Research Article

Mediterranean Marine Science
Indexed in WoS (Web of Science, ISI Thomson) and SCOPUS
The journal is available on line at http://www.medit-mar-sc.net
DOI: http://dx.doi.org/10.12681/mms.25579

Loggerhead sea turtle, *Caretta caretta,* presence and its exposure to floating marine litter in the Sardinia Channel and the Strait of Sicily: results from seven years of monitoring using ferry as platform of observation

Fabrizio ATZORI[1,2], Lara CAROSSO[2], Nicoletta CADONI[2], Francesca FRAU[2], María Leonor GARCÍA GUTIÉRREZ[2], Giuseppe ANDREA DE LUCIA[3], Martina GREGORIETTI[4], Giuliana PELLEGRINO[5], Svitlana LIUBARTSEVA[6], Rita LECCI[7], Giovanni COPPINI[7], Fulvio MAFFUCCI[8], Sandra HOCHSCHEID[9] and Antonella ARCANGELI[10]

[1] Department of Ecology and Biology, University of Tuscia, Via S. Camillo de Lellis 44, 01100, Viterbo, Italy
[2] Capo Carbonara Marine Protected Area (CCMPA), Villasimius, Italy
[3] IAS-CNR, Institute of Anthropic Impacts and Sustainability in Marine Environment, National Research Council, Torregrande, Italy
[4] Department of Earth and Marine Science, University of Palermo, Palermo, Italy
[5] Accademia del Leviatano, Maccarese, Italy
[6] CMCC Foundation, Centro Euro-Mediterraneo sui Cambiamenti Climatici, Bologna, Italy
[7] CMCC Foundation, Centro Euro-Mediterraneo sui Cambiamenti Climatici, Lecce, Italy
[8] Department of Marine Animal Conservation and Public Engagement, Stazione Zoologica Anton Dohrn, Napoli, Italy
[9] Marine Turtle Research Center, Department of Marine Animal Conservation and Public Engagement, Stazione Zoologica Anton Dohrn, Portici, Italy
[10] Department for Biodiversity Conservation and Monitoring, ISPRA, Roma, Italy

Corresponding author: direzione@ampcapocarbonara.it

Contributing Editor: Marianna GIANNOULAKI

Received: 15 December 2020; Accepted: 9 June 2021; Published online: 28 June 2021

Abstract

The loggerhead turtle is the most common sea turtle species in the Mediterranean Sea. Despite relevant research efforts, information about its distribution is still scarce, particularly in the open sea where they may be exposed to different threats, among which marine litter is of great concern.

Here we investigated the distribution of loggerhead turtles and floating marine macro litter (FMML) in the Sardinia Channel and Strait of Sicily, a key area of the central Mediterranean Sea, by using 7 years of data collected by experienced observers aboard passenger ferries along commercial routes. The high-risk exposure areas were identified and the influence of upper layer currents on turtle and FMML distribution was evaluated. Overall, loggerhead sighting rates were higher than those reported from other Mediterranean routes, but the distribution of turtles within the study area was clearly heterogeneous and influenced by the surface circulation pattern. Summer sighting rates were significantly higher in the Sardinia Channel with respect to the Strait of Sicily. Analysis of the co-occurrence of FMML and loggerhead turtles identified a priority risk area in the central Sardinian channel where the large South-Eastern Sardinia Gyre acts as a trap for both animals and FMML. This study corroborates the effectiveness of using passenger ferries as platforms of observation to conduct systematic surveys of sea turtles and floating macro litter in offshore areas. Results highlighted the importance of the Sardinia Channel and Strait of Sicily for the loggerhead turtle and the areas of greater risk of exposure to the marine litter threat.

Keywords: Loggerhead sea turtle; *Caretta caretta*; distribution; Abundance; marine litter; Sicily and Sardinia channels; sea surface currents; risk exposure; monitoring.

Introduction

Although there are only seven existent species in the world, sea turtles are not a relictual group. These animals have been extremely successful, adapting to the changing environmental conditions over the last 120 million years (Motani, 2009). They exhibit some extraordinary adaptations to an aquatic existence, possess a surprising diversity of life history traits, are important components of marine ecosystems, and occupy unique ecological niches (Renous *et al.*, 2000; Wallace *et al.*, 2010; Hochscheid *et al.*, 2007; Maffucci *et al.*, 2013; Wyneken J. *et* *al.*, 2013,). However, sea turtles are extremely vulnerable to mankind. Fishery bycatch, habitat destruction, marine pollution, and climate change pose constant threats to the survival of these species and have led to their inclusion on most lists of vulnerable or endangered species worldwide (Hamann *et al.*, 2010). Over the last few decades, the impact of marine litter, i.e., man-made waste in the marine environment, on sea turtles has become a major concern (Nelms *et al.*, 2016; Galgani *et al.*, 2019; Claro *et al.*, 2019).

The loggerhead turtle, *Caretta caretta* (Linnaeus, 1758), is the most abundant sea turtle species in the Mediterranean Sea (Casale & Margaritoulis, 2010). Nesting occurs mostly in the warmer eastern basin, but the number of nests documented in the Western Mediterranean has significantly increased over the last decade (Maffucci *et al.*, 2016; Carreras *et al.*, 2018). Older juveniles and adults are found throughout the Mediterranean offshore and coastal waters with abundances that vary across regions and seasons (Bolten, 2003; Casale *et al.*, 2018). On Mediterranean foraging grounds, individuals from local nesting beaches mix with juveniles from the Atlantic RMUs (Regional Management Units) that enter this basin trough Gibraltar and disperse aided by the prevailing surface currents towards both the Western and Eastern Mediterranean Sea (Clusa *et al.*, 2013). Several studies showed that significant inter-basin exchange occurs regularly through the Strait of Sicily, the Strait of Messina, the Strait of Otranto, and the Sardinia Channel (Casale *et al.*, 2018 and reference therein). Juvenile and adult loggerhead turtles are accomplished swimmers, but their movements in the open sea are often associated with mesoscale oceanographic features that concentrate prey and may create temporary foraging hot spots that can be opportunistically used (Bentivegna *et al.*, 2007). Despite being a very well researched species, information about the actual distribution and seasonality of loggerhead turtle presence in the Mediterranean oceanic areas are still scarce and mostly based on bycatch data, satellite telemetry, and mark-release-recapture studies (Casale *et al.*, 2018 and references therein).

Following more than 30 years of conservation efforts, in 2015 the Mediterranean loggerhead sub population was listed as Least Concern by the International Union for Conservation of Nature (IUCN) Red List of threatened species (Casale & Tucker, 2015), a result that is completely dependent upon the maintenance of all ongoing conservation activities. Among the many anthropogenic threats, marine litter is an important stressor (Casale & Margaritoulis, 2010; Gall & Thompson, 2015; Galgani *et al.,* 2019; Claro *et al.,* 2019). Entanglement in derelict nets, traps, strapping bands, or plastic bags are regularly reported and may cause serious injuries leading to maiming, amputation, altered buoyancy, and restricted movements which prevent the turtle from behaving normally and may lead to the death of the individual (Duncan *et al.*, 2017). Ingestion of marine litter is also very common, due to the species' generalist feeding strategy, and can cause gastro-intestinal obstruction, internal injuries, a false sense of satiation, and potential absorption of xenobiotics; Lazar & Gračan, 2011; Casale *et al.*, 2016; Nelms *et al.,* 2016; Matiddi *et al.*, 2017). Regular plastic consumption has been one of the reasons for choosing the loggerhead turtle as an indicator species for monitoring the amount and composition of litter ingested by biota in the Mediterranean Sea within the Marine Strategy Framework Directive (MSFD 2008/56/EC, Descriptor 10 C3; Matiddi *et al.*, 2017). Finally, marine litter may cause the degradation of key habitats and produce wider ecosystem effects which may have strong implications for loggerhead turtle survival (Nelms *et al.,* 2016).

The Mediterranean Sea is one of the areas with the highest concentrations of marine litter worldwide due to its limited sea water exchanges with other oceans, heavy coastal anthropization, intense maritime traffic, and multiple significant inputs from rivers that cross highly urbanized areas (Suaria & Aliani, 2014). Every year, millions of tonnes of litter, mostly plastics (Barboza *et al.*, 2019), end up in the sea mainly through storms, water runoff, recreational activities along the coasts, or by being dumped directly from ships (Jambeck *et al.*, 2015; Galgani *et al.*, 2019). Depending on density and composition, after entering the sea, marine litter items can float at the surface for variable periods of time until they sink to the ocean floor, are degraded, fractionated, or washed ashore (Galgani *et al.*, 2019; Miladinova *et al.*, 2020). The distribution of this floating marine litter is shaped by prevailing winds and surface ocean currents that may carry items very far away from their sources and create transient accumulation areas corresponding to convergent zones, sea water fronts, and eddies (Galgani *et al.*, 2015). These areas are also highly productive and may act as temporary foraging hotspots for loggerhead turtles, which increases the probability of exposure to floating marine litter and hence to correlated threats (Nelms *et al.*, 2016). Nevertheless, empirical data on the spatio-temporal overlap between loggerhead turtles and floating litter in the Mediterranean Sea are still scarce (Casale *et al.*, 2018) mostly because of the high costs involved in at-sea surveys using dedicated observation platforms (Arcangeli *et al.*, 2019).

Since 2013, the Fixed Line Transect Mediterranean Network (FLT Med Net, ISPRA) is gathering systematic data on sea turtles and floating marine macro-litter (> 20 cm, FMML hereafter) distribution along specific trans-border routes in the Mediterranean Sea, using regular passenger ferries as observation platforms. The method proved to be effective for long term monitoring on pelagic species (i.e. cetaceans, sea turtle) and the evaluation of potential threats (i.e. marine litter, maritime traffic) (e.g. Tepsich *et al.*, 2020; Arcangeli *et al.*, 2017; Campana *et al.*, 2015; Pennino *et al.*, 2017). A first synoptic analysis conducted in the Western Mediterranean and Adriatic Sea showed a significant seasonal and regional variability of FMML abundance, distribution, and composition (Arcangeli *et al.*, 2019). This study highlighted also the existence of a previously unreported zone of high loggerhead turtle presence in the Sardinia-Sicilian Channels (SSCC), the southern triangle between Sardinia, Tunisia, and Sicily which is coherent with the recent finding of an important oceanic foraging areas for juveniles and adult sized turtles in the southern Tyrrhenian Sea (Blasi & Mattei, 2017; Luschi *et al.*, 2018; Chimienti *et al.*, 2020). Individuals from this area have been observed to switch to neritic foraging when crossing the Strait of Sicily and reaching the Tunisian Plateau, one of the most important Mediterranean neritic habitats (Chimienti *et al.*, 2020). Overall, the SSCC exhibited the highest loggerhead turtle encounter rates among the surveyed routes in the Western Mediterranean and Adriatic Sea and a strong seasonality in the risk of exposure to floating marine litter (Arcangeli *et al.*, 2019). However, this synoptic study considered the SSCC as a whole, without taking into consideration the complexity of the surface circulation patterns (Sorgente *et al.*, 2011; Pinardi *et al.*, 2015) that may affect loggerhead turtle and floating marine macro litter distribution in the area whose understanding requires finer scale investigations.

