Estimation of Sea Surface Current Velocities using AIS Data

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***Abstract*—The Automatic Identification System (AIS) provides information for tracking and monitoring vessel activity in real time. The vessel traffic data from AIS includes position coordinates in latitude and longitude, speed and course over ground, the vessel's unique identification number, and many more. In this work, we investigate the use of AIS data for estimating sea surface current velocities in the Eastern Mediterranean sea. Specifically, we apply the dead reckoning technique to compute the difference between the projected position and the true position of a vessel over time, which is mainly attributed on the force of sea surface currents. The estimated sea surface current velocities and directions are compared with the ones provided by the Copernicus Marine ocean product system. The analysis reveals that the dead reckoning technique can be used reliably for estimating sea currents at a very fine granularity, especially in high-traffic and coastal areas, where there is an increased complexity of obtaining accurate results from other sources.**

***Index Terms*—AIS data, dead reckoning, sea currents, Eastern Mediterranean, Copernicus data**

I. INTRODUCTION

To avoid ship collisions and improve safety at sea, all vessels over 300 GT (gross tonnage) and all passenger ships are obliged to use the Automatic Identification System (AIS), an automated and autonomous tracking system that is extensively used in the maritime world. AIS is designed to provide identification and other information about a ship to other ships and to coastal authorities. Navigational status data is transmitted every 2 to 180 seconds, depending on a vessel's activity. AIS data streams provide on average hundreds of millions of AIS messages every day [1].

For more than a decade, researchers have used AIS data in different areas of maritime research, from traffic monitoring to oil spill modeling [2]. For instance, AIS data have been used in [3] for the estimation of sea surface currents in the San Francisco Bay and in the Gulf of Mexico. It was shown that the combination of AIS and the dead reckoning technique provides an efficient method of determining sea surface currents. The use of AIS data of 16 ships was also investigated during the 2011 Tohoku tsunami where it was shown that AIS data could be useful for tsunami source estimation and forecast [4]. In another study, the use of AIS maritime data and deep learning methods were investigated for the reconstruction of sea surface currents [5]. Through numerical experiments on a real dataset, the authors have shown that AIS data provide a reliable source of observations to derive sea surface currents. In a more recent study, estimations of ocean surface velocities over the region of the Agulhas Current were obtained using a selected AIS dataset from up to 1000 vessels [6]. The AIS information was combined with known surface currents derived from satellite altimetry and drifting buoys for developing a surface current system. It was demonstrated that AIS messages from a high density of vessel traffic can be used for studying and monitoring ocean currents with more detailed resolution and precision. The currents, due to their ability to transport floating matter, have ecological implications as well as pollutant transportation implications in the event of oil spills. Surface currents can also impact search and rescue operations at sea [7].

A variety of techniques have been also explored in the Mediterranean Sea for improving estimates and forecasts of sea surface currents. The mean circulation and dynamics of the Mediterranean Sea are described in [8]. In this area, the Cyprus Coastal Ocean Forecasting and Observing System (CYCOFOS), a hydrodynamical numerical model, was developed for high resolution flow simulations in the Cyprus basin [9]. The CYCOFOS hydrodynamical numerical model was evaluated in the Cyprus coastal area against a regional forecasting model, called ALERMO [10]. In [11], it was demonstrated how assimilation of hydrographic data, obtained from ocean gliders, can significantly improve short-term regional forecasts when combined with the CYCOFOS model.

State-of-the-art methods such as the ones mentioned above can hardly resolve very fine spatial scales, especially in coastal areas, and therefore alternative techniques are required. For this reason, this work aims towards implementing a formalised ocean system, by using the combination of dead reckoning and AIS data, for improving estimations and regional forecasts near the coastal areas of Cyprus at a very fine granularity. The establishment of such a system can facilitate various real-time applications including tracking and monitoring of oil spills or assisting search and rescue operations.

II. RESEARCH METHODOLOGY

This section describes the data and methods used for this work.

