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RESEARCH ARTICLE

REVISED Modelling drift of cold-stunned Kemp's ridley turtles stranding on the Dutch coast [version 2; peer review: 2 approved]

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Abstract

Background

Every few years, juvenile Kemp's ridley turtles (*Lepidochelys kempii*) are stranded on the Dutch coasts. The main population distribution of this critically endangered species primarily inhabits the Gulf of Mexico and the east coast of the United States. This study focuses on five reports from the Netherlands between 2007 and 2022, where juvenile turtles were reported to strand alive during the winter, albeit in a hypothermic state. At ambient ocean temperatures between 10°C and 13°C, Kemp's ridley turtles begin to show an inability to actively swim and remain afloat on the ocean's surface, a condition termed *'cold stunning'*. Understanding their transport in cold-stunned state can help improve the rehabilitation process of stranded turtles.

Methods

Cold-stunned turtles are back-tracked as passive, virtual particles from their stranding location using Lagrangian flow modelling. This study investigates when and where these juvenile turtles cross the threshold temperatures between 10° C and 14° C before stranding by tracking the temperature along the trajectories.

Results

As expected, the simulations show the transport of the cold-stunned turtles via the English Channel. More surprisingly, the analysis

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suggests they likely experience cold-stunning in the southern North Sea region and encounter temperatures below 10°C for only a few days to up to three weeks, and below 12°C for up to a month before stranding.

Conclusions

The estimate of cold-stunned drift duration of the turtles provides additional knowledge about their health status at the time of stranding. Adherence to rehabilitation protocols for Kemp's ridley and post-release monitoring are recommended to improve their long-term survival.

Keywords
Lepidochelys kempii, juvenile sea turtles, critically endangered, cold stunning, Lagrangian modelling, turtles stranding

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REVISED **Amendments from Version 1**

The following major changes were made in the manuscript:

Previous studies investigating strandings of cold-stunned turtles were compared with our method.

We provided rationale behind selecting Kemp's ridley for this study.

The windage analysis has been expanded upon.

Any further responses from the reviewers can be found at the end of the article

1 Introduction

Kemp's ridley turtles (*Lepidochelys kempii*) are the smallest and the most endangered sea turtle species[1]. With 22,341 mature individuals of a single known population and declining numbers over the past three generations, they are critically endangered according to the latest International Union for Conservation of Nature (IUCN) assessment in 2019[2]. The geographic range of Kemp's ridleys primarily extends from the Gulf of Mexico to the east coast of the United States, and nesting sites are predominantly limited to a narrow stretch of 30 km coastline in the western Gulf of Mexico[2,3]. This makes the Kemp's ridley, along with the flatback sea turtle, the sea turtle species with the most geographically restricted distribution[4].

Like other sea turtle species, Kemp's ridley adults spend most time foraging in shallow coastal waters while offsprings move to the pelagic waters within hours of hatching[3,5]. The oceanic stage of young turtles is the least understood stage of most turtle species and is often referred to as *'the lost years'*[6]. Turtle hatchlings are mainly dispersed by ocean currents and likely feed on planktonic prey in fronts and convergence zones[5,7]. Most Kemp's ridleys recruit as juveniles on coasts along the northern Gulf of Mexico and eastern US coast after spending several months to around two years in the open waters[3]. Additionally, juvenile turtles between one and two years of age have also been sporadically reported on coasts along the north-east Atlantic Ocean and Mediterranean Sea[8–14]. In addition to Kemp's ridley turtles, the transatlantic transport of young turtles via gyre followed by the North Atlantic Current or Azores Current is also suggested for leatherback (*Dermochelys coriacea*) and loggerhead (*Caretta caretta*) turtles[5,8,10,15,16].

In a study comparing trajectories of satellite-tagged young turtles and surface drifters, 17 suggested active swimming behaviour for young Kemp's ridleys during the oceanic stage. However, since sea turtles are ectotherms, the ocean's temperature plays a crucial role in different aspects of their life cycle including growth and activity[18]. Kemp's ridley juveniles feeding in the northern Gulf of Mexico and the eastern US coast during spring and summer months are known to perform seasonal southward migration in the fall and winter to avoid cold conditions[19,20]. Those unable to leave the feeding grounds in time often strand and/or die[5,21]. Low temperatures reduce metabolic activity in the turtles, leading to a hypothermic condition termed *'cold stunning'*. In an experimental study[22], Kemp's ridley turtles started sluggishly floating between water temperatures of 10°C and 13°C. Multiple studies since then have observed strandings of alive or dead cold-stunned Kemp's ridley turtles at ocean temperature below 10°C[23–26]. 18 suggested that the duration of exposure to cold conditions is a factor in the survivability of the turtles. Furthermore, due to the effect of flotation, local surface currents, wind and waves, also influence when and where the turtles strand[23,24,26].