In this study, we analysed the data collected along three trans-border transects covering the Sardinian Channel and the Strait of Sicily with the aim to: 1) describe the presence and distribution of loggerhead turtles in this key study area of the central Mediterranean sea over a seven year period (2013-2019); 2) characterize the exposure risk to FMML; 3) understand the influence of the high resolution upper layer currents provided by the E.U. Copernicus Marine Service on the distribution of loggerhead turtles and FMML items in the study area.

Material and Methods

Study area

Data were collected along 3 trans-border transects covering the Sardinia-Sicilian Channels (SSCC), in the area between Sardinia, Sicily and Tunisia (Fig. 1). The study area is defined as a key region for understanding the exchanges between the Eastern and Western Mediterranean basins through the Strait of Sicily and between the Algerian Basin and Tyrrhenian Sea through the Sardinia Channel (Astraldi *et al.*, 1998; Onken *et al.*, 2003).

The Strait of Sicily is a geomorphologically complex area, characterized by several sea mountains composed of sedimentary and volcanic rocks (Civile *et al.*, 2016). There is no universally accepted definition of this important strait that covers a great part of the Central Mediterranean and corresponds to the westernmost part of the subarea 2.2 of the FAO (Food and Agriculture Organization) area 37 (Fig. 1). The topography affects the currents resulting in substantial upwelling, which increases the overall productivity and makes the strait one of the most important biodiversity hotspots in the Mediterranean basin (Di Lorenzo *et al.*, 2018).

Contrary to the Strait of Sicily, which does not reach high depths, the Sardinian Channel extends to a depth of 2,500 m and represents an important passage for marine species, such as large cetaceans, sea turtles, and seabirds (Coll *et al.*, 2010; Arcangeli *et al.*, 2019). In addition, the area acquires greater ecological value due to the presence of two marine protected areas (MPAs) at the two

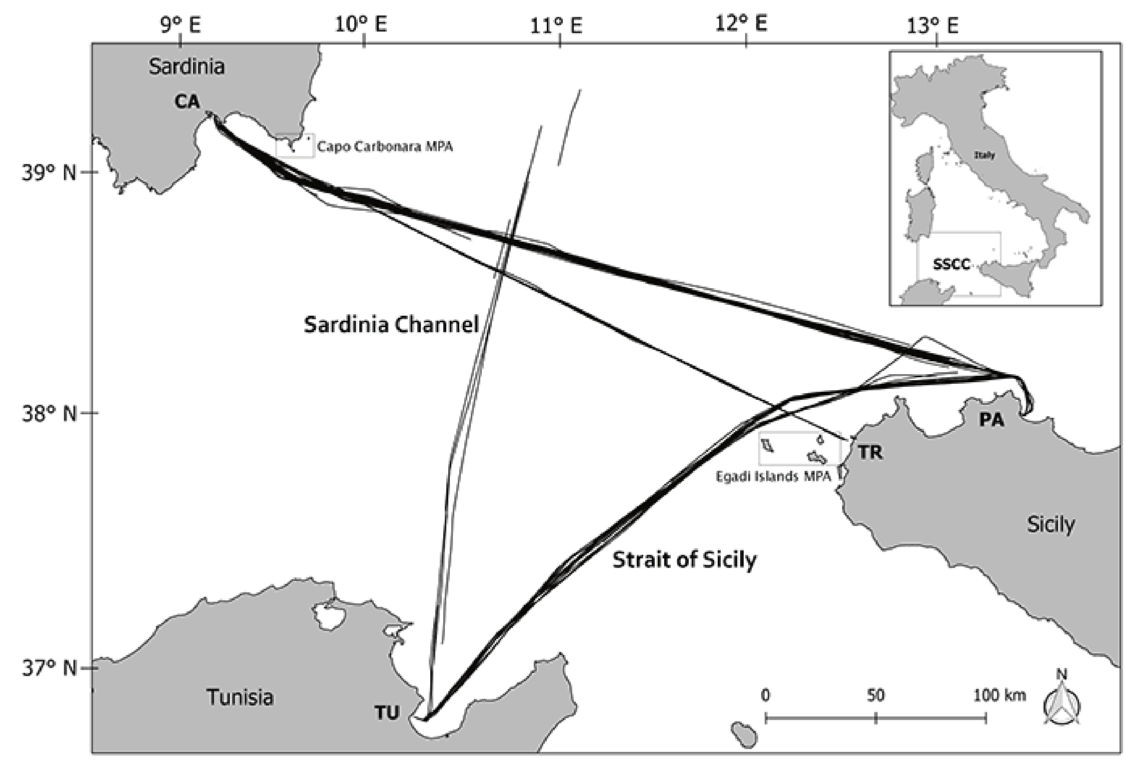

***Fig. 1**:* Study area in the Sardinia-Sicilian Channels (SSCC) (top right box) and effort performed along the surveyed transects (black lines).

borders of the Sardinia Channel: Capo Carbonara MPA (south-eastern coast of Sardinia) and the Egadi Islands MPA (north-western coast of Sicily).

Data collection on sea turtle and marine litter data

Data were collected using ferries as observation platforms, allowing easy repeated sampling along the same transects in a cost-effective way. The monitored transects were Cagliari-Trapani (CA-TR) and Cagliari-Palermo (CA-PA), linking Sardinia and Sicily Islands; Palermo-Tunis (PA-TU), linking Sicily and Tunisia; Tunis-Civitavecchia (TU-CV), considering the part of the transect falling within the selected area only (SSCC) (Fig. 1). Data was collected during the summer period along the CA-PA and CA-TR transects, and over all the seasons (Winter: January to March; Spring: April to June; Summer: July to September; Autumn: October to December) along the PA-TU and TU-CV transects. Two standard protocols were used for collecting data on cetaceans, sea turtles, other pelagic species, and maritime traffic (ISPRA, 2015a), and for collecting data on FMML over 20 cm size (ISPRA, 2015b; Arcangeli *et al.*, 2020). Sea turtle data were collected from 2013 to 2019, while FMML data were collected from 2016 to 2019.

The monitoring was carried out in good weather conditions (≤ 3 on the Beaufort scale for sea turtles and ≤ 2 for marine litter protocols). Two dedicated GPS devices, one for each subject of monitoring, were used to record the position of detected animals or litter and the track line of effort at the finest resolution. The observations were made by naked eye, using binoculars and cameras, when necessary, to confirm species and group size, or litter composition. The monitoring was carried out by experienced dedicated observers, which were specifically trained based on the protocols for both FMML and macro fauna data collection from ferries. This type of platform provided an observation point at 20–25 m high, travelling at a mean speed of 20 Knots. Two observers, one for each side of the command deck, monitored the macro fauna by scanning the sea from the bow (considered to be 0°) to a maximum of 130° in order to avoid recounting animals. At the moment of sighting, information about animal position, data on angle and distance from the ferry, animal orientation, and size classes were recorded. Animal orientation was considered as the direction identified by the head of the animal at the moment of sighting. Data on sea turtle size (i.e. approximate straight carapace length) was recorded whenever visible from the surface along the Cagliari–Palermo route by experienced observers considering three arbitrarily defined size classes: small juveniles (20-35 cm), juveniles (35-70 cm), and adults (>70 cm). The measures were undertaken using the protocol developed for measuring the size classes for marine litter over the 20 cm length (Arcangeli *et al.*, 2020).

For the FMML monitoring, an additional dedicated observer was positioned on the side of the ferry with better visibility, scanning a fixed strip of 50 m width to detect all FMML items greater than 20 cm (see Arcangeli *et al.*, 2020, for details). Litter items were identified and categorized by size classes, material (Artificial polymer material, Glass, Processed wood, Metal, Textile, Paper, Rubber, Natural debris), and general names, according to the MSFD master list (Galgani *et al.*, 2013).

Data analysis

Sea turtle abundance, distribution, and size

Based on the availability of the data and the type of analysis carried out, different routes and/or time intervals were selected. An abundance index was calculated as Sighting Per Unit of Effort [SPUE= (N / km) × 10] ± SE (Standard Error), where "N" was the number of animals sighted and ''km'' was the distance travelled in effort in good weather conditions. SPUE trends over the study period were analyzed using the summer data alone and dividing the surveyed ferry routes in two groups corresponding approximately to the Sardinia Channel and the Strait of Sicily. Given that the PA-TU route crosses both areas, we used the coordinates of the western most part of the Island of Marettimo, Egadi archipelago, to split the transect in two parts, with the northern falling into the Sardinia Channel (PA-TU SC) and the southern belonging to the Strait of Sicily (PA-TU SS).

Seasonality in SPUE was investigated for the Strait of Sicily only, for which monitoring data were available all year round from 2014 to 2019.

Statistical differences were investigated using the non-parametric Kruskal-Wallis (KW) test with the Bonferroni correction, and the post hoc pairwise comparison of Mann-Whitney (MW) U-test testing the hypothesis of equal medians among samples. All analyses were performed using the software Past 2.17c (Hammer *et al.*, 2001).

Sea turtle spatial distribution was examined by overlapping a grid of 5x5 km cells to the study area and by calculating the SPUE within each cell, using each cell as the statistical unit. The SPUE cell was calculated as: [(number of animals sighted per cell / km of effort within each cell) × 10]. To account for uneven effort, sea turtle analysis was performed only on cells with a minimum sample effort of 10 km. SPUE per cell was calculated over the entire study area, and the Kernel Density Estimation (KDE) was performed based on the SPUE cell, using a search radius of 30 km to show areas of highest probabilities of sea turtle occurrence and identify potential hotspot areas (Arcangeli *et al.*, 2017). Hotspots were then graphically represented by the 75% isopleths.