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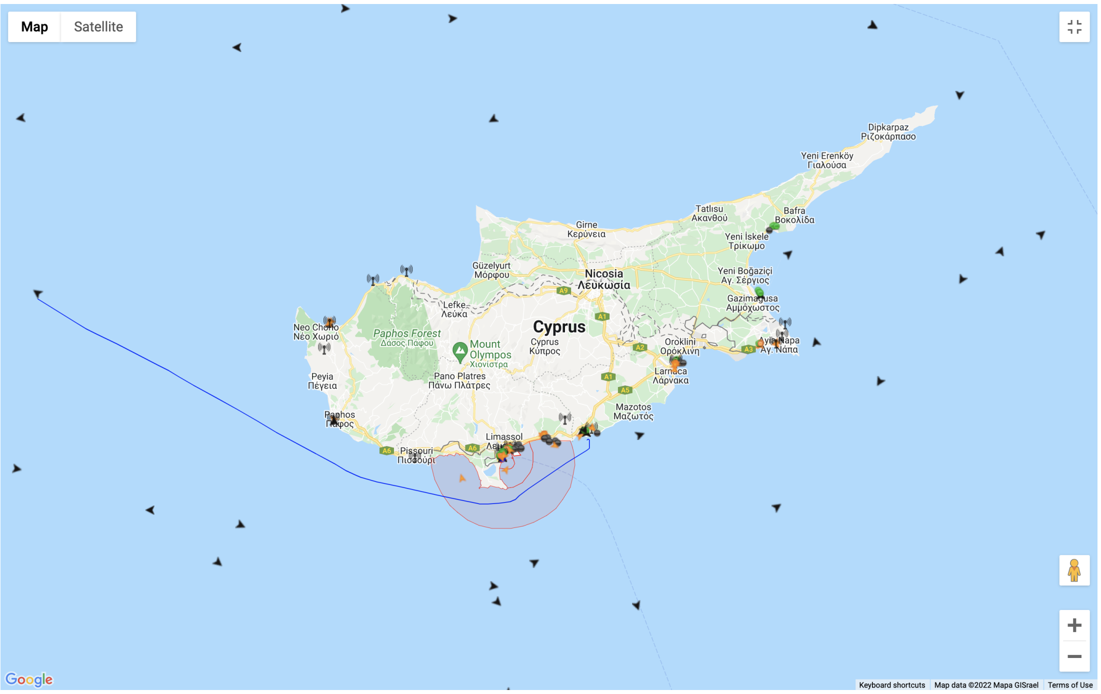

Fig. 1: The route of the considered vessel taken from the CUT-AIS Ship Tracking Intelligence Platform [13]. The vessel covered a distance of approximately 210 Km.

A. Data

The Cyprus University of Technology (CUT) has developed, through the Sea Traffic Management in the Eastern Mediterranean (STEAM) project [12], a Ship Tracking Intelligence Platform for monitoring and visualising ship traffic using AIS data. The data is organized and stored into a relational database server and contains all the necessary measurements required for the dead reckoning technique. These measurements correspond to vessel activities in the Eastern Mediterranean sea and around Cyprus, since 2017. The chosen dataset for this study covers activities for 181 different vessels during a 24 hour period, on February 1st, 2022. However, the results shown in this paper are obtained by considering in detail a single randomly-selected vessel. The route of the considered vessel, which is shown in Figure 1, is taken from the CUT-AIS Ship Tracking Intelligence Platform [13].

On the other hand, the Copernicus Marine Environment Monitoring Service (CMEMS) is the marine component of the Copernicus Programme and provides regular and systematic information about the physical state and dynamics of the global ocean and the six regional seas in Europe. The Copernicus services rely on satellite data, in-situ measurements, and data from numerical models. It provides quarterly, hourly, daily and monthly sea current velocities. In this work, the sea current velocities from the Copernicus Marine Service: product MEDSEA_ANALYSISFORECAST_PHY_006_013 [14], a coupled hydrodynamic-wave model implemented over the whole Mediterranean Basin. The sea current velocities, provided by [14], around the Cyprus island and for the same count day, i.e., February 1st, 2022, are shown in Figure 2.

Note, the model horizontal grid resolution is approximately 4.6 Km. Thus, sea current velocity and direction per approximately 21 Km^2 grid cell are assumed to be the same. On the other hand, the longitude and latitude resolution reported in AIS messages is about 10–100 m. Therefore, our approach that uses AIS data can calculate sea currents at a much finer granularity, reaching as low as 100 m^2. Such resolution can be crucial, especially for search and rescue operations or oil spill detection and mapping.

