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Corresponding author:
Camila Carvalho de Carvalho;
Email: camilacarvalho.bio08@gmail.com

The longest documented travel by a West Indian manatee

Camila Carvalho de Carvalho[1,2,3,4], Iury Tercio Simoes-Sousa[5], Lucas Pereira Santos[1], Katherine Fiedler Choi-Lima[1], Letícia Gonçalves Pereira[1], Maria Danise de Oliveira Alves[1,2,6,7], Adrian Carrero[8], Juan Carlos Santander[8] and Vitor Luz Carvalho[1,2,3]

[1]Associação de Pesquisa e Preservação de Ecossistemas Aquáticos – AQUASIS, Caucaia, Ceará, Brazil; [2]IUCN South American Sirenian Specialist Group, Gland, Switzerland; [3]IUCN Sirenian Specialist Group, Gland, Switzerland; [4]Instituto de Desenvolvimento Sustentável Mamirauá – IDSM, Grupo de Pesquisa em Mamíferos Aquáticos Amazônicos, Tefé, Amazonas, Brazil; [5]Woods Hole Oceanographic Institution, Woods Hole, MA, USA; [6]Centro Universitário Frassinetti do Recife – UniFafire, Recife, Pernambuco, Brazil; [7]Secretaria de Meio Ambiente, Sustentabilidade e de Fernando de Noronha de Pernambuco – Semas, Recife, Pernambuco, Brazil and [8]Ministerio del Poder Popular para el Ecosocialismo – MINEC, Caracas, Distrito Capital, Republic Bolivarian of Venezuela

Abstract

In Northeastern Brazil, successful release programmes have been implemented for the conservation of West Indian manatees (*Trichechus manatus*) since the 1990s. Recently, the non-government organization AQUASIS started releasing manatees in the state of Ceará, where oceanographic conditions and the absence of sheltered places pose new challenges for the release and monitoring of manatees. This research investigates the movement of a manatee named Tico, released in Icapuí, Ceará, Brazil, that travelled approximately 4017 km over 62 days through deep oceanic waters. Correlating Tico's trajectory and velocity with surface currents revealed the influence of the North Brazil Current (NBC) and its vortices on his movement. Tico crossed the diluted Amazon River plume with surface salinity as low as 26 $g\,kg^{-1}$ in early August, potentially encountering areas of even lower salinity. Additionally, Tico experienced several storms, with significant rainfall during his journey, which may have provided freshwater. The erratic movement patterns and significant weight loss prompted the rescue of Tico on Isla la Blanquilla, Bolivarian Republic of Venezuela. Tico is currently being temporarily housed in Parque Zoológico y Botánico Bararida in Venezuela. Understanding the nature of Tico's long-distance movement could help inform decisions about his future. AQUASIS proposes to return Tico to Brazil, a region with an ecologically and genetically distinct population from Venezuela, for a second release attempt, incorporating lessons learned from the first release. Furthermore, AQUASIS has the necessary human and financial resources to ensure the continuous monitoring of Tico during his readaptation to the wild.

Introduction

Rehabilitation and the subsequent release of endangered species are key strategies to connecting subpopulations, preventing the loss of genetic diversity, and reestablishing populations within their historic distribution ranges (IUCN/SSC, 2013). In Brazil, a long-term rescue, rehabilitation, and release programme was initiated in the 1990s to address the low population density and high stranding rates of newborn West Indian manatees (WIMs), *Trichechus manatus* (Luna *et al*., 2021b).

This successful programme encompasses the northeastern coastal region, where WIMs distribution and occurrence are influenced by factors such as food and freshwater availability, salinity, distance from the coast, and water depth (Santos *et al*., 2022). Among these factors, distance to freshwater and presence of seagrass meadows were the most important habitat features (Favero *et al*., 2020; Deeks *et al*., 2024). WIMs utilize marine, estuarine, and freshwater environments, and several lines of biogeographical, physiological and behavioural evidence indicate that regular access to freshwater is required, including for nursing calves (Ortiz and Worthy, 2006).

In terms of diet, manatees are exclusively herbivorous, primarily feeding on seagrass and a variety of algae and mangrove plants (Borges *et al*., 2008; Ciotti, 2012; Attademo *et al*., 2021). As WIMs are dependent on a low-energy and low-protein diet, they spend a considerable time foraging, with the proportions of food items they consume varying according to availability and nutritional value (Meirelles *et al*., 2016). Extended periods without food and freshwater drive manatees to obtain water through fat oxidation (Ortiz *et al*., 1999), resulting in weight loss and dehydration over time. These physiological needs, along with the biological and ecological characteristics of manatees, limit them to coastal and shallow waters (Santos *et al*., 2022) and directly influence their movements (Deutsch *et al*., 2022).

Despite successful conservation efforts- where 76.7% of releases were considered successful (Normande *et al*., 2015)- the subspecies *Trichechus manatus manatus* (Antillean manatee) remains classified as 'Endangered' on the International Union for Conservation of Nature (IUCN) Red List (Self-Sullivan and Mignucci-Giannoni, 2008) and the Brazilian National List (MMA, 2022). However, some researchers have suggested that this classification may need to be reevaluated to 'Critically Endangered' in Brazil (Meirelles *et al.*, 2022).

The strandings of calves has also increased in recent years, mainly in the semi-arid coast that encompasses Ceará (4.1 strandings/year) and Rio Grande do Norte states (Figure 1) (Meirelles, 2008; Balensiefer *et al.*, 2017; Meirelles *et al.*, 2024; Moreira-Lima *et al.*, 2024). Possible factors related to the increase in strandings include mangrove deforestation (Choi, 2011; Medeiros *et al.*, 2021) and the recruitment of young breeding females into the population, who may struggle to provide adequate care and protection for their calves, along with the loss of maternal ability due to inbreeding (Carvalho and Borges, 2016; Meirelles *et al.*, 2024). Environmental barriers such as ocean currents and tidal changes can also play a role in separating calves from their mothers (Balensiefer *et al.*, 2017).

In response to this situation along the semi-arid coast, the non-government organization (NGO) Association for the Research and Preservation of Aquatic Ecosystems (AQUASIS), which has rescued more than 70 live calves since 1994, began releasing manatees in the state of Ceará. In 2019, an innovative enclosure, using modular high-density polyethylene floats, was constructed in the marine environment (~200 m from coast) for the acclimatization period (Choi-Lima *et al.*, 2022). This structure has been housing manatees since 2020, and out of these, five were released with attached telemetry equipment.

Of all the animals released to date, three (one female and two males) moved towards the northwest, with average daily movement speed varying between 4.38 and 13.38 km day^{-1} among individuals. These three animals travelled more than 500 km from the release site, beyond the limits of the state of Ceará.

One female was monitored for only three days due to transmitter malfunction, and new coordinates received a month later indicated a movement towards the African continent, suggesting either a departure from the coast or transmitter drift (Viana Júnior *et al.*, 2022). One male remained in areas close to the release site, was monitored for 319 days, and exhibited an average daily movement speed of 4.49 km day^{-1}.

Although the average daily movement speed of the released individuals showed similar values to those of non-rehabilitated ('wild') animals monitored in the region (ranging from 4.88 to 11.10 km day^{-1}, mean = 7.28 km day^{-1}) (Petrobras, 2014; Normande *et al.*, 2024), the released animals frequently moved westward without stopping to explore resources. Releases in the region have been more challenging due to the absence of coastal protected environments (rivers, estuaries, reefs), typically preferred by sirenians (Axis-Arroyo *et al.*, 1998), which provide protection from strong winds and tide conditions.

