 12 shows the position of the ship, the drifters and the cyclogesotrophic current from the release until this moment. In the panel (a) we can see the seashot corresponding to the first deployment. We can observe that the distance D is of the order of the eddies, but not yet the biggest eddies present in the flow. It makes sense that, in this case, the dynamics is still local but changes from a regime where they have been in the same eddy to an intermediate one. At the moment of the writing, five months after the release, he system did not reach yet the diffusive regime.

Regarding the third deployment, we can interpret the results shown in the previous section by looking at Figure 12. Two weeks after the deployment, the drifters move still all together and the distance they travelled

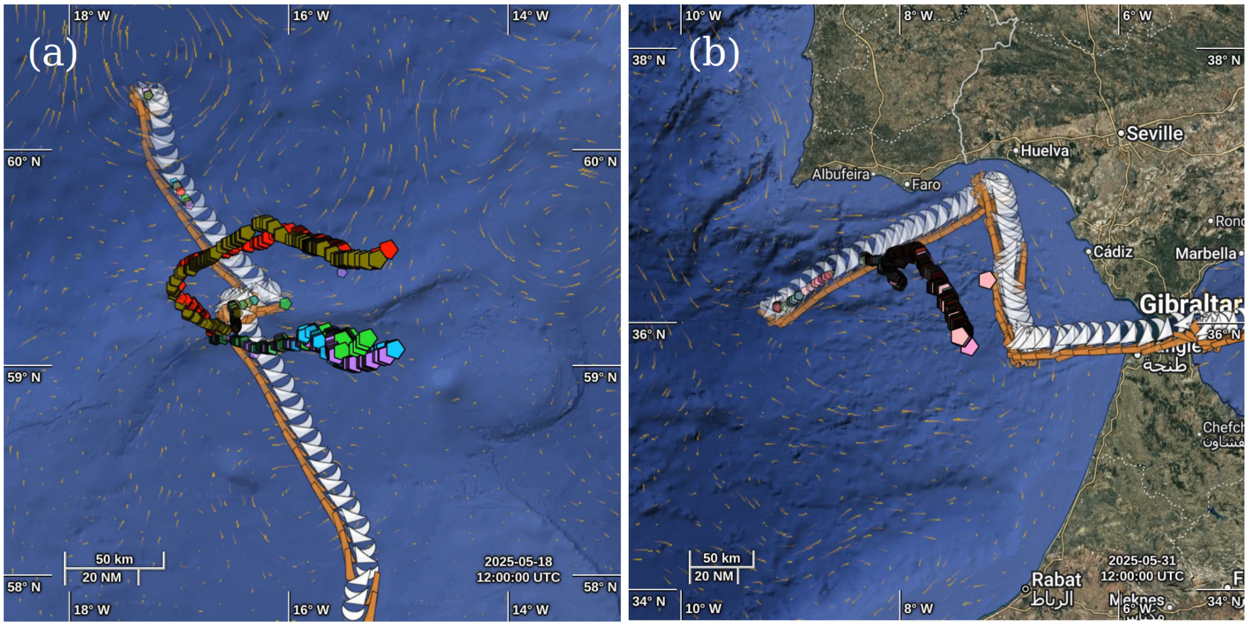

Figure 12: Seashots taken from OVL OceanDataLab, showing the trajectory of the Statsraad Lehmkhul, the cyclogesotrophic current (from Vardyn) and the position of the SPOT drifters over two weeks, starting the day of the deployment for (a) the first deployment and (b) the third one.

is much smaller than the eddies present in the flow. It is expected, then, that the system remains in a local regime for longer. Our observations are in agreement with the previous results from the literature. add citations.

Source: Discussion

5 Conclusion

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