B. Dead reckoning

In this section, we describe the application of the dead reckoning technique for the estimation of sea surface currents. Dead reckoning is the process of calculating a ship's approximate displacement by using the last established position and velocity vector (speed and direction) over elapsed time. Moreover, this work will use dead reckoning to calculate the angle that a ship is displaced from its intended course, and then use this to estimate the magnitude and direction of the sea current that caused the ship displacement. Before doing so, data transformation is required for converting raw AIS data into a suitable and appropriate format in order to apply the dead reckoning technique. Note also that the impact of the wind, known as the Leeway Drift, is not considered in the present work, since the wind-induced drift is small compared to that of sea surface currents [15]. Therefore is it assumed that the difference between the projected position and the true position is mainly attributed on the force of sea surface currents. Details on the dead reckoning approach are demonstrated in Algorithm 1, whereas the formulae that have been used in this work are shown in the next subsections.

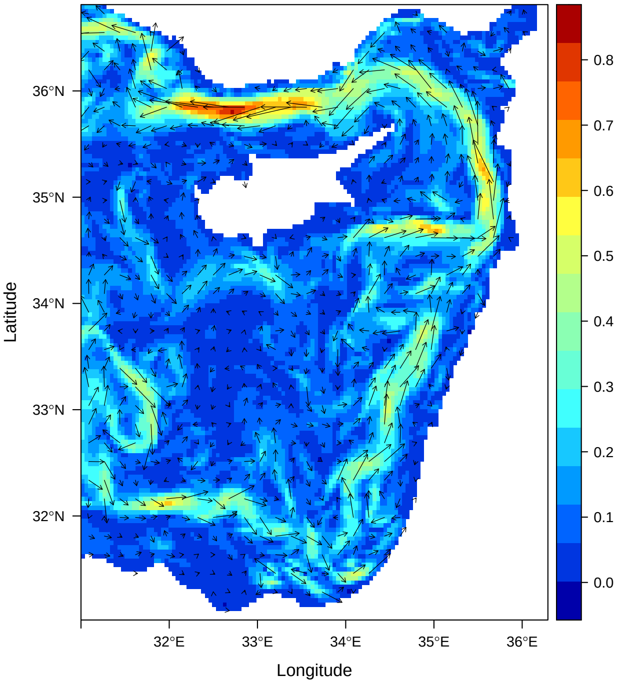

Fig. 2: Sea current velocities in the Eastern Mediterranean sea provided by the Copernicus Marine Service: product MEDSEA_ANALYSISFORECAST_PHY_006_013 [14].

Algorithm 1: Sea current velocity estimation using dead reckoning and AIS data

Input: AIS measurements (received timestamps, vessel positions, speed over ground, course over ground)
Output: Sea current velocities

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Apply the filtering technique shown in Algorithm 2.
for all AIS messages, $j$, with $j = 1, 2, ..., (n_{tot} - 1)$ do
    Calculate the vessel actual distance $D_j^{\text{actual}}$ using Eqs.(1)–(3), and the actual vessel bearing $\theta_j$ using Eq. (4).
    Calculate the dead reckoning distance $D_j^{\text{reckoning}}$ using Eq. (5).
    Calculate the ship displacement $D_j^{sd}$ using Eqs. (6)–(8).
    Calculate sea current magnitude $SC_j$ and angle $\theta_j^{SC}$ using Eqs. (9)–(10).
end for
Remove data outliers with respect to the sea current speed variable.
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Algorithm 2: Data Filtering Technique

Input: Original AIS dataset
Output: Dataset with at least 60 seconds difference in timestamps between AIS messages.

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$t_{\text{previous}}$ = received timestamp of $1^{st}$ AIS message
for each next AIS message, $j, j = 2, ..., (n_{tot} - 1)$ do
    if $t_j - t_{\text{previous}} \geq 60$ seconds then
        store $j$ in the dataset
        $t_{\text{previous}} = t_j$
    end if
end for
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1) Data Filtering: Algorithm 2 shows the steps conducted for the data filtering technique. From the simulation results, we noticed that there are cases where there are abnormally high vessel speeds computed, especially when the time difference in timestamps between two consecutive reported AIS messages is short (less than 60 seconds). After examining the available data, it is now assumed that the speed variation is caused by inaccurate reported AIS GPS positions. For this reason, a simple filtering data cleaning technique is first applied for keeping consecutive messages that have more than 60 seconds difference in timestamps.