One of the released manatees that headed west, an 8-year-old male named Tico, travelled a total of 4017 km, reaching Isla La Blanquilla, Dependencias Federales, Bolivarian Republic of Venezuela (Figure 1A). Throughout the large distance travelled, Tico also moved through deep oceanic regions, which posed a risk for survival due to predation, inhospitable oceanic conditions, and a lack of food and freshwater resources. Further research and investigation are needed to better understand the factors influencing such movements in manatees (Castelblanco-Martínez *et al.*, 2021).

Tico was captured alive by Venezuelan collaborators under AQUASIS's guidance due to the imminent risk to his life, which was related to high energy expenditure and low resource availability. Since then, discussions have been ongoing regarding Tico's future and the conditions of his repatriation. Understanding the factors that influenced Tico's movement will help provide insights for researchers and decision-makers about the animal's future. Therefore, our aim is to investigate the following questions: (i) Were Tico's movements influenced by ocean currents near the continental slope off Brazil? (ii) What resources may have favoured the animal's survival in deep water? (iii) What would be the most appropriate destination for this animal, recaptured in another country, from a conservation perspective?

Materials and methods

Rehabilitation, release and monitoring

Tico was rescued on October 15, 2014, at *Praia das Agulhas*, Fortim, Ceará, Brazil (04°23′54″S 37°47′56″W), as a newborn (Figure 2A). The 1.21 m and 30.1 kg animal stranded alongside another calf at a similar stage of development, subsequent genetic confirmation uncovered that they were twins (Moreira *et al.*, 2022), the first recorded case of Brazilian WIMs twins born in the natural environment. During the initial two years of rehabilitation at the AQUASIS Marine Mammal Rehabilitation Centre (MMRC) (Figure 2B), Tico was fed a milk formula consisting of varying concentrations of lactose-free milk, isolated soy milk, and unsalted butter. Additionally, an artificial diet composed of a mix of vegetables (mainly lettuce, cabbage, and chard), algae and grass were provided; freshwater was supplied from hoses under the pools. The quantity of vegetables offered was gradually increased according to the nutritional requirements and energy expenditure of the animals. At MMRC, manatees are fed an amount equivalent to up to 5% of their body weight.

The general weaning process at MMRC starts at around 18 months, with a gradual reduction in total volume and frequency of feedings, culminating in complete weaning by around 24 months. However, due to Tico's lower weight compared to other herd members at the time of weaning (Tico = 174 kg; mean = 233 kg), the weaning process was extended until 25 months (Borges *et al.*, 2012; Carvalho and Borges, 2016). Weight was determined using the following formula: (umbilical girth)^2 × total length × 4.01 × 0.00001 (Rigney and Flint, 2011).

In December 2020, Tico was translocated to an acclimatization enclosure at the age of seven years and two months (total length = 2.68 m; weight = 346 kg). The extended rehabilitation period was due to logistical and financial limitations. During this phase, Tico received a daily feeding amounting of up to 11% of his body weight, reflecting his heightened energy expenditure. The diet consisted of at least 15% (~50% when available in large quantities) seagrass species (*Halodule wrightii* and *Ruppia maritima*) and cultivated vegetables: lettuce (10 to 17%), cabbage (15 to 25.5%), beetroot (1.6%), chard (15 to 25.5%), banana (1.3%) and elephant grass (*Cenchrus purpureus)* (10 to 17%). The proportion of each component depended on the availability of seagrass in the environment.

Tico was released on July 6, 2022 (total length = 2.68 m; weight = 295 kg), at *Praia de Peroba*, Icapuí, Ceará. Brazil (04°39″24″S 37° 37′06″W) (Figure 2C, D). Prior to release, Tico was isolated from other manatees, and the enclosure net was lowered to grant access to the open marine environment. Two days before release, a tag system comprising a peduncle belt, a 1.5 m tether, and a floating transmitter was attached to the animal (Figure 2E, F). The device model used was the TMT 464-2 GPS/Argos System (Telonics, Mesa, AZ, USA – ID 111986), equipped with a global positioning system (GPS) with an ARGOS link and a VHF transmitter. The equipment was programmed to collect coordinates every hour, and the VHF system operated 24 h a day, enabling continuous tracking of the manatee in the field. Following release, daily field monitoring continued from 8 a.m. to 5 p.m., primarily conducted by land using

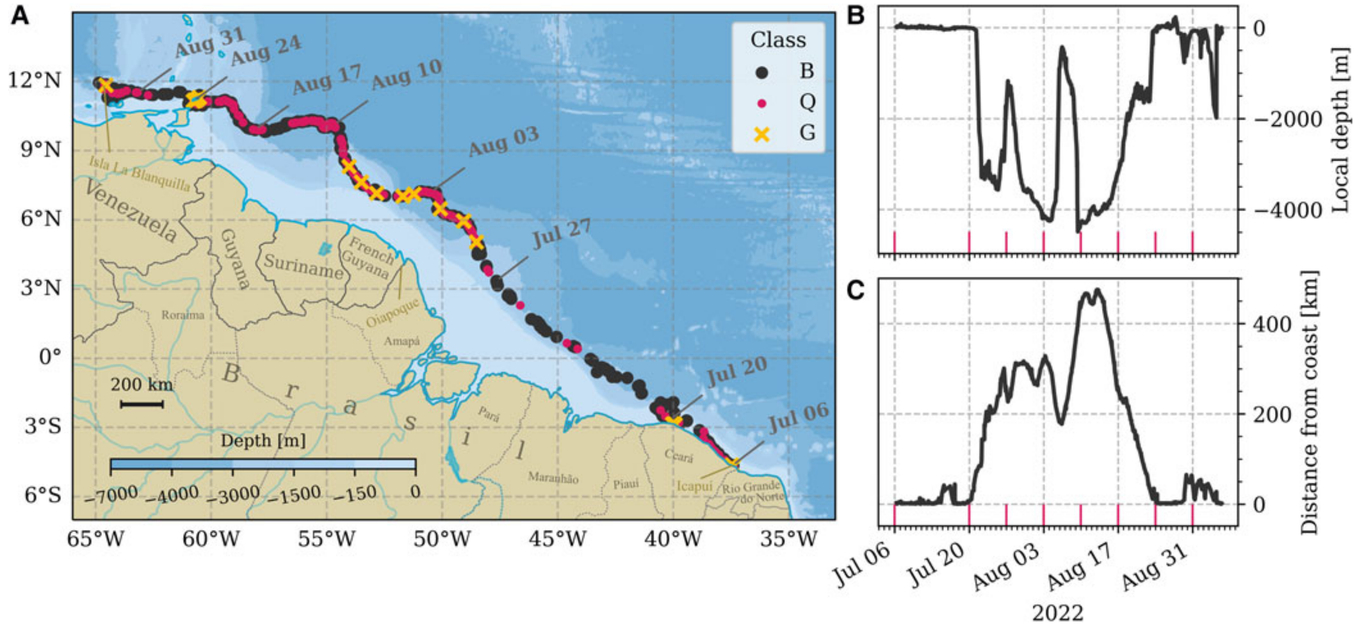

Figure 1. (A) Geopolitical (gray) and bathymetric (blues) map with Tico's positions (classes B, Q, and G). (B) Depth at Tico's position and (C) distance from the coast time series.

cars and binoculars or by sea using small boats. Behavioural data on activity performed and interactions were also recorded during field tracking.