To verify the influence of the year and the spatial position on the abundance of sea turtles, and highlight potential significant patterns, Generalized Additive Models (GAMs) were performed using the number of individuals per cell as the response variable and considering year, km on effort and the cell's position as the predictor variables. GAM, extension of generalized linear model, is a non-parametric regression technique not restricted by linear relationships and is flexible regarding the statistical distribution of the data (Murase *et al.*, 2009; 2014), that allows non-normal residuals as well as a general links between predictors and the response variable (Chebana *et al.*, 2014). In addition, GAMs use a smooth function to link the dependent variable to the predictors, whose purpose is to highlight significant patterns. Based on the data structure, two families, Zero-inflated Poisson and Negative Binomial, and different values of k were tested. The Explained Deviance (analogous to variance in a linear regression), adjusted r2, AIC and GCV scores were used to validate the models and identify the best model settings. Model analyses were performed using the "mgcv" package of RStudio, version 1.2.5042.

Upper layer circulation modelling and influence on sea turtles

In line with Tintoré *et al.* (2019), the ocean circulation in the area has been represented by the 2013 – 2019 reanalysis subset extracted from the Copernicus Marine Environment Monitoring Service (CMEMS) product (Simoncelli *et al.*, 2019). Along with the other hydrodynamic variables, the service provides daily ocean current data with a horizontal resolution of 1/16° (ca. 6.5 km) over the 72 unevenly distributed vertical levels. The multivariate data assimilation is maintained for vertical profiles of temperature and salinity, and along-track satellite observations of the sea surface height. The upper layer kinematics in the SSCC area (Fig. 1) is computed by vertically averaging the currents over the four model levels of ~ 1.5 m, 4.6 m, 8.0 m and 11.6 m.

Sea turtle orientation data were explored considering the two investigated channel's data separately. In the sea stretch between Sardinia and Sicily, two routes, CA-TR (2013) and CA-PA (2014-2019), were independently analysed. In the Strait of Sicily, only data from the PATU route (2014-2019) were analysed.

Upper layer currents were calculated for each point of the turtle detection by means of bilinear interpolation of the model dataset described above. After that, the currents were averaged along the three transects: CA-TR, CA-PA, and PA-TU, and normalized by the number of observations per each transect using a percentage scale to make them comparable for further analysis.

Floating marine litter and risk exposure

Floating Marine Macro Litter was recorded per material category, but considering that the artificial polymer items are a major threat to sea turtles (93% of the total litter items), the plastic component was used to perform the risk exposure analysis. The FMML and risk analyses were performed using the summer dataset from 2016 to 2019 along the CA-PA and PA-TU routes.

The amount of plastic was normalized by accounting for the effort and calculated as density [(D) = n / (w × l)] being "n" the number of items recorded, "w" the width of the monitored strip and "l" the length of the surveyed transect (in km) (Matsumura & Nasu, 1997; Thiel *et al.*, 2003; Shiomoto & Kameda, 2005).

Spatial distribution of plastic densities was analysed using QGis 2.14.21. The study area was divided into a 5×5 km grid cell, and only the cells crossed by at least 10 km effort were selected from the entire grid for the analysis in order to account for bias due to uneven effort. A buffer was built around each surveyed track corresponding to the value of the transect width. The buffered tracks were then associated within the intersected cells and pooled together. The total surveyed area, the number of plastic items and the density values were calculated per each cell (Arcangeli *et al.*, 2018). The kernel density estimation was then performed based on the density value per cell using a 30 km radius, and the isopleths on 75% of the total values obtained by KDE of plastic density were created. To highlight the areas of overlap between the concentration of litter and high densities of sea turtles, a KDE analysis was performed based on the SPUE cell values of sea turtles using the same time period as the litter data (2016–2019).

The high-risk exposure areas, where sea turtles are most likely to encounter plastic items (Darmon *et al.*, 2017), were identified by considering only the cells where both effort data on plastics and loggerhead turtles were available. The litter density values and turtle SPUE values were used to calculate an exposure risk index: considering that the exposure changes depending on both the occurrence of the sensitive species and the concentration of the threat (i.e., plastic items), the risk exposure index was calculated by multiplying the litter density value and sea turtle SPUE per cell. For representation, the obtained values were equally divided into four categories of "no exposure", when the sea turtles and/or plastic items were not present, "low," "medium," and "high risk."

Results

Sea turtle abundance, distribution, and size

From 2013 to 2019, a total of 47,564 km were travelled on effort in standard conditions during 205 surveys over the entire study area, and 1,392 loggerhead sea turtle sightings were recorded, with a mean SPUE of 0.23 ± 0.025 SE animals per 10 km of effort.

The majority of these surveys were conducted during the summer period (n = 99, total km travelled on effort = 23,794.76 km) when 1,144 sightings were recorded for a mean SPUE of 0.38 ± 0.05 SE. The distribution of loggerhead turtles within the SSCC area during summer appears to be heterogeneous, with a higher presence in the Sardinia Channel with respect to the Strait of Sicily (average SPUE 0.39 ± 0.05 and 0.17 ± 0.05 SE respectively, KW, $p < 0.05$). No statistically significant inter-annual difference was detected among SPUE summer averages in either of these areas (KW, $p > 0.05$, Fig. 2), with the highest sighting rates recorded in 2015 and 2017 in the Sardinia Channel (SPUE index of 0.60 ± 0.21 SE and 0.49 ± 0.14 SE respectively). The absence of inter-annual differences was confirmed also by the analysis of the yearly average SPUEs available for the Strait of Sicily (KW, $p > 0.05$).

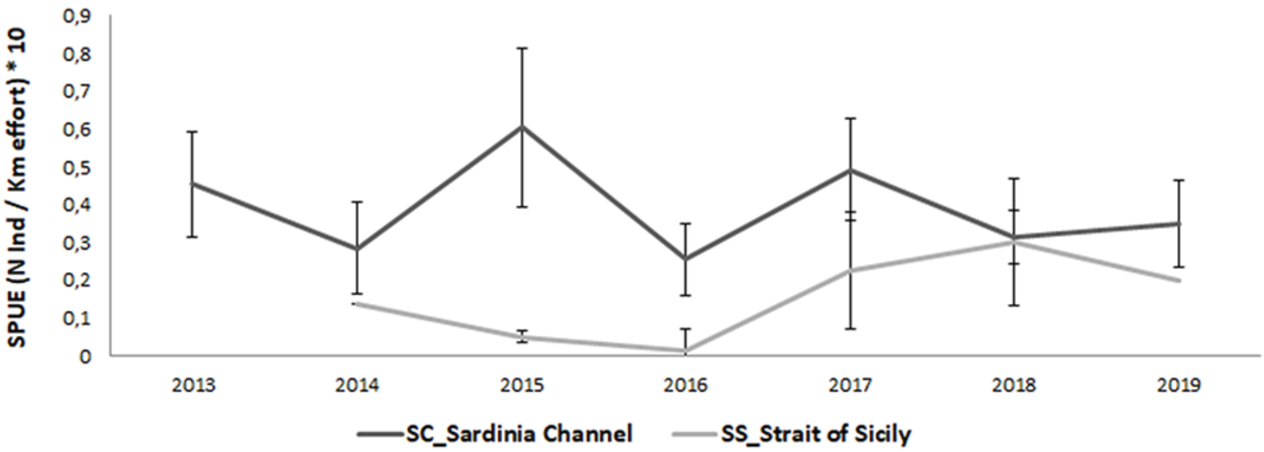

Fig. 2: Sea turtle summer sightings per unit effort (SPUE) recorded during the years (N = 1,144 individuals; 23,794,8 km of effort) in the SC_Sardinia Channel and SS_Strait of Sicily. Error bars represent SE.

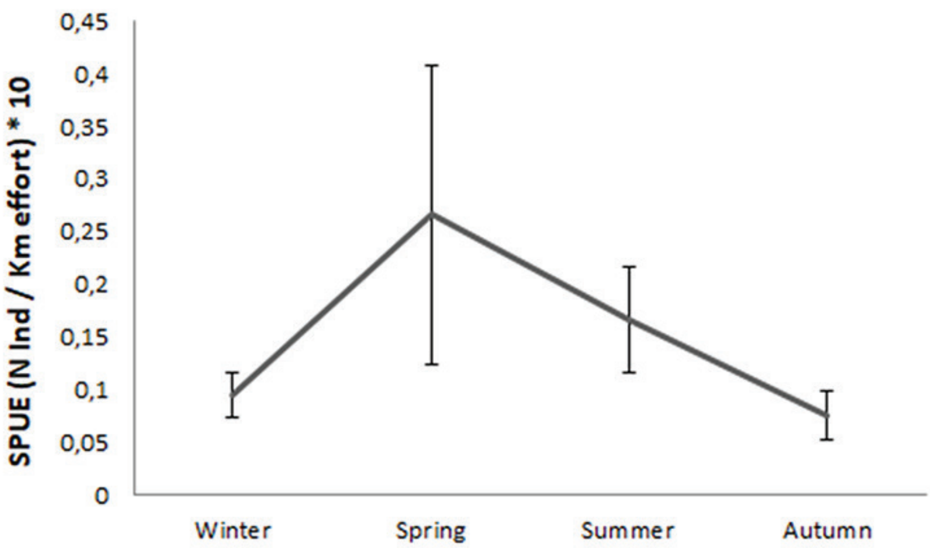

Fig. 3: Seasonal variability of sea turtles detected along the Sicilian Strait.

Intra-annual analysis in the Strait of Sicily showed that the higher sighting rate was recorded during spring (0.27 ± 0.14 SE) compared to summer, winter, and autumn (0.17 ± 0.05 SE, 0.10 ± 0.02 SE and 0.08 ± 0.02 SE, respectively) (Fig. 3), although no significant differences between seasons were detected (KW, p>0.05).

The spatial analysis showed a patchy distribution of sea turtles, where cells with higher sighting values were particularly concentrated in the area of the Sardinia Channel and towards Sicily, in the stretch of sea around the Egadi MPA (Fig. 4).