2) Haversine formula: The Haversine formula calculates the shortest distance that a vessel travels between two points over the earth's surface. For instance, the vessel distance, d_j, between any two positions is given by the equation

$$d_j = \sin^2\left(\frac{\phi_{j+1} - \phi_j}{2}\right) + \cos(\phi_j) \times \cos(\phi_{j+1}) \times \sin^2\left(\frac{\lambda_{j+1} - \lambda_j}{2}\right) \tag{1}$$

where ϕ_j and λ_j are respectively the latitude and longitude points, at the reported AIS position j, with $j = 1, 2, ..., (n_{tot} - 1)$ and n_{tot} being the total number of AIS messages. The distances d_j are stored in the original dataset. The angular distance between the same two positions is computed using the following equation:

$$c_j = 2 \times \tan^{-1}\left(\frac{\sqrt{d_j}}{\sqrt{1 - d_j}}\right). \tag{2}$$

Finally, the angular distance c_j is scaled by the radius of the Earth, R, in order to compute the actual distance traveled, D_j^{actual}, between points j and $j + 1$, such as

$$D_j^{\text{actual}} = R \times c_j. \tag{3}$$

The radius is chosen to be in kilometers, i.e., $R = 6378 Km$. Moreover, the actual heading of the vessel between any two positions is calculated by

$$\theta_j = \tan^{-1}\left(\frac{y_j}{x_j}\right), \text{ for } j = 1, 2, ..., (n_{tot} - 1), \tag{4}$$

where $y_j = \cos(\phi_j) \times \sin(\phi_{j+1}) - \sin(\phi_j) \times \cos(\phi_{j+1}) \times \cos(\lambda_{j+1} - \lambda_j)$ and $x_j = \sin(\lambda_{j+1} - \lambda_j) \times \cos(\phi_{j+1})$.

3) Dead Reckoning Formula: By multiplying the speed over ground (sog) by the time difference in timestamps between the position reports, the length of the dead reckoning vector can be computed. This vector is in the direction of the course over ground (cog), which provides an orientation of this vector with respect to the compass. The equation for computing dead reckoning, $\mathrm{D}^{\text{reckoning}}$, is given by

$$\mathrm{D}_j^{\text{reckoning}} = \mathrm{sog}_j \times \Delta t_j, \text{ for } j = 1, 2, ..., (n_{tot} - 1), \quad (5)$$

where sog_j is the speed over ground at position j, and Δt_j is the time difference in timestamps between the two reported positions, i.e., $\Delta t_j = t_{j+1} - t_j$.

4) Ship Displacement Formula: The ship displacement can be found by computing the difference between the actual distance traveled and the dead reckoning distance. In order to calculate the ship displacement between two positions j and $j+1$, both $\mathrm{D}_j^{\text{actual}}$ and $\mathrm{D}_j^{\text{reckoning}}$, are decomposed into x and y components, such that

$$x_j^{sd} = \mathrm{D}_j^{\text{reckoning}} \times \cos(\mathrm{cog}_j) - \mathrm{D}_j^{\text{actual}} \times \cos(\theta_j), \quad (6)$$

$$y_j^{sd} = \mathrm{D}_j^{\text{reckoning}} \times \sin(\mathrm{cog}_j) - \mathrm{D}_j^{\text{actual}} \times \sin(\theta_j). \quad (7)$$

The magnitude of the ship displacement can be now estimated using the equation

$$\mathrm{D}_j^{sd} = \sqrt{(x_j^{sd})^2 + (y_j^{sd})^2}. \quad (8)$$

5) Sea Surface Currents Formula: Once the ship displacement between the two positions is computed, dividing it by the time between measurements, Δt_j, gives the magnitude of the ocean surface current magnitude, SC_j, such as

$$\mathrm{SC}_j = \frac{\mathrm{D}_j^{sd}}{\Delta t_j}. \quad (9)$$

Moreover, the angle of the surface currents is calculated by

$$\theta_j^{SC} = \tan^{-1}\left(\frac{\mathrm{y}_j^{sd}}{\mathrm{x}_j^{sd}}\right), \text{ for } j = 1, 2, ..., (n_{tot} - 1). \quad (10)$$

III. RESULTS

In this section, we first demonstrate the use of dead reckoning (Algorithm 1) for computing the sea current velocities for the considered case study shown in Figure 1. Next, we compare the estimated sea current velocities with those provided by the Copernicus Marine Service [14] at the coordinates where the considered vessel has passed.