Data analysis

Geographic locations were acquired remotely through the Argos satellite system, and the data files were converted using the Telonics Data Converter software (Telonics, Mesa, AZ, USA). Initially, only GPS positions from classes G (5 m error) and QFP (error from 5 to 500 m) were considered for the analysis due to their lower error rates. However, there was an important region where most positions belonged to Argos class B (Figure 1A). While these positions do not have a pre-estimated accuracy, they exhibited the same pattern as the other classes elsewhere, indicating that it was possible to filter out the noise that may be generated by the error of positions in this class. The estimated accuracy of each class was provided by the Argos System (https://www.argos-system.org/wp-content/uploads/2023/01/CLS-Argos-System-User-Manual.pdf).

Therefore, classes QFP, G, and B were used for the analyses. All positions were interpolated to a 1-hour resolution and were filtered using a 2-day centred Hanning filter to avoid contamination of noise in the velocity measurements (Figure S1). All the data analyses were performed using open-source Python packages. As described in the Data Availability Statement, the code for the processing and plotting is available through an open repository on Zenodo (https://zenodo.org/records/13773988).

The average daily movement speed (in km day^{-1}) was estimated by summing the distances travelled over determined period and dividing by the number of days.

Three different datasets were compared for the surface velocity estimates: Ocean Surface Current Analysis Real-time (OSCAR), HYCOM Global Ocean Forecasting System (GOFS) 3.1 Analysis (https://www.hycom.org/data/glby0pt08/expt-93pt0) and the NEMO Global Ocean Physics Analysis and Forecast from the Copernicus Marine Environment Monitoring Service (European Union - Copernicus Marine Service, 2016) (Figure 3).

Each of the datasets was interpolated to Tico's positions and filtered using the same method applied to the telemetry data. The Pearson correlation coefficient was used to compare the magnitude and velocity components from each dataset with Tico's trajectory. The dataset that showed the higher correlation was chosen for the posterior analysis and was overlapped with Tico's coordinates to create a map. Additionally, the streamlines were compared with Tico's trajectory to provide a more comprehensive understanding of the large-scale current patterns that influenced Tico's path. This qualitative analysis helps to identify specific currents and vortices that steered Tico's movement, complementing the quantitative comparisons of velocity magnitudes and directions in the first part of the analysis.

Data from the General Bathymetric Chart of the Oceans (GEBCO) were used, utilizing a grid interval of 5 arc-seconds, to estimate ocean depth at Tico's positions (Figure 1B), identify the shelf break, and produce the maps presented in this study. In addition, satellite-derived estimates for the sea surface salinity from the Soil Moisture Active Passive (SMAP) were used to identify the position of the Amazon River plume, while rainfall estimates over Tico were obtained from the Integrated Multi-satellitE Retrievals for GPM (IMERG). These two datasets were crucial for investigating whether Tico had access to freshwater along his trajectory. The SMAP data is daily and has a resolution of 0.6 degrees, filtered with an 8-day moving average. The IMERG data represents accumulated daily rainfall with a spatial resolution of 0.1 degrees.

Results

Release and monitoring

Tico was monitored for 62 days (n = 1085 location fixes), between 6th July and 5th September (2022), travelling around 4017 km from Icapuí, Ceará, Brazil, through La Blanquilla Island, Venezuela (straight line distance = 3520 km) (Figure 1). After the release, Tico initially stayed exploring Icapuí beaches, but on the fifth day, he began moving continuously to the northwest.

On day 9 after release, over 300 km from the release site, Tico moved more than 40 km away from the coast, an unusual behaviour for a manatee (Lima *et al.*, 2015; Normande *et al.*, 2016; Santos *et al.*, 2022). The team initiated a rescue operation, organizing a boarding attempt, but Tico returned to the coast. Ten days after release, Tico had already covered 344.7 km. On day 12 (17th

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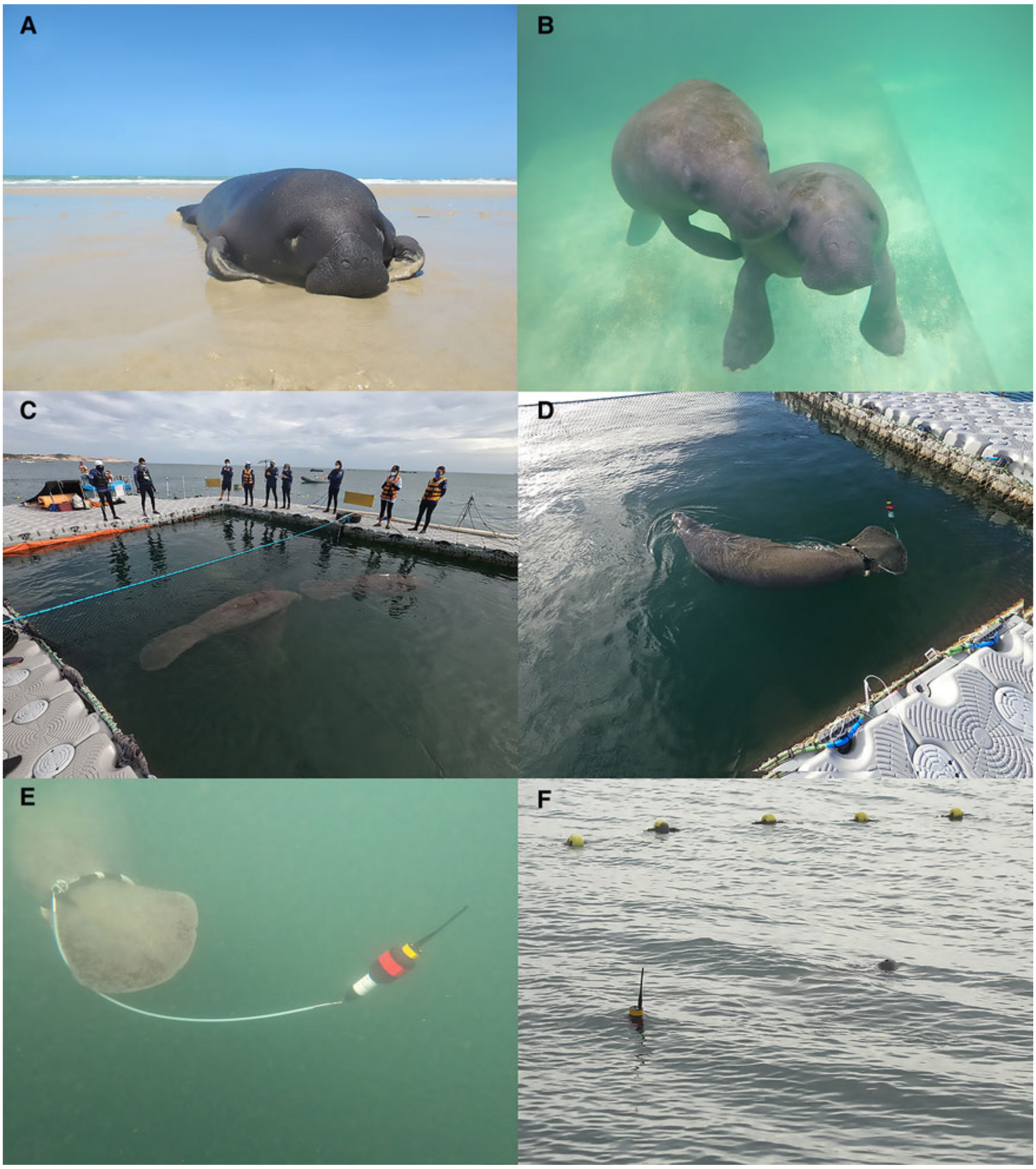

Figure 2. (A) Tico stranded in Praia das Agulhas, Fortim/CE. (B) Tico and his twin Teco during rehabilitation. (C) Release in the acclimatization enclosure; (D) Tico with the telemetry equipment before release. (E) Details of the equipment (belt, tether, and transmitter). (F) Tico observed beside the acclimatization enclosure after release.