The GAMs were performed considering a total of 851 cells. The chosen model predicted 64.6% (deviance explained) of the variation in space and time of the loggerhead turtle abundance. The shapes of the functional forms for selected covariates illustrated that the number of sea turtles did not change over the years, with only a slight increase in abundance during 2015 and 2017. Results on distribution, using the latitude and longitude as covariates, confirmed the importance of the central area in the Sardinian channel.

A total number of 294 loggerhead turtles were categorized in the three arbitrary size classes along the CAPA route during the summer season from 2017 to 2019: the majority of the individuals were juveniles (56%) followed by adults (26%) and small juveniles (18%).

Model-based upper-layer circulation and sea turtle orientation

As shown in Figure 5a, the upper layer patterns were found to be in line with the basin-scale circulation patterns described by e.g., Malanotte-Rizzoli *et al.* (1997), Sorgente *et al.* (2011), and Pinardi *et al.* (2015).

More specifically, the study area is controlled by the Atlantic waters moving eastward as the Algerian Current (AC) that splits in two branches caused by a topographic effect after crossing the Sardinia Channel. The first branch penetrates into the Tyrrhenian Sea as the Bifur-

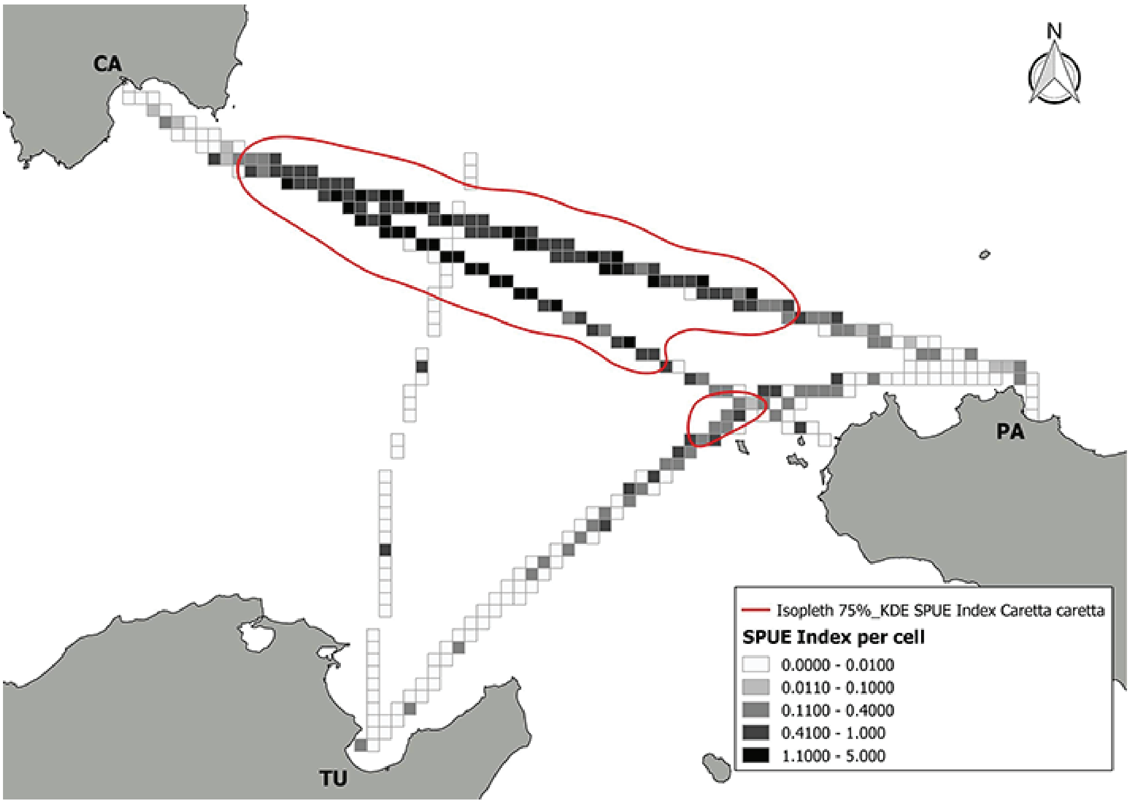

Fig. 4: Spatial distribution of the abundance index (Sightings Per Unit Effort, SPUE) of sea turtles in the monitored areas. The 75% isopleths show the hot spot area of loggerhead turtle identified by the kernel analysis (kernel density estimation; KDE) based on the index of abundance. All data are pooled together.

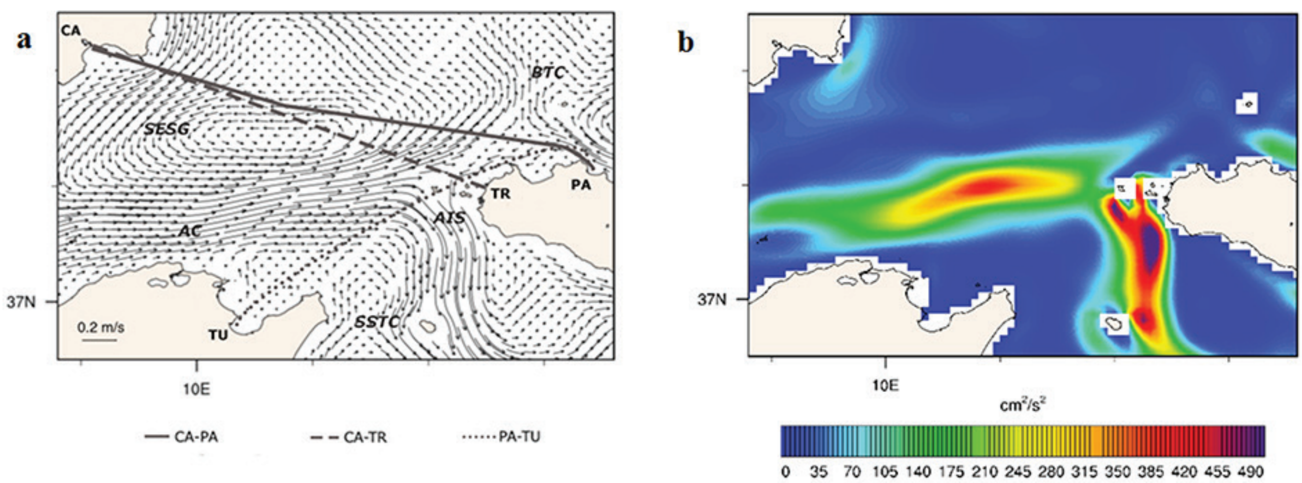

Fig. 5 a: Model upper layer currents averaged over the days of observations with surveyed transects in the Sardinia-Sicilian Channel area (SSCC). The averaged 2013–2019 model currents reveal the Algerian Current (AC), Bifurcation Tyrrhenian Current (BTC), Atlantic-Ionian Stream (AIS), Strait of Sicily Tunisian Current (SSTC) and South-Eastern Sardinia Gyre (SESG); **b:** model-based mean kinetic energy per unit mass (MKE) in cm^2/s^2 averaged over the days of observations.

cation Tyrrhenian Current (BTC) that flows along the northern coast of Sicily. The second one moves eastward representing a two-jet structure that embraces the Atlantic-Ionian Stream (AIS), mainly flowing eastward along the southern coast of Sicily, and the Strait of Sicily Tunisian Current (SSTC) running south-eastward over the Tunisian continental slope. The central part of the area is under the influence of the south-eastern Sardinia Gyre (SESG), a wind curl driven cyclonic gyre, whose diameter varies between 200 km and 300 km (Sorgente *et al.*, 2011).

The model currents averaged over the days of observations (Fig. 5b) indicate the main basin-scale circulation patterns including the Algerian Current (AC), Bifurcation Tyrrhenian Current (BTC), Atlantic-Ionian Stream (AIS), Strait of Sicily Tunisian Current (SSTC), and South-Eastern Sardinia Gyre (SESG). The time-specific differences from the overall 2013–2019 averaged map (Fig. 5a) include a seasonal intensification of the Algerian Current that allows the development of the coastal currents which flow northward in the Gulf of Tunis and along the southern shore of the Gulf of Hammamet; the north-eastern recirculation related to the summer upwelling on the Adventure Bank (western Sicilian shelf); the westward coastal current in the Gulf of Castellammare; as well as amplification of the South-Eastern Sardinia Gyre. Additionally, the kinetic energy of mean flow per unit mass (MKE) was calculated to quantify the energy levels involved in the upper layer of circulation: $MKE_{ij}=1/2meant[u_{ij}^2(t)+v_{ij}^2(t)]$, where meant is the time average over the days of observations; $u_{ij}(t)$ and $v_{ij}(t)$ are the zonal and meridional components of the velocity field at the (i, j) grid point, respectively. As shown in Figure 5b (right), all the observational transects (CA-PA, CA-TR, and PA-TU) were mainly located in the MKE interval of ~ 60–80 cm^2/s^2 which is typical of the summer season, with the exception of the transect parts crossing the high kinetic zones such as the PA-TU segment south-west of the Egadi Islands.

Considering their geographical location and the different ecological characteristics, the orientation data of loggerhead turtles were analysed separately for the two areas. In the area between Sardinia and Sicily, a total of 726 turtles were considered from 2013 to 2019: 143 turtles from CA-TR data (2013) and 583 from CA-PA data (2014-2019). Regarding the CA-TR route, the results showed that turtles were orientated predominantly towards the northwest (~39%) and secondly, towards the southwest (~21%). The upper layer currents along this transect were directed mainly to the southwest (~50%), which was associated with a wide western branch of the South-Eastern Sardinia Gyre, that controlled the water flow over nearly half of the CA-TR transect. Contributions of the northeast transport (~29%) was caused by a relatively narrow jet of the Bifurcation Tyrrhenian Current (Fig. 6a) on the Sicilian edge of the transect. Along the CA-PA route, the turtles mainly oriented towards the west (~37%), while the north, east, and south sectors contributed almost equal percentages (Fig. 6b). Like the aforementioned transect, the currents indicated a dominance of the southwest transport of ~45% on the Sardinian part of the route with a ~35% deflection to the west due to a northern branch of the South-Eastern Sardinia Gyre that influenced the Sicilian edge of the transect. As Figure 6c shows, the distribution of the turtles' spatial orientation along the PA-TU transect (N=195, 2014-2019) was almost isotropic with a slight elongation from southwest (21%) to northeast (19%). Each of the north, northwest, and west directions contributed ~ 9÷11%. Symmetrically, each of the south, southeast, and east directions contributed ~ 8÷12%. The upper layer currents mostly indicated the eastward transport (~56%) caused by the Algerian Current in the Tunisian part of the transect and the northeast direction (~22%), when the PA-TU route was collinear to the Bifurcation Tyrrhenian Current.