A. Sea Current Estimation using AIS Data & Dead Reckoning

The considered vessel for this study sent a total of 3290 AIS messages. The vessel heads from Vassiliko Port, near Limassol, towards north-west of Cyprus. Figure 1 shows the vessel route.

Two different test cases are examined in this first study. The first test case considers all AIS messages without filtering, while the second test case also applies the filtering cleaning technique from Algorithm 2.

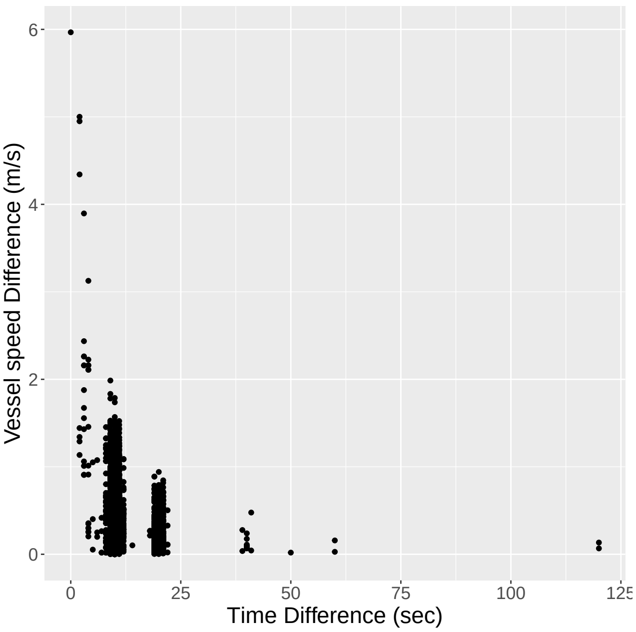


Fig. 3: The difference between the reported AIS speed and the calculated speed, with respect to the time-difference of two consecutive AIS messages.

For instance, Figure 3 illustrates the speed-difference (m/s) between the exact and the reported AIS vessel speed with respect to the time-difference (sec) of two consecutive AIS messages. As shown, high vessel speeds occur when the time-difference between two consecutive AIS messages is short. For this reason, the second test case applies Algorithm 2 for removing consecutive AIS messages with less than 60 seconds difference in timestamps. The new dataset has 654 observations. Even though after filtering, a significant amount of data is removed from the original dataset, note that the remaining data is still quite adequate for providing a fine-grain analysis of the ship route.

The median and mean values of sea surface current speeds, obtained from the first test case (Complete Dataset), as well as those obtained from the second test case (Filtered Dataset), are shown in Table I. As can be seen, the median and mean values of sea current speeds, obtained from the Complete Dataset is four times higher than those obtained from the Filtered Dataset. In particular, the mean value of sea current speeds in the Complete Dataset is 0.62m/s whereas the mean value of sea currents speeds in the Filtered Dataset is 0.15m/s. Moreover, the maximum sea current speeds of 1.75m/s showing in the Filtered Dataset suggests that more data cleaning is required in the dataset. Therefore, outliers from the sea currents speed variable are removed from the Filtered Dataset using the *outliers* function in R. A point is an outlier if it is above the 75th (Q_3) percentile or below the 25th (Q_1) percentile of the sea currents speed distribution by a factor of 1.5 times the IQR where IQR = $Q_3 - Q_1$. After applying data cleaning with respect to the outliers, the considered dataset has 634 observations (Final Dataset). It becomes evident that the estimated sea current speeds range from 0.01 m/s to 0.33 m/s, values which are in agreement with the corresponding values from Copernicus for the region of Cyprus.

Moreover, the sea current velocities of the Final Dataset, estimated at the points where the considered vessel has passed,

TABLE I: The mean and median values of the estimated sea current speeds, using the dead reckoning technique.

Sea current estimations (m/s) using AIS				
Dataset	median	mean	min	max
Complete	0.58	0.62	0.01	6.18
Filtered	0.14	0.15	0.01	1.75
Final	0.14	0.14	0.01	0.33

are illustrated in Figure 4. The sea current velocities were estimated for a time range of around 15 hours, from 00:05:24 until 15:58:26. Therefore, it is worth comparing the estimated sea current speed velocities with those provided by the Copernicus Marine Service at the same longitudinal positions that are shown in Figure 4, and for the same time period. The details are presented in the following section.