July), Tico was found trapped in a fishing corral in Acaraú, Ceará (392 km from release site). He was then captured, examined, and released at the same site, since he did not show any signs of injuries or dehydration.

In the next three days the animal started to move away from the coast again (48.3 km on 20th July and 92.6 km on 21st July). Since his release on July 6th until he reached the shelf break on 21st July, Tico exhibited an average daily movement speed of 37.1 km day^{-1}. On day 17 (22nd July), the animal was 180 km away from the coast at the shelf break (Figure 1C), and 621 km away from the release site, in front of Camocim, Ceará. In the next days, the animal moved more than 540 km along the slope, passing through Piauí, Maranhão, Pará, and Amapá states. Despite collaborative efforts involving the Navy, NGOs, fishers, and universities, the team faced challenges in sourcing a boat capable of navigating far from the coast. Projections developed by CENPES/PETROBRAS (Leopoldo Américo Miguez de Mello Research, Development, and Innovation Centre) were used to predict Tico's locations and plan a flight from Oiapoque, Amapá, to verify if the equipment was still attached to him. Initially, the projections indicated that Tico was less than 200 km from Oiapoque (04°14′N, 049°56′W). However, by 28th July, the animal was over 360 km away (04° 00′N, 048°05′W), rendering the flight unfeasible due to the aircraft's autonomy.

On 5th August (one month after release), the animal reached international waters near French Guiana, having travelled more than 2000 km, limiting rescue efforts. Remote monitoring continued, and the coordinates indicated that Tico was approaching Tobago Island, Trinidad, and Tobago. Local researchers were contacted, and monitoring was conducted in the area by a local team, confirming Tico's presence and active behaviour on 24th August. On 25th August, Tico was spotted at the Port of Scarborough on Tobago Island, but he continued northward, circumnavigated the island, and was not seen again. Nevertheless, remote monitoring

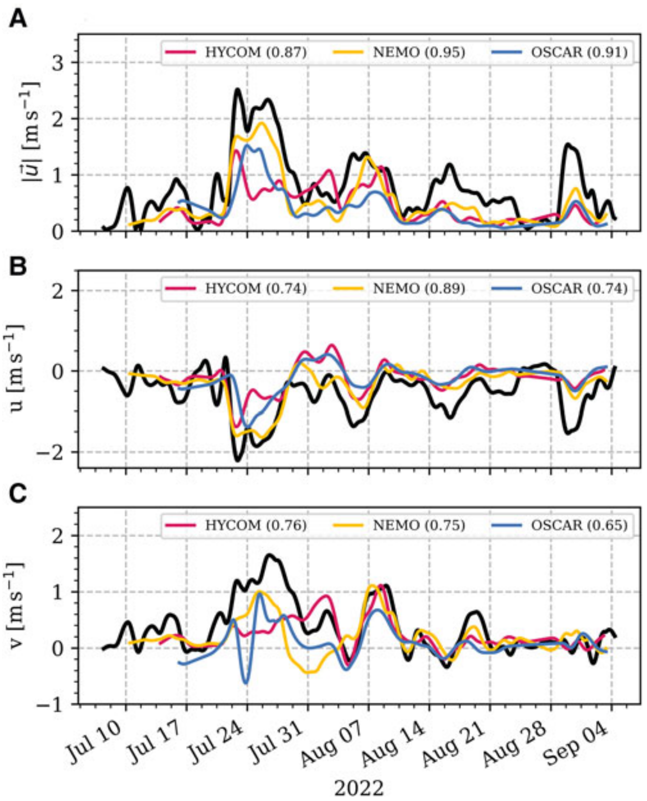

Figure 3. Comparison of the surface velocity estimates: Ocean Surface Current Analyses Real-time (OSCAR), HYCOM Global Ocean Forecasting System (GOFS) 3.1 Analysis and the NEMO Global Ocean Physics Analysis and Forecast from Copernicus Marine Environment Monitoring Service (CMEMS).

persisted. The AQUASIS team travelled to Tobago Island to assist with the search and capture efforts, but Tico began moving away towards the Caribbean Islands in Venezuela.

Recapture and health assessment

The decision to recapture Tico was based on the pattern of his movements, considered erratic according to previous studies: 'a continuous movement in one direction without using the coastal environment for the establishment of permanence areas' (Lima *et al*., 2015). Additionally, given Tico's significant muscle wasting and the presumed extended period without access to food and freshwater, urgent veterinary attention was necessary to assess his health.

Therefore, members of the Caribbean Marine Mammal Stranding Network mediated contact with the Director of Biodiversity at the Ministry of Popular Power for Eco-socialism (MINEC) and Venezuela's administrative authority for the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES). Search and capture operations involved the Coast Guard, Inparques, and the Bolivarian National Armada, under the guidance of the AQUASIS team. Tico was successfully captured on La Blanquilla Island, Venezuela, on 5th September. Subsequently, Tico underwent a 13-h naval transport to a quarantine facility at the Waterland aquarium, located on the Islands of Margarita (Viloria *et al*., 2022). From the time Tico reached the shelf break on 22nd July until he was recaptured, Tico demonstrated an average daily movement speed of 76.56 km day^{-1}.

Upon examination, Tico exhibited stability with evident weight loss (−85 kg; total weight = 210 kg) and mild changes in haematological and biochemical parameters, including decreased haematocrit, eosinophilia, and increased lactate dehydrogenase. Faecal samples indicated the consumption of unidentified plants, suggesting foraging along the coast of Tobago. Although the specific plants were not identified, further investigation is recommended.

Technicians in Venezuela administered an enema to address a suspected obstruction, successfully removing a plastic bag from Tico's digestive tract. Tico's diet consisted of lettuce, supplemented with a higher proportion of fruits (bananas, apples, papayas) and vegetables (mainly carrots and beets). Initially, food was administered directly into the mouth to facilitate medication and supplement administration. On November 2nd, Tico was transferred to the *Parque Zoológico y Botánico Bararida* in the city of Barquisimeto, Lara, Venezuela, involving air and land transportation operations.

The influence of ocean currents

While all ocean surface velocity datasets exhibited similar patterns, the NEMO velocity fields showed the best fit to the velocity estimates from Tico's trajectory. The Pearson correlation coefficient was 0.95 for the velocity magnitude, and 0.89 and 0.75 for the zonal and meridional velocity components, respectively. Consequently, the NEMO dataset was selected to create a map featuring Tico's coordinates for trajectory comparison. The time series and correlation coefficients in Figure 3 suggested that currents played a dominant role in Tico's heading speed and direction after crossing the shelf break, and the streamline maps (Figure 4) offered a broader context for interpreting these velocities and how they translated into large-scale current features guiding Tico's movement.