Floating marine litter and risk exposure

During the marine litter monitoring in the two channels, almost 10,800 km were travelled on effort covering a total area of 694 km^2. The total number of plastic items recorded was 2,756, with an average density that did not differ significantly over the years (KW, $p>0.05$). The KDE performed on plastic distribution, showed areas of litter accumulation localised near the Cagliari, Palermo, and Tunis ports, and generally high-density values along the Sardinia Channel, to the west of the Egadi Islands and in the southern portion of the Strait of Sicily (black dotted line in Fig. 7). Sea turtle hotspots highlighted by the KDE analysis, were also localised in the middle of the Sardinia Channel and western Egadi Islands (red line in Fig. 7). The overlap between the 75% KDE isopleths of plastic and sea turtles highlighted overlapping areas in the central Sardinia channel and west of the Egadi MPA (Fig. 7). The risk exposure index analysis confirmed highest risk values in the middle of the Sardinia channel, in localized spots near the Ports of Cagliari and Palermo, and in the portion of sea west of the Egadi Islands (Fig.7).

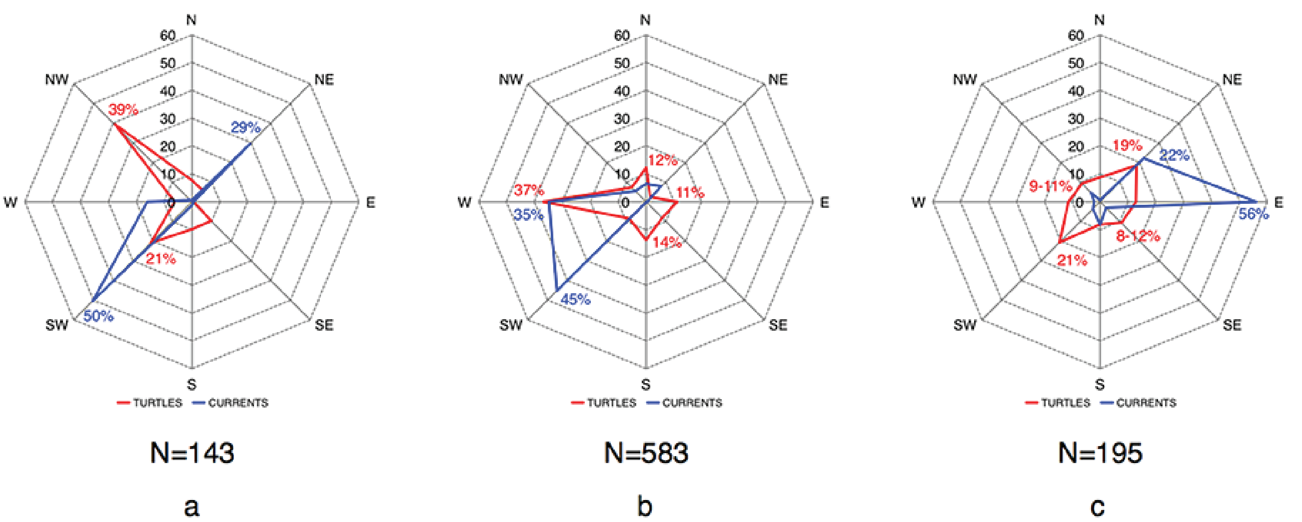

Fig. 6: R-charts represent the average frequency in directions (%) for turtles (in red) and currents (in blue) along the routes of CA-TR 2013 (a), CA-PA 2014–2019 (b), and PA-TU 2014–2019 (c). N. represents the number of observed turtles.

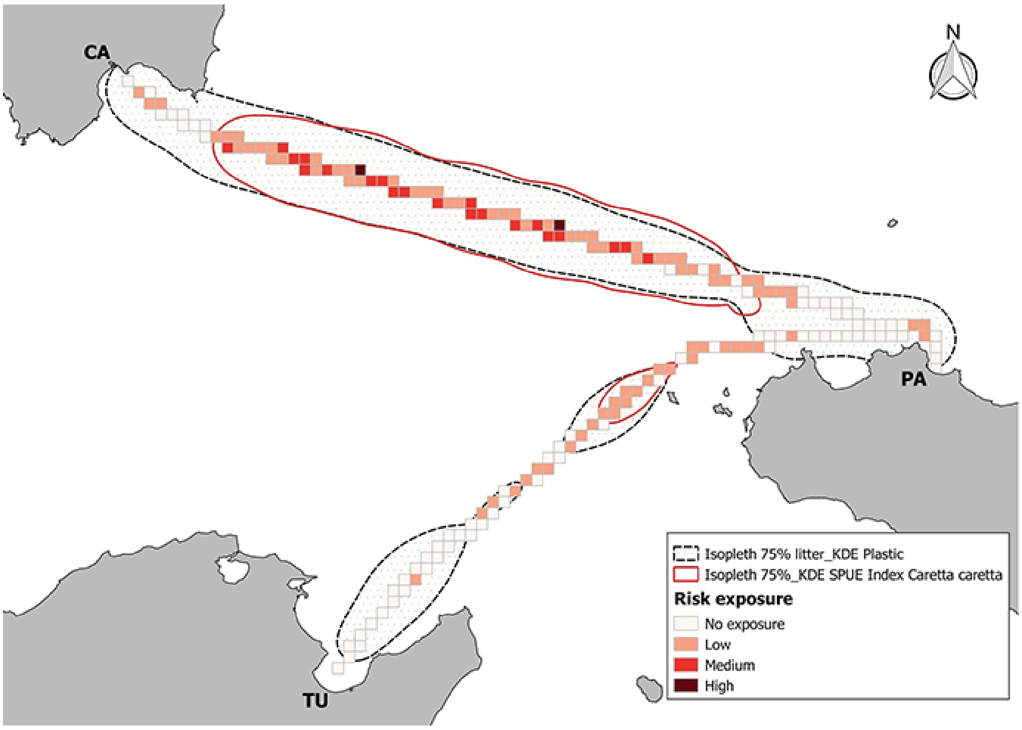

Fig. 7: Isopleths corresponding to 75% of the total values obtained by KDE of plastic density (dotted line and area) and KDE of loggerhead turtle SPUE Index (continuous line). The risk exposure Index is represented by cells of increasing colour gradient.

Discussion

Effective management of marine migratory species, such as the loggerhead turtle, is a complex endeavour. These highly mobile animals use several ontogenetic habitats throughout their life, segregated by hundreds or even thousands of kilometers, where they may be exposed to different threats. Understanding the spatio-temporal overlap between species distribution and anthropogenic stressors is essential for tackling threats in the right place at the right time, but it may be complex or logistically prohibitive, particularly in the highly dynamic and vast open sea (Arcangeli *et al.*, 2019). Surveys on dedicated research platforms are considered the most reliable approach for collecting empirical data on sea turtle distribution and abundance over vast regions, but they are generally unaffordable to carry out regularly (Lauriano *et al.*, 2011; Casale *et al.*, 2018; Arcangeli *et al.*, 2019). The use of the so-called platforms of opportunity, such as passenger ferries or cruise vessels, is a cost-effective complementary approach that can help monitor marine megafauna on a long-term basis (Kiszka *et al.*, 2007; Viddi *et al.*, 2010; Leeney *et al.*, 2012; Boer *et al.*, 2018). Although the routes are not designed by the researchers, which poses some constraints on the statistical analysis, relating animal sightings to effort can be used to infer relative abundance indices and to monitor temporal or spatial variation of a species' presence (Viddi *et al.*, 2010; Arcangeli *et al.*, 2019).

Here we analysed data from seven consecutive years (2013-2019) of sea turtle monitoring along commercial ferry routes in the Sardinia Channel and Strait of Sicily, which play a crucial role in the circulation of the whole Mediterranean Sea. This region is a high-energy site that dynamically modulates the exchanges between the Mediterranean sub-basins. In fact, the Strait of Sicily provides the direct interface between the Eastern and Western Mediterranean, while the Sardinia Channel allows the water exchanges to occur between the Algerian sub-basin and the Tyrrhenian Sea (Astraldi *et al.*, 1998). The Tyrrhenian-Sicily-Sardinia area reveals the basin-scale semi-permanent circulation and mesoscale phenomena associated with ocean eddies, meandering currents, fronts, and upwellings, that are induced by the wind, topography, or instabilities in large-scale circulation (Onken *et al.*, 2003; Béranger *et al.*, 2004). The particular geomorphological and hydrodynamic characteristics make the region extremely interesting from an ecological point of view, and a key area for understanding loggerhead sea turtle displacement in the Mediterranean Sea.

Sea turtle abundance, distribution and size

Overall mean sighting rate was comparable to that reported for this area in the first synoptic survey of loggerhead turtle distribution in the Western Mediterranean, Ionian, and Adriatic Seas (Arcangeli *et al.*, 2019). This is not surprising considering that the two studies share a large portion of the dataset. However, our finer scale analysis revealed a clear heterogeneity in loggerhead turtle distribution within the study area. The conspicuously high mean SPUE observed in the SSCC was mainly a result of the higher summer encounter rates observed in the Sardinian Channel with respect to the Strait of Sicily. However, this comparison is based on summer data only, whereas seasons may affect loggerhead turtle presence differently in these two areas. Among the many factors that influence species presence and habitat use, seasonality plays a key role as the main driver of biological and ecological processes. Detailed analysis on seasonality was performed for the Strait of Sicily, where the effort was consistent during all seasons. The Strait is an important area used by sea turtles for feeding purposes and as an inter-basin exchange passage. Indeed, it seemed that encounter rates in the Strait of Sicily were higher during spring than during other seasons, confirming observations recorded by Arcangeli *et al.* (2019), albeit it must be acknowledged that these results were not statistically significant. To date there is no clear evidence in the published literature that supports a seasonal use of the Strait of Sicily. Bentivegna (2002) reported seasonal migrations at the beginning of autumn from the Western to the eastern Mediterranean, but three out of four turtles used the Strait of Messina and only one took the route via the Strait of Sicily. A more recent study by Chimienti *et al.* (2020) revealed that four out of eleven large juvenile turtles tracked in the Tyrrhenian Sea left this basin during summer and travelled through the Strait of Sicily, while others remained in the circulation system of the Tyrrhenian Sea including the Sardinian Channel area. Simulation of hatchling dispersal from the southwest Italian coast showed that most of the small turtles were retrained in the surface circulation of the Tyrrhenian Sea and eventually moving north into the Ligurian Sea, while only a small percentage leaked through the Strait of Sicily into the Eastern Mediterranean (Maffucci *et al.*, 2016).