Strandings of cold-stunned Kemp's ridley turtles are a yearly phenomenon during the winter along the US east coast[21,23,26]. In the US, juvenile Kemp's ridleys can start stranding within a day of ocean temperature dropping below 10°C, and these cold conditions can last up to a few weeks, causing an increase in stranded turtles count[21,24,25]. The stranding count can vary from a few tens to hundreds of individuals in a year[21,26], with the largest stranding of 1,180 Kemp's ridleys in 2014/2015 at Cape Cod Bay, Massachusetts[3]. Cold conditions in the north-east Atlantic Ocean can also lead to strandings of juveniles in the UK, Ireland, France, Netherlands, and Spain[8,10–13,27,28]. These strandings are, however, comparatively sporadic. A recent study by 29 has raised concern that range expansion caused by global warming can result in the rise of Kemp's ridley strandings. In addition to strandings, Kemp's ridleys also face threats from human activities like habitat destruction, fisheries, oil spills, and illegal harvesting[1,3]. Therefore, it is important to continue efforts to protect these young and endangered turtles and to expand on our understanding of their strandings along the European coastlines.

Cold-stunned stranded turtles are generally found in poor health conditions and rehabilitation programmes play a crucial role in attempts to save these individuals[3,10,30,31], with some individuals known to successfully survive for a few years post-release[32]. Nevertheless, the long-term survival of rescued individuals is still largely unknown for Kemp's ridley turtles[33]. Rehabilitation protocols developed primarily in the US over decades of experience working with stranded turtles, are also referenced in Europe and the UK. However, less rehabilitation experience has been acquired due to a small number of strandings and thus, there has been little validation of these protocols for the European strandings. Additionally, these stranded juvenile turtles in the European waters might have poorer health compared to ones stranded closer to their native habitats in the US, as observed in 28. Rehabilitating and releasing endangered or threatened species like Kemp's ridley sea turtles into the wild may enhance their survival prospects and contribute to species conservation[34], especially in the case of individuals nearing reproductive age. Even though costly, the translocation of rehabilitated Kemp's ridley sea turtles contributes to sea turtle welfare and offers additional benefits such as education, research, and collaboration among various organizations involved in the conservation efforts[33].

This study focuses on the five strandings of cold-stunned Kemp's ridley juveniles that occurred in the Netherlands between 2007 and 2022 and investigates their transport in the cold-stunned state. Since this turtle species is not known to forage in the southern North Sea, it is anticipated that they likely face hypothermic conditions along their occasional drift from the North Atlantic Ocean, which could take multiple months. Specifically, using Lagrangian ocean modelling, the study aims to answer the following questions: *Around which region would Kemp's ridley turtles have encountered critical threshold water temperatures? How long have they drifted in the cold-stunned state before stranding on the Dutch coast?* These questions can assist in estimating the health status of the stranded individuals (e.g., the last time it might have fed).

Previously, pathways of cold-stunned or dead turtles have been studied using different methods like tracking of drift bottles experiment and satellite-tracked drifters released offshore, and forward and backward in time virtual particle simulations using ocean data[26,35,36]. In addition, these studies then analyse environmental factors like temperature, wind, and currents data to interpret the stranding patterns of cold-stunned turtles. Here, we combine these approaches to model the drift of cold-stunned turtles from their observed stranding locations and dates using surface currents, waves, and wind data, along with temperature sampling along the trajectory of virtual particles in a previously unstudied region.

The strandings of juvenile Kemp's ridley turtles in the Netherlands are unique, though rare, as they always stranded alive, unlike loggerhead, green, and leatherback turtles, which arrive at different life stages and are often dead or in various stages of decomposition[10]. This higher survival rate may be attributed to the observed higher tolerance of Kemp's ridleys to lethal temperatures of 5-6.5°C for 20-24 hours compared to loggerhead or green turtles[22]. Secondly, Kemp's ridleys stranding in the Netherlands belong to a single population originating from the Gulf of Mexico[2], while species such as loggerhead turtles, which have multiple subpopulations in the Atlantic Ocean[37], can arrive in the Netherlands from different regions. This conclusion is based on an analysis of loggerhead turtles that stranded in the Netherlands in 2023 and 2024, conducted by the *Gendika B.V.* laboratory in Veendam (Netherlands), using the method described in 38 (unpublished). Although it is not known whether the young Kemp's ridley individuals in the north-east Atlantic Ocean can naturally return to their native grounds as sub-adults or adults[10] and contribute to the future populations, the information acquired can improve the probability of successful rehabilitation of the stranded individuals of this critically endangered species. Only two of the seven Kemp's ridley juveniles recorded to strand in the Netherlands until 2022 survived and were successfully rehabilitated to the Gulf of Mexico[10].