Tico´s trajectory visually followed the lines of surface currents, especially after crossing the equator around 24th July (Figure 4, Video A1[1]). The strongest currents experienced by Tico occurred between 22nd and 28th July, with speeds reaching approximately 2.2 m s^{-1} (~8 km h^{-1}), characteristic of the North Brazil Current (NBC) in this region (Johns *et al*., 1990, 1998; Simoes-Sousa *et al*., 2021). In August, the trajectory meandered, following the edge of an NBC ring between 7–10°N (Figure 4C). These vortices propagate towards the Antilles and are characteristic of this region, formed by the retroflection of the NBC and the subsequent formation of the North Atlantic Equatorial Countercurrent (Johns *et al*., 1990; Silveira *et al*., 2000; Castelão and Johns, 2011; Aroucha *et al*., 2020). The analyses supported the theory that the intensity and direction of the main axis of the NBC and its vortices influenced Tico's movement.

Resource availability

In terms of freshwater availability, Tico crossed the diluted plume of the Amazon River by early August, which had a minimum surface salinity of 26 g kg^{-1} (Figure 5A, C). It's important to note that the SMAP Sea Surface Salinity spatial resolution is considerably coarse to represent the smaller-scale features, which means Tico might have crossed locations with even lower salinity in this region.

Furthermore, during rehabilitation at AQUASIS MMRC, some manatees were observed consuming rainwater droplets at the surface, which may serve as a possible source of freshwater (Carvalho, VL, pers. obs.). Daily accumulated rainfall interpolated to Tico's positions indicated that he encountered several storms (Figure 5B, D). The first occurred around 28th July, with approximately 22 mm of rainfall. Between 31st July and 6th August,

[1]Link https://www.youtube.com/watch?v=SaIj6LsaQ_o

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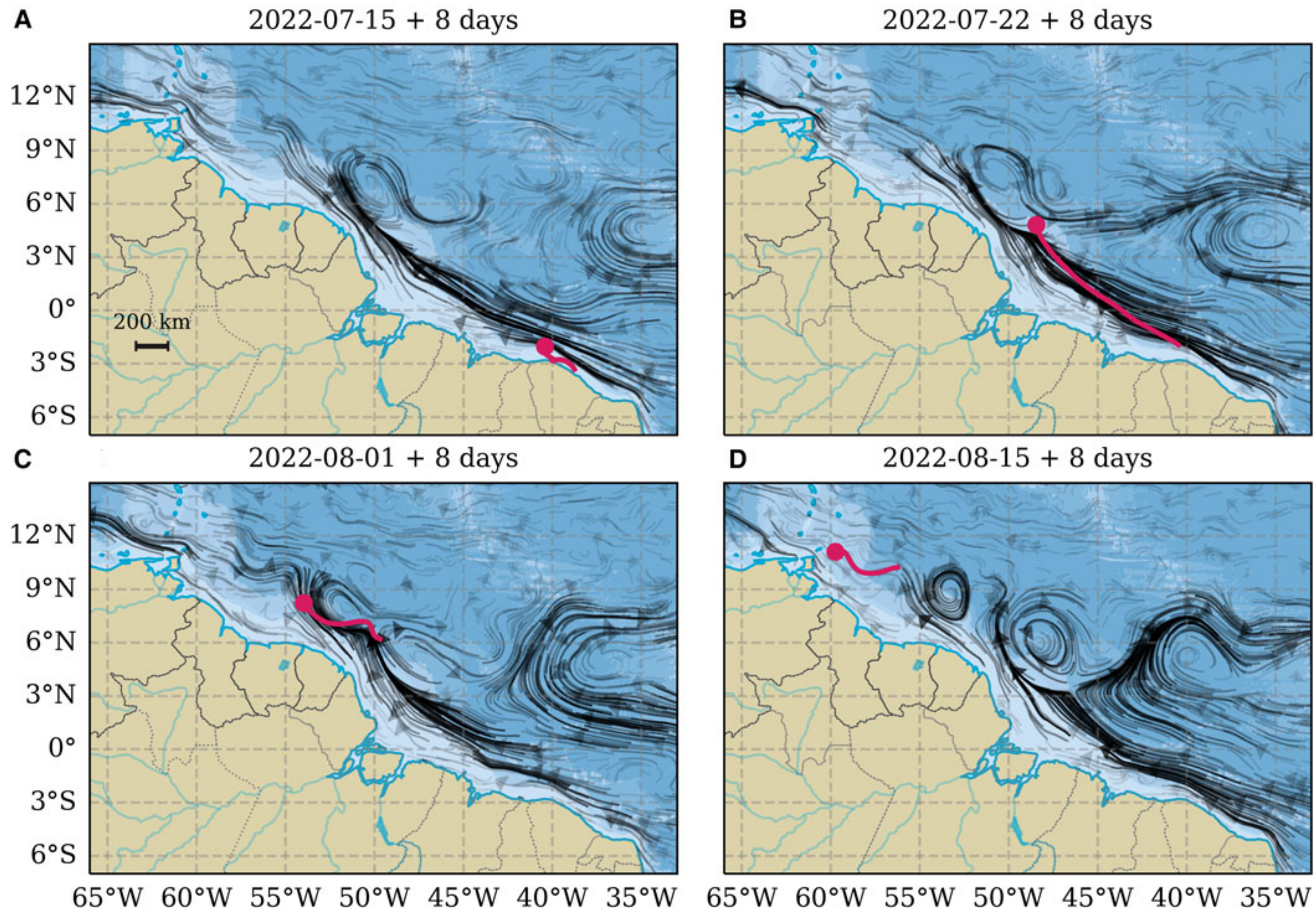

Figure 4. NEMO stream function (grey arrows) and Tico's trajectory (red line) for different time intervals (A–D). Light blue represents shallower depths.

moderate rainfall of around 10 mm occurred daily. From 7th to 18th August, rainfall was minimal, but from 19th to 27th August, Tico passed through a major storm, with a maximum of over 43 mm on 26th August.

Discussion

Tico's long-scale movement

This study recorded the longest distance travelled by a WIM, with the animal spending more than a month in deep waters, drifting with the NBC from Northeastern Brazil to Venezuela. Tico, an 8-year-old rehabilitated male, undertook an unpredictable journey of more than 4000 km in a north-westward direction. To determine whether this type of movement is rare or common, it is important to note that only one study has tracked the movements of non-rehabilitated animals in Brazil. This study monitored six animals in Ceará and Rio Grande do Norte states from May 2012 to April 2013. These tracked animals remained within a 10-m isobath and exhibited home ranges varying from a minimum of 41.33 km^2 for a female with a calf to a maximum of 155.56 km^2 for an adult male (Petrobras, 2014). Given the small sample size of tagged individuals, further research is warranted to better understand the long-distance movements of WIMs in this population.

It is possible that no manatee has taken this route before, given the low genetic connectivity between the Brazilian WIM population and neighbouring populations in South and Central America, which suggests rare or non-existent recent migration between those populations (Vianna *et al.*, 2006; Lima *et al.*, 2021). Furthermore, Tico's movement was unusual in several parameters, including distance travelled, speed, trajectory, and the influence of currents. To date, only ten manatees have undertaken a journey comparable to Tico's in terms of distance, travelling beyond the typical range or extending past typical seasonal migration areas (Deutsch *et al.*, 2022). The longest movement recorded was by a Florida manatee (FM) (*Trichechus manatus latirostris*), which travelled approximately 4800 km along the Atlantic coast of the United States (Reid *et al.*, 1995). It is uncommon to observe very long-distance movements (>1000 km) among sirenians (Sheppard *et al.*, 2006; Castelblanco-Martínez *et al.*, 2013), even during migration periods driven by changes in water temperature in FMs (Deutsch *et al.*, 2003). Migratory FMs travelling to and from the Gulf of Mexico have the longest recorded journeys, with a mean distance of 695 km and a maximum reported distance of 1150 km (Aven *et al.*, 2016; Castelblanco-Martínez *et al.*, 2021).