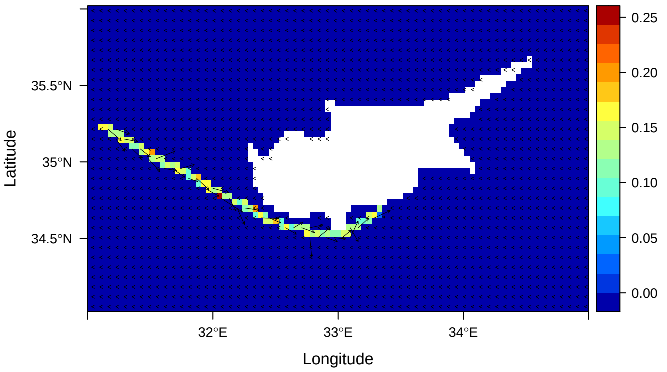


Fig. 4: The estimated sea current velocities at the positions where the vessel has passed.

B. Comparison with Copernicus Marine Environment Monitoring Service (CMEMS)

In this section, the estimated sea surface current velocities from the considered case study are compared with the velocities provided by the Copernicus Marine Service [14]. The Copernicus Marine Service provides quarterly, hourly, daily and monthly sea current velocities. The estimated sea current velocities obtained in the study correspond to the time period 00:05:24 and 14:58:26. Therefore, this study examines 16 hourly datasets from the Copernicus Marine Service, from 00:30:00 until 15:30:00, as well as a daily dataset for the 1st of February, 2022. The considered studied area ranges from 31° to 35°, from east to west (longitude), and from 34° to 36°, from south to north (latitude).

The sea current velocities for four selected hourly time periods, 01:30 - 02:30, 05:30 - 06:30, 09:30 - 10:30 and 13:30 -14:30 are shown in Figure 5.

The plots clearly show that sea currents velocities do not change much over the considered period. Their speeds vary from 0.05 m/s to 0.90 m/s. Moreover, the mean and median sea current speeds over the whole considered area, and for the four selected time periods are shown in Table II. As shown in Table II, sea current speeds provided by the Copernicus Marine Service do not vary over the considered time period since their mean and median values remain almost the same during the day.

TABLE II: The mean and median sea current speed values provided by the Copernicus Marine ocean product system in the whole studied domain and for the four different time periods.

Copernicus sea current speeds (m/s) at different time periods				
Summary	01:30-02:30	05:30-06:30	09:30-10:30	13:30-14:30
Mean	0.15	0.16	0.16	0.17
Median	0.12	0.12	0.12	0.13

Finally, the estimated sea current velocities obtained in the study are compared with the daily dataset provided by the Copernicus Marine Service. The comparison is conducted for the 75 coordinate points where the vessel has passed, using the area granularity provided by Copernicus. We calculate the error statistics, i.e., the difference between AIS and Copernicus results for both sea current magnitude and direction. Results are shown in Table III.

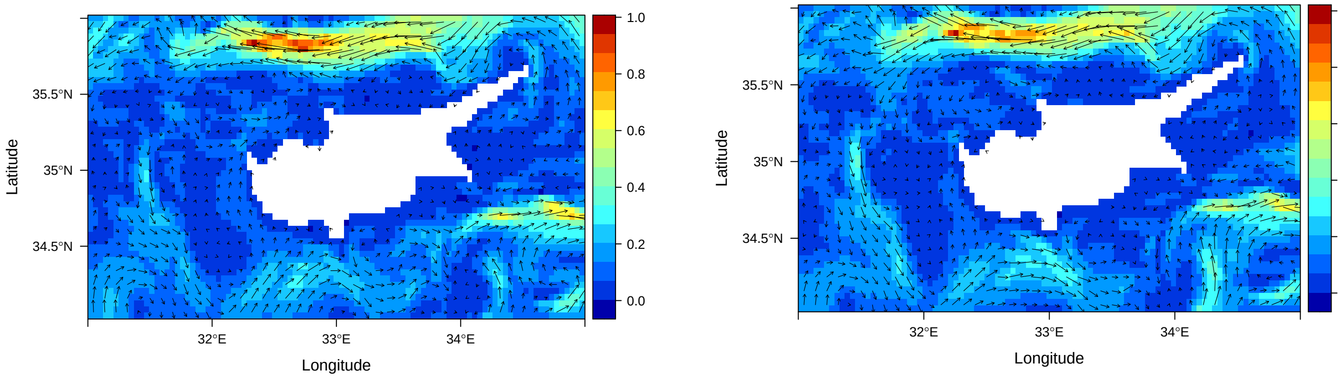
TABLE III: Summary of the error statistics between AIS and Copernicus results for both SC magnitude and direction in the coordinates where the vessel has passed.