Westward migrations through the Strait of Sicily by turtles coming from the Ionian Sea are instead far less documented, although they certainly occur, as was indirectly shown through mixed stock analysis, which attributed large proportions of turtles found in the Tyrrhenian Sea to Eastern Mediterranean rookeries (Maffucci *et al.*, 2006; Maffucci *et al.*, 2013; Karaa *et al.*, 2016). However, it seems that loggerhead turtles move into the western basin when they are an older age, because the probability that hatchlings drift with ocean currents into the western Mediterranean is low (Casale & Mariani, 2014; Hays *et al.*, 2010), whereas the distance from major rookeries to the western Mediterranean is less than the migration ceiling (maximum migration distance: 2150 km) known for the species (Hays & Scott, 2013). In fact, a few single individuals have been tracked into the Western Mediterranean during post-nesting migration, yet the majority of adult females remain in the Eastern Mediterranean and show high fidelity to neritic foraging grounds (Broderick *et al.*, 2007; Stokes *et al.*, 2015; Snape *et al.*, 2016). Also, turtles foraging on the nearby Tunisian shelf area and in the deeper waters of the southern Strait of Sicily (Casale *et al.*, 2008) could move into the northern part of the strait and contribute to the presences observed on the Sicily-Tunisian ferry line. Therefore, summing up this information, there is no clear evidence of seasonal use of the Strait of Sicily, but rather a constant year-round presence of loggerhead turtles.

The distribution of loggerhead turtles along the Sicily-Tunisia line, concentrating more in the northern sector of the transect, is most certainly driven by the strong Algerian current which transports turtles from both the Western Mediterranean and those moving with the South-Eastern Sardinia Gyre (see Fig. 5a and b). The surface current patterns also identify the waters off western Sicily, including the Egadi Islands, as a highly dynamic area, which may constantly receive turtles that passively drift with the Algerian current and continue either northwards with the Bifurcation Tyrrhenian Current or southwards with the Atlantic-Ionian Stream. The association of turtle distribution with surface current patterns has been widely documented, particularly for juvenile oceanic specimens foraging in the Mediterranean which passively drift within a basin broadly favourable for developing loggerhead turtles (Cardona & Hays, 2018; Clusa *et al.*, 2013).

The prevailing surface currents at the time of observations were also likely responsible for the high turtle encounter rates in the Sardinia Channel area. Here, turtles foraging in the Tyrrhenian Sea and those coming from the Algerian Sea meet in the South-Eastern Sardinia Gyre, as some satellite tracking studies have shown (Chimienti *et al.*, 2020; Eckert *et al.*, 2008) and probably find good foraging opportunities. Actually, turtle presence in the SSCC is higher than could have been expected from these satellite tracking studies, where only a few individuals wandered into this area. The SSCC thus gains a previously unrecognized importance as an area that aggregates oceanic foraging loggerhead turtles and has a great potential for revealing trends in turtle abundance if integrated into long-term monitoring programs such as the FLT Med Net.

Based on the experience gained in identifying the size of floating litter items, the observers also estimated turtle sizes during monitoring and revealed a rough distribution of size classes in the SSCC. As could have been expected, the majority of individuals were juveniles in the typical size range of oceanic stage loggerhead turtles, but a quarter of the sighted turtles were also adult sized. This is an interesting result, since adult turtles mostly prefer neritic foraging areas, and there are no nearby known rookeries that would explain the presence of adult turtles passing through during their reproductive migrations. It would be worth examining the state of maturity and sex ratio of these large turtles. However, loggerhead turtles are also known for their foraging plasticity, and many subpopulations, including the Mediterranean, have reported that even adult turtles continue to forage in the water column, either opportunistically or over a longer term (Hatase *et al.*, 2002; Hawkes *et al.*, 2006; Casale *et al.*, 2008). Therefore, the observed proportion of adult-sized turtles may in fact be representative of the foraging aggregation in the western Mediterranean pelagic habitats (Luschi *et al.*, 2013; Chimienti *et al.*, 2020).

Judging the size of smaller objects and turtles from almost 20 m above the sea level platform is challenging, and the proportion of small juveniles observed here could have been underestimated, while post-hatchling and yearling turtles could have been present but passed by entirely unnoticed. As already discussed above, the area surveyed here is unlikely to host the youngest individuals of the

Mediterranean loggerhead subpopulation, so that the bias in the sampling method may be negligible. Nonetheless, the methods for assessing turtle size from moving observation platforms could be refined, so that the proportion of small juveniles can be estimated more accurately. This would be particularly useful for future monitoring programmes in this area, because a recent increase in loggerhead nesting activity in the Western Mediterranean, that has been attributed to climate warming, may lead to the development of new nursery areas in this basin (Maffucci *et al.*, 2016; Abalo-Morla *et al.*, 2018).

Upper layer currents did not appear to have a clear influence on loggerhead sea turtle orientation. In the Strait of Sicily, an area with very high kinetic energy and strong directed currents, turtles were almost isotropic (Fig. 5a and b). On the other side, in the Sardinia Channel the overall westward orientation of the individuals was in a certain agreement with the prevailing current system. It must be acknowledged that we could not associate information about turtles' orientation with those on their behaviour at time of spotting in our analysis and this may have affected the results. Further data are required in order to understand the relevance of collecting information about turtle orientation during at sea surveys from passenger ferries.

Floating litter and risk assessment

The observed plastic KDEs at the finer scale of this study are found to be partially consistent with the model patterns of sea surface plastic concentration (Liubartseva *et al.*, 2018), which were simulated statistically based on the upper layer circulation and static distribution of marine litter sources. In fact, the observations indicate the highest densities in the middle of the Sardinia Channel, and medium accumulation values outside the Ports of Cagliari and Palermo, and the Gulf of Tunis, while the model showed the local maximum of plastic in Tunis, followed by the Port of Palermo and then by the area close to Cagliari. Moreover, the Capo Carbonara MPA located in the NW part of the CA-PA and CA-TR transects is found to be one of the least polluted sites in the study area according to the model. The reason for such inconsistency might be due to the absence of seasonality in the model sources of plastic. Indeed, during peak tourist season, marine litter increases by up to 40% in the Mediterranean (Dalberg Advisors, 2019), which calls for seasonal re-distribution among the model sources of plastic over the basin. Modeling results might be also improved by using Lagrangian drifters that statistically characterize the upper layer kinematics (Poulain & Zambianchi, 2007, Poulain *et al.*, 2009).

By contemporaneously collecting *in situ* data on vulnerable species and floating plastic, this method identified areas and seasons in which sea turtles are most exposed to this hazard, which is essential information when delineating priority mitigation measures (Darmon *et al.*, 2017; Arcangeli *et al.*, 2019).

The central Sardinian channel is a priority risk area, at least during the summer season. The large South-Eastern Sardinia Gyre appears to act as a trap for both the animals and floating plastics, increasing the local exposure risk for sea turtles. Other risk areas were identified, as expected, near the main ports of Cagliari and Palermo, but there were not low or "no risk" detected in the Tunis Gulf. Despite the seasonal intensification of the Algerian Current over the days of observations, a plastic accumulation area was identified by the kernel analysis outside the Gulf of Tunis, proving that local input is likely a more significant driver than oceanographic circulation alone, especially during peak tourist season. Nevertheless, given the low number of sea turtles recorded in that area, the risk was found to be low or absent. On the contrary, along the western side of the Egadi MPA, corresponding to the Algerian Current bifurcation, the high presence of sea turtles was found to have a significant, albeit low, risk index despite the high kinetic energy recorded in the upper layer flow. Our results showed that the spatio-temporal overlap between sea turtles and floating macro litter distributions is influenced by a variety of factors related to the biological cycle of species, sources of littering, and the variable distribution of both, for which sea surface circulation plays a major role, and that the analysis of empirical data is essential for validating and further refining model previsions.

Conclusion

Well identified indicators must be developed to evaluate the conservation status of species and their habitats, as well as the effectiveness of conservation measures. Given the long and complex life cycle of the loggerhead sea turtle, and the wide distributional range, long term studies are needed to gather the required information, and in particular, to fill the knowledge gaps on the distribution and abundance in the vast open sea. Linking information about species presence to the main threats to which they are potentially exposed is also essential for identifying those critical habitats where mitigation measurements must be urgently enforced. Our results proved, once again, that the use of passenger ferries as platforms for observation can be a useful and effective method to gather information on loggerhead sea turtles and marine litter in remote offshore areas and to conduct systematic long term surveys over the vast and highly dynamic pelagic realm.

Acknowledgements

We are greatly thankful to the ferry companies participating in the research programme, Tirrenia and Grimaldi lines, who kindly hosted the researchers on board during all periods and to all the experienced observers who contributed to the data collection on board.

References

Abalo-Morla, S., Marco, A., Tomás, J., Revuelta, O., Abella, E. *et al.*, 2018. Survival and dispersal routes of head-started loggerhead sea turtle (*Caretta caretta*) post-hatchlings in the Mediterranean Sea. *Marine Biology*, 165 (3), 51.

Arcangeli, A., Campana, I., Bologna, M.A., 2017. Influence of seasonality on cetacean diversity, abundance, distribution and habitat use in the western Mediterranean Sea: implications for conservation. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 27 (5), 995-1010.

Arcangeli, A., Campana, I., Angeletti, D., Atzori, F., Azzolin, M. *et al.*, 2018. Amount, composition, and spatial distribution of floating macro litter along fixed trans-border transects in the Mediterranean basin. *Marine Pollution Bulletin,* 129, 545-554.