Along the coast of Ceará, satellite tagging of six non-rehabilitated WIMs showed that only one adult male monitored for 339 days moved more than 50 km to the east (Petrobras, 2014; Normande *et al.*, 2024). Additionally, rehabilitated manatees in Brazil exhibited a mean linear distance from the release site of 73.4 km (Normande *et al.*, 2016). However, sirenians can exhibit restricted movements during periods of resource scarcity due to factors such as rainfall, water level, and temperature fluctuations, the latter particularly affecting animals in higher latitudes (Deutsch *et al.*, 2022). Consequently, long-term studies that monitor animals for periods longer than one year are recommended to gain a more comprehensive understanding of their movement patterns and resource use.

Tico strayed more than 400 km from the coast at some points, while the maximum distance recorded for successful cases of

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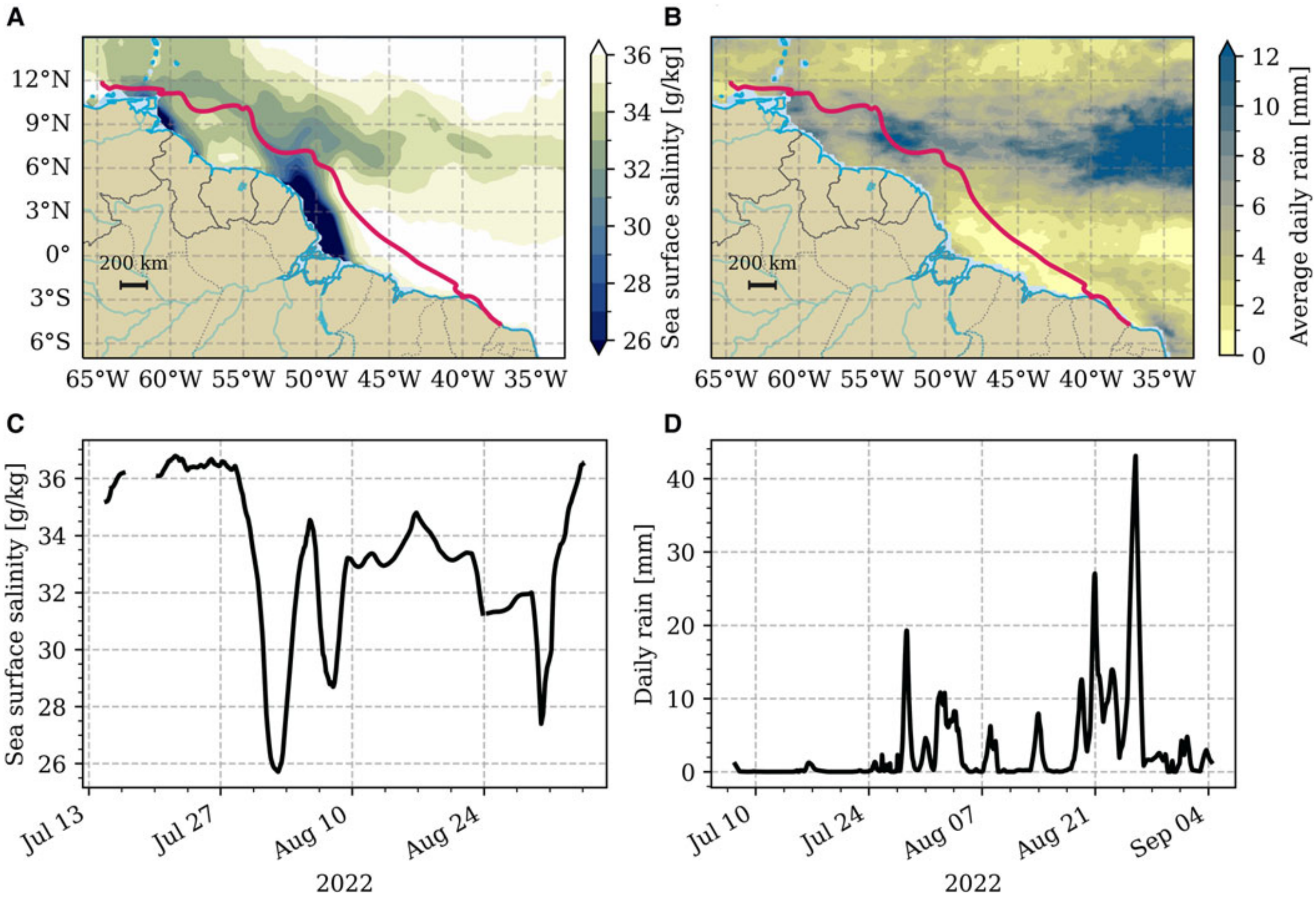

Figure 5. Tico's trajectory (red) plotted with: (A) Soil Moisture Active Passive (SMAP) sea surface salinity and (B) Interpolated IMERG daily accumulated rainfall data; (C) SMAP sea surface salinity values and (D) Daily rain of Tico's trajectory.

rehabilitated WIMs in Brazil was only 3.31 km (Normande *et al.*, 2016). Although Deutsch *et al.* (2003) recorded FMs movements in open waters, this was uncommon, as 93% of migrating manatees moved through intracoastal channels protected by barriers. The FMs performing rapid and directed large-scale movements across deep waters were primarily those travelling to Caribbean islands. However, this route is much shorter (< 1000 km) than Tico's journey, and FMs are considerably larger and have more energy reserves.

Regarding movement speed, the fastest documented movement for a FM during migration was 116 km in 32 h, which equates to a daily rate of at least 87.2 km (3.6 km h^{-1}) (Deutsch *et al.*, 2003). This speed is similar to that reached by Tico while travelling in deep waters, at some points achieving speeds of approximately 8 km h^{-1} (comparable to the NBC). Tico's travel direction was always consistent with the direction of surface currents, a pattern observed for other marine species, such as elephant seals (*Mirounga leonina*) (Campagna *et al.*, 2006).

Although both FMs and Antillean manatees have been observed using tidal currents to their advantage, including in riverine environments, where they use the outgoing current to reduce energy expenditure (Littles *et al.*, 2019), there is no record of ocean currents influencing long-term movements in sirenians. Previous studies and our analysis of surface currents support the hypothesis that the NBC influenced Tico's movement, exhibiting patterns and propagation speeds consistent with those expected for a drifting animal.

Moving to areas beyond the known range within the same Evolutive Significant Unit (ESU) can lead to increased genetic diversity through the mixing of previously isolated populations. This and similar records could also provide new insights into the expansion of the species through evolutionary time (Domning, 2005; Deutsch *et al.*, 2022). The genetic implications are discussed in the section 'Justifications for repatriation and importance for conservation' (below). Besides that, these extralimital movements can also pose risks, such as exposure to unfamiliar environmental conditions and pathogens, excessive muscle wasting and weight loss, potentially affecting the health and survival of the individuals. Some FMs that travelled long distances presented poor body condition and cold stress (Rood *et al.*, 2020), which led to the hypothesis that even non-rehabilitated manatees could perform erratic movements due to environmental changes, since their habitats are under pressure from human activity and climate-related changes (Aven *et al.*, 2016).