Error statistics between AIS and Copernicus sea current velocities					
	mean	median	sd	min	max
Magnitude difference (m/s)	0.06	0.08	0.04	0.004	0.18
Direction difference (°)	97	101	54	2	178

The estimated sea current speeds reported in Table III show a good agreement with those provided by the Copernicus Marine System with respect to magnitude, but not with direction. Dead reckoning could be a promising method for estimating sea current speeds in the Eastern Mediterranean; however, more vessel routes should be considered before reaching any valid conclusions.

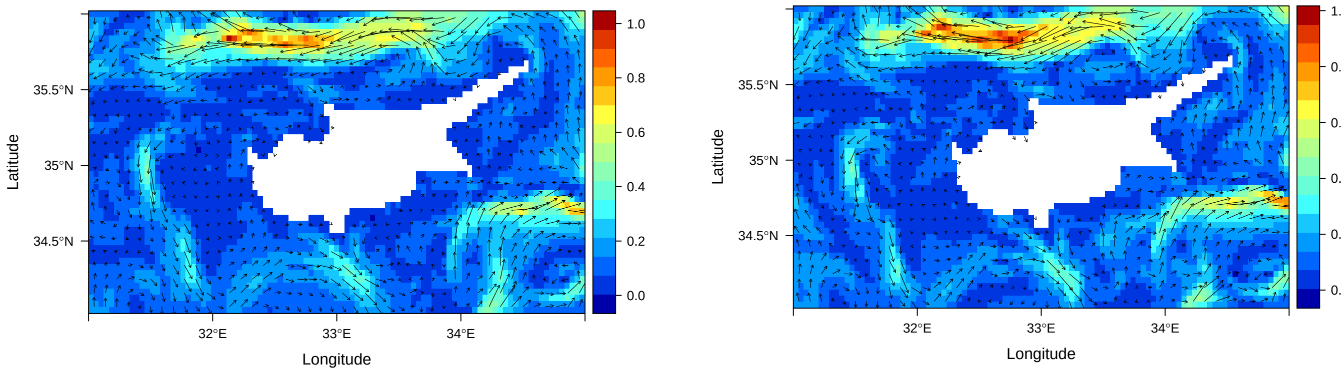
IV. CONCLUSIONS AND FUTURE WORK

Automatic identification system (AIS) data provides a wealth of information regarding vessel traffic and is used for a variety of applications such as collision detection and avoidance, route prediction and optimization, search and rescue operations, and more. This work proposes combining AIS data with the dead reckoning technique for estimating sea surface current velocities in the Eastern Mediterranean. In particular, the angle that a ship is displaced from its intended course is used to estimate the magnitude and direction of the sea currents that caused the ship displacement. The estimated sea surface current velocities are assessed by comparing them with the velocities provided by the Copernicus Marine Service. The preliminary results from this paper show that dead reckoning and AIS data could be an efficient method for estimating sea



(a) 01:30-02:30

(b) 05:30-06:30



(c) 09:30-10:30

(d) 13:30-14:30

Fig. 5: Hourly sea current velocities for 4 representative time periods: (a) 01:30-02:30, (b) 05:30-06:30, (c) 09:30-10:30, and (d) 13:30-14:30; obtained from the Copernicus Marine Service: product MEDSEA_ANALYSISFORECAST_PHY_006_013 [14].

current velocities, in particular at very fine spatial scales and at high-traffic coastal areas.

The next goal of this work is to investigate the proposed method by analysing multiple vessel coastal trajectories around the island of Cyprus, over a longer time span, and in domains with stronger flows. In addition, this work aims to incorporate the sea current information from AIS into the hydrodynamic ocean numerical model, CYCOFOS, for improving forecasts. The work will particular focus on the implementation and evaluation of the developed hydrodynamical ocean model in a real-world scenario in the Eastern Mediterranean, involving either the monitoring and tracking of oil spills or search and rescue missions for locating survivors floating in the open sea.

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