Arcangeli, A., Maffucci, F., Atzori, F., Azzolin, M., Campana, I. *et al.*, 2019. Turtles on the trash track: loggerhead turtles exposed to floating plastic in the Mediterranean Sea. *Endangered species research*, 40, 107-121.

Arcangeli, A., David, L., Aguilar, A., Atzori, F., Borrell, A. *et al.*, 2020. Floating marine macro litter: Density reference values and monitoring protocol settings from coast to offshore. Results from the MEDSEALITTER project. *Marine Pollution Bulletin 160,* 111647.

Astraldi, M., Gasparini, G. P., Sparnocchia, S., 1998. Water masses and seasonal hydrographic conditions in the Sardinia–Sicily–Tunisia region. *Rapport commission international mer Méditerranée*, 35, 122-123.

Barboza, L.G.A., Cózar, A., Gimenez, B.C., Barros, T.L., Kershaw, P.J. *et al.*, 2019. Macroplastics pollution in the marine environment. p.305-328. In: *World seas: An environmental evaluation*. Sheppard,C. (Ed.), Elservier, Amsterdam.

Bentivegna, F., 2002. Intra-Mediterranean migrations of loggerhead sea turtles (*Caretta caretta*) monitored by satellite telemetry. *Marine Biology*, 141 (4), 795-800.

Bentivegna, F., Valentino, F., Falco, P., Zambianchi, E., Hochscheid, S., 2007. The relationship between loggerhead turtle (*Caretta caretta*) movement patterns and Mediterranean currents. *Marine Biology*, 151 (5), 1605-1614.

Béranger, K., Mortier, L., Gasparini, G. P., Gervasio, L., Astraldi, M. *et al.*, 2004. The dynamics of the Sicily Strait: a comprehensive study from observations and models. *Deep Sea Research Part II: Topical Studies in Oceanography*, 51 (4-5), 411-440.

Blasi, M.F., Mattei, D., 2017. Seasonal encounter rate, life stages and main threats to the loggerhead sea turtle (*Caretta caretta*) in the Aeolian Archipelago (southern Thyrrenian Sea). *Aquatic Conservation: Marine and Freshwater Ecosystems*, 27 (3), 617-630.

Broderick, A.C., Coyne, M.S., Fuller, W.J., Glen, F., Godley, B. J., 2007. Fidelity and over-wintering of sea turtles. *Proceedings of the Royal Society B: Biological Sciences*, 274 (1617), 1533-1539.

Boer, M.N. de Jones, D., Jones, H., Knee, R., 2018. Spatial and temporal baseline information on marine megafauna-data facilitated by a wildlife tour operator. *Open Journal of Marine Science*, 8 (01), 76.

Bolten, A.B., 2003. Variation in sea turtle life history patterns: neritic vs. oceanic developmental stages. p. 243-257. In: The biology of sea turtles, Vol 2. Lutz, P.L., Musick, J.A., Wyneken, J. (Eds). CRC Press, Boca Raton, Florida.

Campana, I., Crosti, R., Angeletti, D., Carosso, L., David, L. *et al.*, 2015. Cetacean response to summer maritime traffic in the Western Mediterranean Sea. *Marine Environmental Research* 109, 1-8.

Cardona, L., Hays, G.C., 2018. Ocean currents, individual movements and genetic structuring of populations. *Marine biology*, 165 (1), 10.

Carreras, C., Pascual, M., Tomás, J., Marco, A., Hochscheid, S. *et al.*, 2018. Sporadic nesting reveals long distance colonisation in the philopatric loggerhead sea turtle (*Caretta caretta*). *Scientific reports*, 8 (1), 1435.

Casale, P., Margaritoulis, D., 2010. Sea turtles in the Mediterranean: Distribution. *Threats and Conservation Priorities. IUCN, Gland, Switzerland.*

Casale, P., Mariani, P., 2014. The first 'lost year' of Mediterranean Sea turtles: dispersal patterns indicate subregional management units for conservation. *Marine Ecology Progress Series,* 498, 263-274.

Casale, P., Tucker, A. D., 2015. *Caretta caretta*. The IUCN Red List of Threatened Species 2015: e. T3897A83157651.

Casale, P., Abbate, G., Freggi, D., Conte, N., Oliverio, M. *et al.*, 2008. Foraging ecology of loggerhead sea turtles *Caretta caretta* in the central Mediterranean Sea: evidence for a relaxed life history model. *Marine Ecology-Progress Series,* 372, 265-276.

Casale, P., Freggi, D., Paduano, V., Oliverio, M., 2016. Biases and best approaches for assessing debris ingestion in sea turtles, with a case study in the Mediterranean. *Marine pollution bulletin*, 110 (1), 238-249.

Casale, P., Broderick, A. C., Camiñas, J. A., Cardona, L., Carreras, C., *et al.*, 2018. Mediterranean Sea turtles: current knowledge and priorities for conservation and research. *Endangered species research*, 36, 229-267.

Chebana, F., Charron, C., Ouarda, T.B., Martel, B., 2014. Regional frequency analysis at ungauged sites with the generalized additive model. *Journal of Hydrometeorology*, 15 (6), 2418-2428.

Chimienti, M., Blasi, M.F., Hochscheid, S., 2020. Movement patterns of large juvenile loggerhead turtles in the Mediterranean Sea: Ontogenetic space use in a small ocean basin. *Ecology and Evolution*, 10 (14), 6978-6992.

Civile, D., Lodolo, E., Caffau, M., Baradello, L., Ben-Avraham, Z., 2016. Anatomy of a submerged archipelago in the Sicilian Channel (central Mediterranean Sea). *Geological Magazine*, 153 (1), 160-178.

Claro, F., Fossi, M.C., Ioakeimidis, C., Baini, M., Lusher, A.L. *et al.*, 2019. Tools and constraints in monitoring interactions between marine litter and megafauna: insights from case studies around the world. *Marine pollution bulletin*, 141, 147-160.

Clusa, M., Carreras, C., Pascual, M. Gaughran, S.J., Piovano, S. *et al.*, 2013. Fine-scale distribution of juvenile Atlantic and Mediterranean loggerhead turtles (*Caretta caretta*) in the Mediterranean Sea. *Marine Biology,* 161 (3), 509-519.

Coll, M., Piroddi, C., Steenbeek, J., Kaschner, K., Lasram, F.B.R. *et al.*, 2010. The biodiversity of the Mediterranean Sea: estimates, patterns, and threats. *PloS one, 5*(8), e11842.

Dalberg Advisors, 2019. *Stop the Flood of Plastic: How Med-*

iterranean countries can save their sea. WWF Mediterranean Marine Initiative. 46p.

Darmon, G., Miaud, C., Claro, F., Doremus, G., Galgani, F., 2017. Risk assessment reveals high exposure of sea turtles to marine debris in French Mediterranean and metropolitan Atlantic waters. *Deep Sea Research Part II: Topical Studies in Oceanography*, 141, 319-328.

Di Lorenzo, M., Sinerchia, M., Colloca, F., 2018. The North sector of the Strait of Sicily: a priority area for conservation in the Mediterranean Sea. *Hydrobiologia*, 821 (1), 235-253.

Duncan, E.M., Botterell, Z.L., Broderick, A.C., Galloway, T.S., Lindeque, P.K. *et al.*, 2017. A global review of marine turtle entanglement in anthropogenic debris: a baseline for further action. *Endangered Species Research*, 34, 431-448.

Eckert, S.A., Moore, J.E., Dunn, D.C., van Buiten, R.S., Eckert, K.L., *et al.*, 2008. Modeling loggerhead turtle movement in the Mediterranean: importance of body size and oceanography. *Ecological Applications*, 18 (2), 290-308.

Galgani, F., Hanke, G., Werner, S., Oosterbaan, L., Nilsson, P. *et al.*, 2013. *Guidance on monitoring of marine litter in European seas.* MSFD Technical Subgroup on Marine Litter, Joint Research Centre (JRC) scientific and policy reports, 128 pp.

Galgani, F., Hanke, G., Maes, T., 2015. Global distribution, composition and abundance of marine litter. p.29-56. *Marine Anthropogenic Litter.* Bergmann, M., Gutow, L., Klages, M. (Eds.), Springer, Cham.

Galgani, L., Beiras, R., Galgani, F., Panti, C., Borja, A., 2019. Impacts of marine litter. *Frontiers in Marine Science*, *6*, 208.

Gall, S.C., Thompson, R.C., 2015. The impact of debris on marine life. Marine pollution bulletin, 92 (1-2), 170-179.

Hamann, M., Godfrey, M.H., Seminoff, J.A., Arthur, K., Barata, P.C.R., *et al.*, 2010. Global research priorities for sea turtles: informing management and conservation in the 21st century. *Endangered species research,* 11 (3), 245-269.

Hammer, Ø., Harper, D.A.T., Ryan, P.D., 2001. PAST-palaeontological statistics, ver. 1.89. *Palaeontol. electron,* 4 (1), 1-9.

Hatase, H., Matsuzawa, Y., Sakamoto, W., Baba, N., Miyawaki, I., 2002. Pelagic habitat use of an adult Japanese male loggerhead turtle *Caretta caretta* examined by the Argos satellite system. *Fisheries Science,* 68, 945-947.

Hawkes, L.A., Broderick, A.C., Coyne, M.S., Godfrey, M.H., Lopez-Jurado, L.F., *et al.*, 2006. Phenotypically linked dichotomy in sea turtle foraging requires multiple conservation approaches. *Current Biology*, 16 (10), 990-995.

Hays, G.C., Scott, R., 2013. Global patterns for upper ceilings on migration distance in sea turtles and comparisons with fish, birds and mammals. *Functional Ecology*, 27 (3), 748-756.

Hochscheid, S., Bentivegna, F., Bradai, M.N., Hays, G.C., 2007. Overwintering behaviour in sea turtles: dormancy is optional. *Marine Ecology Progress Series*, 340, 287-298.

Hays, G.C., Fossette, S., Katselidis, K.A., Mariani, P., Schofield, G., 2010. Ontogenetic development of migration: Lagrangian drift trajectories suggest a new paradigm for sea turtles. *Journal of the Royal Society Interface*, 7 (50), 1319-1327.