Since the beginning of the rehabilitation and release programme in Brazil, three cases of manatees moving into deep oceanic waters have been reported; one returned after 24 days beyond the continental shelf (Normande *et al.*, 2015) and two had to be recaptured, one of them was recaptured at a local depth of 100 m. Both wandering manatees showed great weight loss and dehydration (Lima *et al.*, 2012). Tico lost weight, showed mild dehydration, and when he was recaptured (previous attempts failed due to logistical difficulties), it was found that he had ingested a plastic bag. If the intervention had not been carried out in time, the animal might have died. The decision to recapture Tico was based on the evaluation of his body condition and movement patterns, drawing from previous experiences with rehabilitated manatees (Lima *et al.*, 2012; Normande *et al.*, 2015).

Studies with FMs have shown that within the same population, there is a diversity of movement patterns, with both resident and

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migrating animals (Deutsch *et al.*, 2003). Therefore, natural long-scale movements do exist and could be influenced mainly by seasonal variations in abundance or nutritional quality of food resources, as seen in other large herbivores (Deutsch *et al.*, 2003). This was probably not the reason that triggered Tico's movement, as the animal passed through areas with food availability along the coast and had only been released for ten days when he began moving through deep waters, an insufficient period to understand the dynamics of food resource availability.

There is also evidence in FMs that individuals learn migratory behaviour, as tracked juveniles have been observed adopting the same migratory patterns as their mothers (Deutsch *et al.*, 2003). It is important to emphasize that Tico is a rehabilitated animal that was stranded as a newborn calf and did not receive any type of learning from his mother. Therefore, Tico's movement could indicate disorientation and a lack of navigation skills, since the functioning of the navigation and orientation systems in sirenians remains largely unknown (Marsh *et al.*, 2011).

Although it is not possible to confirm that such movements are not carried out by non-rehabilitated animals in the population, Tico's movements are atypical in terms of velocity (high speed), distance (> 2000 km), and trajectory (more than a month in deep waters) compared to the reports of manatees in other populations. This highlights the rare and unusual nature of Tico's movement.

Resource availability and survival

Due to the depth of offshore waters, the most common natural food sources for manatees, such as seagrass (*Halodule wrightii*) and green and red algae (Attademo *et al.*, 2021), are unlikely to occur in sufficient quantities, as they primarily grow in shallow waters. Therefore, one possibility raised regarding what Tico was feeding on was floating *Sargassum* seaweed, which is present in large quantities in the South Atlantic Ocean (Sissini *et al.*, 2017; Wang *et al.*, 2019) and was previously recorded as a potential food resource for WIMs (Borges *et al.*, 2008; Rodrigues *et al.*, 2021).

It is also possible that the animal did not find any food resources during his time in deeper waters. Some authors propose that sirenians can remain for long periods without feeding (three to four months), as hypothesized for Amazonian manatees (*Trichechus inunguis*) during the dry season. The low metabolic rate and fat deposits suggest that a *T. inunguis* weighing 300 kg could survive for approximately 155 days at an active metabolic rate during prolonged periods of fasting (Best, 1983).

Among other marine mammals, there are some species that fast during specific periods, such as baleen whales during migration (Nichols *et al.*, 2022) and northern elephant seals (*Mirounga angustirostris)* while breeding, moulting or weaning (Vázquez-Medina *et al.*, 2011). If Tico didn't find any food resources during his journey, he might have survived by reducing the metabolic rate and energy expenditure, possibly by drifting instead of swimming. Tico was one of the smallest (in length and weight) manatees in rehabilitation in AQUASIS, the animal that was weaned with the lowest weight, and even so, he had the resistance and energy reserves to survive many days on the high seas with limited resources.

Regarding freshwater, rainfall occurred daily during this period, and while we cannot confirm whether Tico drank the rainwater, previous observations at Aquasis MMRC suggests that such a scenario could have occurred (Carvalho, VL, pers. obs.). Although there are controversies regarding freshwater intake, as some authors consider it to be a preference rather than a physiological need (Reynolds *et al.*, 2017), there is evidence of manatees drinking water regularly and that habitat use is influenced by freshwater sources (Favero *et al.*, 2020). Rehabilitated and released WIMs used freshwater sources 1–12 times per month (Santos *et al.*, 2022) and some studies showed that manatees deprived of freshwater could present signs of dehydration and may stop feeding (Ortiz *et al.*, 1998). Even though manatees have adaptations to survive without freshwater for periods of time (Ortiz *et al.*, 1999), they would likely consume freshwater if available, as it appears to be energetically advantageous (Olivera-Gómez and Mellink, 2005).

Justifications for repatriation and importance for conservation

Although the species is globally endangered (Deutsch *et al.*, 2008), studies have shown that the global habitat suitability for manatees is expected to decrease significantly, with the projected decline in the manatee populations being most pronounced in tropical regions, notably in Brazil (Deeks *et al.*, 2024). These predictions are concerning, especially considering that the most recent abundance studies in Brazil indicate a small population of around 1100 individuals along approximately 4000 km of the Brazilian coastline (Alves *et al.*, 2013).

Tico is a rehabilitated and important animal for the conservation programme in Brazil and the release and reproduction of the animal in Venezuela is not recommended for the following reasons. Population studies divide the species *T. manatus* into two evolutionary units (ESUs), which diverged more than 260,000 years ago: ESU 1 (Caribbean), including Venezuela, Colombia, Central America, Florida, and Antilles; and ESU 2 (Atlantic), which includes the Brazilian population (Santos *et al.*, 2016; Lima *et al.*, 2021). Both ESUs are separated by an interspecific hybrid zone between *T. manatus* and *T. inunguis*, likely formed in the sympatric area around the Amazon River estuary, but extending through the Guianas coastline up to the Orinoco River mouth in Venezuela (Lima *et al.*, 2019; Vilaça *et al.*, 2019). Tico is undoubtedly a *T. manatus*, as confirmed by the genotyping of 10 microsatellite loci (Silva, 2015; Moreira *et al.*, 2022) and characterization of his mitochondrial genome (Furni, 2019). Tico belongs to the Atlantic ESU, consistent with all evaluated manatees from northeastern Brazil. Mitochondrial DNA (mtDNA) analysis data also showed the presence of a single haplogroup (a monophyletic group of related haplotypes) on the Brazilian coast (Vianna *et al.*, 2006; Luna, 2013; Lima *et al.*, 2019), evidencing the presence of a unique population of T. *manatus* in Brazil (Luna *et al.*, 2021a).

Considering Tico belongs to Atlantic ESU and is considered 'pure' (non-hybrids with Amazonian manatees), reproduction with Venezuelan (Caribbean ESU) manatees is not recommended. This is due to the long historical divergence between Brazilian and Venezuelan manatees separated by a hybrid zone, supported by mtDNA (Vianna *et al.*, 2006; Santos *et al.*, 2016; Lima *et al.*, 2021), genomic (Vilaça *et al.*, 2019), chromosomal and skull morphology data (Barros *et al.*, 2017).

The reproduction between individuals of the same species, but from genetically distinct and geographically structured populations, can lead to exogamic depression and consequently loss of adaptability to local environmental conditions (Luna *et al.*, 2012). The classification into distinct ESUs is already sufficient for species to be managed singularly from a conservation standpoint (Santos *et al.*, 2016). In the case of the WIMs from Brazil and Venezuela, there is strong evidence that they are from different biological units (subspecies or species) (Furni, 2019), which requires more caution regarding artificially managed reproduction. It is important to emphasize that Tico was an animal kept under human care for many years and that his displacement does not represent a known natural migration route, since there is no evidence of gene flow between WIMs from Brazil and

Venezuela. Although breeding with animals from a different ESU may not lead to deleterious genetic effects in the offspring, it would constitute an unnecessary artificial intervention. This is relevant given the existing conservation challenges facing the species and its subspecies, as well as the ongoing taxonomic uncertainties. If reproduction were to occur in captivity, it would make ex-situ conservation actions from this hybrid offspring unfeasible and genealogical records could become complicated, limiting the exchange of individuals between institutions. It is worth noting that this process would be distinct from the natural and ancient hybridization that occurs between *T. manatus* and *T. inunguis* in the mouth of the Amazon River and the coast of the Guianas, which may extend to Venezuela. This region works as a genetic sink, receiving contribution from animals belonging to the Caribbean ESU and the Atlantic ESU, thereby restricting gene flow between these ESUs. The resulting hybrids from these crosses may possess unique adaptive advantages to this environment influenced by the Amazon River plume (Lima *et al*., 2024).

Being held captive is also not an appropriate fate for Tico because the animal meets the requirements for release. Despite having demonstrated atypical movements, Tico still qualifies for another release attempt, as recommended by the National protocols (Lima *et al*., 2007; Luna *et al*., 2021b). Lima *et al*. (2007) indicated that up to three release attempts can be made before the individual is considered unsuitable for release. There are cases of successful rehabilitated manatees that were released for the second and third time and became adapted to the wild (Normande *et al*., 2015, 2016). Changes in acclimatization, release period, and/or release method could improve the chances of Tico's survival in the wild.

Releasing animals requires monitoring for at least a year to ensure successful readaptation (Luna *et al*., 2021b) and this monitoring necessitates substantial financial and human resources to facilitate field activities, including daily monitoring in the initial months post-release. Obtaining resources for this purpose can be challenging, but AQUASIS already possesses the necessary resources for acclimatizing and releasing the animal, which favours the animal's return to Ceará, Brazil.

Furthermore, Tico's learning experience during his first release may facilitate his readaptation in a second attempt at the same site. The release region in Brazil also features areas with aggregations of manatees, which may facilitate the readaptation process. Despite limited understanding of innate behaviours and the effects of learning and memory on the movement patterns of marine megafauna, there could be a transfer of navigational information among individuals, even in short-term social groups (Hays *et al*., 2016).

According to the Article 1st of Brazilian Institute for the Environment and Renewable Natural Resources (IBAMA) Normative Instruction No. 140/2006 it is possible to institute a request for importing a species of wild fauna that belongs to Brazil in terms of the CITES. Once it has been showed that Tico's displacement was atypical, the Brazilian Ministry of Environment and Climate Change (MMA), in collaboration with members from IBAMA and the Centre of Aquatic Mammals (CMA) – Chico Mendes Institute for Biodiversity Conservation (ICMBio), along with the Venezuelan CITES administrative authority and the Ministry of Ecology, agreed to repatriate Tico. CMA/ICMBio and IBAMA have endorsed a scientific memorandum in favour of Tico's repatriation (IBAMA Technical Note No. 146/2022), but a permit is still pending, and an aircraft is required for transportation.

Conclusion

In conclusion, Tico's journey provides a unique perspective on the behaviour of a rehabilitated manatee in this region, showcasing long-distance movements not previously documented for the species. To better understand the frequency and significance of such behaviour, further analysis, and research are needed. This includes telemetry studies with non-rehabilitated manatees and the integration of temperature and salinity sensors to investigate the impact of small-scale physical processes.

Unfortunately, a single case study like Tico's does not provide definitive conclusions. The animal achieved speeds comparable to those of the NBC, and his trajectory aligns with its vortices, suggesting a potential influence from this ocean current and possibly indicating energy conservation strategies. Analysing multiple unusual long-distance movements and utilizing tools such as the Quasi-Planktonicity Index and Lyapunov exponents (Della Penna *et al*., 2015) will enable researchers to explore the influence of ocean currents and identify potential environmental triggers.

The decision to capture the animal in Venezuela and subsequently administer an enema was crucial for his survival. Several arguments were discussed regarding the benefits of releasing Tico in Brazil. Once back at MMRC, the plan is to transfer him to the acclimatization enclosure and then release Tico back into the same location.

Supplementary Material. The supplementary material for this article can be found at https://doi.org/10.1017/S0025315424000894

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Authors' contributions. C.C.C: Conceptualization, Data Curation, Formal analysis, Investigation, Methodology, Project administration, Visualization, Writing – Original Draft, Writing – Review & Editing; I.S.S: Conceptualization, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – Original Draft, Writing – Review & Editing. L.P.S: Conceptualization, Formal analysis, Methodology, Visualization, Writing – Original Draft, Writing – Review & Editing; K.F.C and V.L.C: Conceptualization, Project administration, Visualization, Writing – Original Draft, Writing – Review & Editing. L.G.P, M.D.A, A.C and J.C.S: Conceptualization, Visualization, Writing – Original Draft, Writing – Review & Editing.

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Declaration of Generative AI and AI-assisted technologies in the writing process. During the preparation of this work the author(s) used Chat-GPT in order to review the first draft of the document. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Data Availability Statement. The code for downloading, processing, and analysing the meteorological and oceanographic data is openly available on Zenodo via Simoes-Sousa (2024). This repository contains all scripts used for data access, processing, analysis, and figure generation to assist users in reproducing the results and adapting the methods for future research. All data used in this study are publicly available, ensuring transparency in the research methodology. In addition, we have archived the specific data subsets and processed data used in our analyses on Zenodo, available via Aquasis and Simoes-Sousa (2024). Detailed information on the data sources is provided below:

1. **Precipitation Data**: The half-hourly precipitation data at a 0.1-degree resolution is sourced from the Multi-satellite Retrievals for GPM (IMERG) (Huffman *et al*., 2019). This dataset is available at NASA GES DISC and can be accessed via this link: https://disc.gsfc.nasa.gov/datasets/GPM_3IMERGDL_06/summary.
2. **Sea Surface Salinity Data**: The 8-day running average Sea Surface Salinity data is obtained from the Soil Moisture Active Passive (SMAP) mission (JPL, 2020 and Fore *et al*., 2016). This dataset is hosted at NASA PODAAC and can be accessed through this link: https://podaac.jpl.nasa.gov/dataset/SMAP_JPL_L3_SSS_CAP_8DAY-RUNNINGMEAN_V5.
3. **Bathymetric Data**: Bathymetric data is provided by the General Bathymetric Chart of the Oceans (GEBCO Compilation Group, 2024). The data is accessible from the GEBCO website at this link: https://www.gebco.net/data_and_products/gridded_bathymetry_data/.
4. **OSCAR Data**: The OSCAR (Ocean Surface Current Analyses Real-time) data were obtained from JPL Physical Oceanography DAAC (PODAAC) and developed by Earth & Space Research (ESR).
5. **NEMO Model Output**: The NEMO model output used in this study is available at https://doi.org/10.48670/moi-00016 (last accessed 23 June 2023).
6. **HYCOM Analysis Data**: The HYCOM analysis data can be accessed at this link: https://www.hycom.org/data/glby0pt08/expt-93pt0.

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