ISPRA, 2015a. *Fixed line transect using ferries as platform for observation monitoring cetacean macro fauna and main threats protocol.* Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA), Technical Annex I, 19 pp.

ISPRA, 2015b. *Marine litter and marine macro-fauna protocol for the agreement 'Fixed line transect using ferries as platform of observation for monitoring cetacean populations*. Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA), Technical Annex II, 10 pp.

Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M. *et al.*, 2015. Plastic waste inputs from land into the ocean. *Science,* 347, 768-770.

Karaa, S., Maffucci, F., Jribi, I., Bologna, M.A., Borra, M. *et al.*, 2016. Connectivity and stock composition of loggerhead turtles foraging on the North African continental shelf (Central Mediterranean): implications for conservation and management. *Marine Ecology,* 37 (5), 1103-1115.

Kiszka, J., Macleod, K., Van Canneyt, O., Walker, D., Ridoux, V., 2007. Distribution, encounter rates, and habitat characteristics of toothed cetaceans in the Bay of Biscay and adjacent waters from platform-of-opportunity data. *ICES Journal of Marine Science*, 64 (5), 1033-1043.

Lauriano, G., Panigada, S., Casale, P., Pierantonio, N., Donovan, G.P., 2011. Aerial survey abundance estimates of the loggerhead sea turtle *Caretta caretta* in the Pelagos Sanctuary, northwestern Mediterranean Sea. *Marine Ecology Progress Series*, 437, 291-302.

Lazar, B., Gračan, R., 2011. Ingestion of marine debris by loggerhead sea turtles, *Caretta caretta*, in the Adriatic Sea. *Marine pollution bulletin*, 62 (1), 43-47.

Leeney, R.H., Witt, M.J., Broderick, A.C., Buchanan, J., Jarvis, D.S. *et al.*, 2012. Marine megavertebrates of Cornwall and the Isles of Scilly: relative abundance and distribution. *Journal of the Marine Biological Association of the United Kingdom*, 92 (8), 1823-1833.

Linnaeus, C. 1758. *Systema naturae per regna tria naturae, secundum classes, ordines, genera, species, cum characteribus, differentiis, synonymis, locis*. Ed. 10, Tomus 1. L. Salvii, Stockholm, Sweden, 823 pp.

Liubartseva, S., Coppini, G., Lecci, R., Clementi, E., 2018. Tracking plastics in the Mediterranean: 2D Lagrangian model. *Marine pollution bulletin*, 129 (1), 151-162.

Luschi, P., Mencacci, R., Vallini, C., Ligas, A., Lambardi, P. *et al.*, 2013. Long-term tracking of adult loggerhead turtles (*Caretta caretta*) in the Mediterranean Sea. *Journal of Herpetology, 47(2),* 227-231.

Luschi, P., Mencacci, R., Cerritelli, G., Papetti, L., Hochscheid, S., 2018. Large-scale movements in the oceanic environment identify important foraging areas for loggerheads in central Mediterranean Sea. *Marine Biology,* 165 (1), 4.

Maffucci, F., Kooistra, W., Bentivegna, F., 2006. Natal origin of loggerhead turtles, *Caretta caretta*, in the neritic habitat off the Italian coasts, Central Mediterranean. *Biological conservation,* 127 (2),183-189.

Maffucci, F., D'Angelo, I., Hochscheid, S., Ciampa, M., De Martino, G. *et al.*, 2013. Sex ratio of juvenile loggerhead turtles in the Mediterranean Sea: is it really 1: 1?. *Marine Biology*, 160(5), 1097-1107.

Maffucci, F., Corrado, R., Palatella, L., Borra, M., Marullo, S. *et al.*, 2016. Seasonal heterogeneity of ocean warming: a mortality sink for ectotherm colonizers. *Scientific reports*, 6(1), 1-9.

Malanotte-Rizzoli, P., Manca, B.B., d'Alcalà, M.R., Theocharis, A., Bergamasco, A., *et al.*, 1997. A synthesis of the Ionian Sea hydrography, circulation and water mass pathways during POEM-Phase I. *Progress in Oceanography*, 39 (3), 153-204.

Matiddi, M., Hochsheid, S., Camedda, A., Baini, M., Cocumelli, C. *et al.*, 2017. Loggerhead sea turtles (*Caretta caretta*): A target species for monitoring litter ingested by marine organisms in the Mediterranean Sea. *Environmental pollution*, 230, 199-209.

Matsumura, S., Nasu, K., 1997. Distribution of floating debris in the North Pacific Ocean:sighting surveys 1986-1991. p. 15-24. In: *Marine debris: sources, impacts, and solutions*. Coe, JM., Rogers, DB. (Eds.). *Springer-Verlag*, New York, NY.

Miladinova, S., Macias, D., Stips, A., Garcia-Gorriz, E., 2020. Identifying distribution and accumulation patterns of floating marine debris in the Black Sea. *Marine Pollution Bulletin*, *153*, 110964.

Motani, R., 2009. The evolution of marine reptiles. *Evolution: Education and Outreach*, *2*(2), 224-235.

Murase, H., Nagashima, H., Yonezaki, S., Matsukura, R., Kitakado, T., 2009. Application of a generalized additive model (GAM) to reveal relationships between environmental factors and distributions of pelagic fish and krill: a case study in Sendai Bay, Japan. *ICES Journal of Marine Science,* 66 (6), 1417-1424.

Murase, H., Hakamada, T., Matsuoka, K., Nishiwaki, S., Inagake, D. *et al.*, 2014. Distribution of sei whales (*Balaenoptera borealis*) in the subarctic–subtropical transition area of the western North Pacific in relation to oceanic fronts. *Deep Sea Research Part II: Topical Studies in Oceanography*, 107, 22-28.

Nelms, S.E., Duncan, E.M., Broderick, A.C., Galloway, T.S., Godfrey, M.H. *et al.*, 2016. Plastic and marine turtles: a review and call for research. *ICES Journal of Marine Science*, 73 (2), 165-181.

Onken, R., Robinson, A. R., Lermusiaux, P.F., Haley, P.J., Anderson, L.A., 2003. Data-driven simulations of synoptic circulation and transports in the Tunisia-Sardinia-Sicily region. *Journal of Geophysical Research: Oceans*, 108 (C9).

Pennino, M.G., Arcangeli, A., Prado Fonseca, V., Campana, I., Pierce, G.J. *et al.*, 2017. A spatially explicit risk assessment approach: Cetaceans and marine traffic in the Pelagos Sanctuary (Mediterranean Sea). *PloS one*, *12*(6), e0179686.

Pinardi, N., Zavatarelli, M., Adani, M., Coppini, G., Fratianni, C. *et al.,* 2015. Mediterranean Sea large-scale low-frequency ocean variability and water mass formation rates from 1987 to 2007: A retrospective analysis. *Progress in Oceanography,* 132, 318-332.

Poulain, P.M., Zambianchi, E., 2007. Surface circulation in the central Mediterranean Sea as deduced from Lagrangian drifters in the 1990s. *Continental Shelf Research*, 27 (7), 81-1001.

Poulain, P.M., Gerin, R., Mauri, E., Pennel, R., 2009. Wind effects on drogued and undrogued drifters in the eastern Mediterranean. *Journal of Atmospheric and Oceanic Technology*, 26 (6), 1144-1156.

Renous, S., Bels, V., Davenport, J., 2000. Locomotion in marine Chelonia: adaptation to the aquatic habitat. *Historical Biology*, 14 (1-2), 1-13.

Shiomoto, A., Kameda, T., 2005. Distribution of manufactured floating marine debris in near-shore areas around Japan. *Marine Pollution Bulletin,* 50 (11), 1430-1432.

Simoncelli, S., Fratianni, C., Pinardi, N., Grandi, A., Drudi, M. *et al.*, 2019. Mediterranean Sea Physical Reanalysis (CMEMS MED-Physics) [Data Set]. *Copernicus Monitoring Environment Marine Service (CMEMS).*

Snape, R.T., Broderick, A.C., Cicek, B.A., Fuller, W.J., Glen, F. *et al.*, 2016. Shelf life: neritic habitat use of a turtle population highly threatened by fisheries. *Diversity and Distributions,* 22 (7), 797-807.

Sorgente, R., Olita, A., Oddo, P., Fazioli, L., Ribotti, A., 2011. Numerical simulation and decomposition of kinetic energy in the Central Mediterranean: insight on mesoscale circulation and energy conversion. *Ocean Science,* 7 (4), 503-519.

Stokes, K. L., Broderick, A. C., Canbolat, A. F., Candan, O., Fuller, W. J., *et al.*, 2015. Migratory corridors and foraging hotspots: critical habitats identified for Mediterranean green turtles. *Diversity and Distributions*, 21 (6), 665-674.

Suaria, G., Aliani, S., 2014. Floating debris in the Mediterranean Sea. *Marine Pollution Bulletin*, 86 (1-2), 494-504.

Tepsich, P., Schettino, I., Atzori, F., Azzolin, M., Campana, I., *et al.*, 2020. Trends in summer presence of fin whales in the Western Mediterranean Sea Region: new insights from a long-term monitoring program. *PeerJ* 8:e10544.

Thiel, M., Hinojosa, I., Vásquez, N., Macaya, E., 2003. Floating marine debris in coastal waters of the SE-Pacific (Chile). *Marine Pollution Bulletin,* 46 (2), 224-231.

Tintoré, J., Pinardi, N., Álvarez-Fanjul, E., Aguiar, E., Álvarez-Berastegui, D. *et al.*, 2019. Challenges for sustained observing and forecasting systems in the Mediterranean Sea. *Frontiers in Marine Science,* 6, 568.

Viddi, F.A., Hucke-Gaete, R., Torres-Florez, J.P., Ribeiro, S., 2010. Spatial and seasonal variability in cetacean distribution in the fjords of northern Patagonia, Chile. *ICES Journal of Marine Science*, 67 (5), 959-970.

Wallace, B.P., DiMatteo, A.D., Hurley, B.J., Finkbeiner, E.M., Bolten, A.B., *et al.*, 2010. Regional Management Units for marine turtles: A novel framework for prioritizing conservation and research across multiple scales. *PLoS ONE* 5(12): e15465.

Wyneken, J., Lohmann, K.J., Musick, J.A., 2013. *The biology of sea turtles*. *Vol. III*, CRC Press, Boca Raton, FL.