2 Methods

Dutch strandings

Seven strandings of Kemp's ridley turtles have been reported in the Netherlands until 2022[11,12,39]. Two of those strandings took place in December of 1954 and 1970, while the others happened in this century (Table 1). The 2007 stranding location was obtained from 40 and the rest from waarneming.nl, a citizen-science-based online platform where different flora and fauna observations in the Netherlands are curated. These strandings were also confirmed in the literature, with details about turtles' status[10–12]. All the stranded turtles were alive at the time of reporting, which might reflect the accessibility of flat and sandy Dutch beaches from nearby population centres, increasing the likelihood that these turtles were not stranded for long before being found. The curved carapace length notch to tip (CCLn-t) (see Figure 1b in 41) of these individuals was between 20–30 cm[10–12,39] and were identified as juveniles[42].

Ocean model data and simulation set up

Two-dimensional tracking of particles, backward in time from the stranding locations and dates, is performed using the Parcels Lagrangian framework[43]. To simulate the ocean conditions in the stranding years, reanalysis data is used which assimilates observations from satellite and in-situ instruments. Daily mean ocean surface currents that include the effect of tides are obtained from the reanalysis data for the European North West Shelf along with ocean surface temperatures, all available since 1993 at the spatial resolution of 0.111° × 0.067° (~ 7 km)[44]. In addition, the effect of Stokes drift (a net transport in the direction of wave propagation due to surface waves)[45] on the transport of these particles is accounted for using three-hourly data from 46, available since 1980 at ~1.5 km resolution (0.0135° × 0.0303°). Since floating turtles might be partially exposed to the atmospheric wind, the effect of wind on their transport is also investigated[47]. Three-hourly wind at 10 m above sea level is obtained from ERA5 reanalysis data at 0.25° × 0.25° resolution (~17.51 km × 27.83 km, computed at 51° N)[48]. Of the seven known strandings in the Netherlands until 2022, analysis is done for the five strandings since 2007 (see Table 1) for which ocean surface currents data is available.

Table 1. Locations and date for stranded juvenile Kemp's ridley turtles on the Dutch coast used in this study. *Source:* 2007 stranding from 40 and the rest from *waarneming.nl.*

Location	Latitude (°)	Longitude (°)	Date
IJmuiden	52.451733	4.554254	13/01/2007
Westenschouwen	51.7420	3.7578	21/11/2008
Monster	52.0277	4.1591	12/12/2011
Den Helder	52.9627	4.7323	22/12/2014
Westkapelle	51.5242	3.4384	02/12/2021

In the simulations, 10,000 particles are released at the adjacent coastal cell of each stranding location and traced backward in time (Table 1)[49]; an approach also used for tracking marine debris in 50. We assume that the near-shore arrival of the turtles at the stranding location is well approximated using ocean data on currents, tides, waves, and wind; although in reality, fine-scale coastal processes can be quite complex to simulate. The simulations run backward in time from the reported date of stranding for a total of 120 days, using a fourth-order Runga-Kutta advection algorithm with a time-step of 10 minutes. Particles are advected with a combined flow obtained from summing ocean currents, Stokes drift, and windage as a fraction of the 10 m atmospheric wind. Since it is not known to what extent windage affects the juvenile turtles' drift, a sensitivity analysis is done with four settings of windage factor: 0.0% (i.e., no windage), 0.1%, 1.0%, 2.0%, and 3.0%. Similar windage settings have been tested for floating marine debris in 51 and 52. The ocean surface temperature is also sampled along the simulated trajectory. Output particle locations and instantaneous temperatures are stored daily in the output file. With an A-grid ocean data and coastal releases, particles can get stuck on coastlines relatively easily[43]. To avoid particles from getting stuck, an anti-beaching kernel is applied, where if a particle enters a land grid cell, it is pushed back into the water with an arbitrary velocity of 1 m/s resulting in 600 m displacement (with a 10 minute time step) perpendicular to the shoreline[50]. However, particles can still get stuck in regions very close to convoluted coastlines or on small islands; these particles are then marked as beached.

Identifying the cold-stunning event

Due to the flotation of the cold-stunned Kemp's ridley turtles, their movement is simulated as passively drifting virtual particles at the ocean's surface (also suggested in 23 and 26). The most recent event before stranding when the interpolated ocean surface temperature on a particle trajectory drops below a threshold temperature is extracted from its trajectory and marked as a cold-stunning event, similar to the approach used in 26. We assume that turtles can swim above the threshold temperature and hence, their movement cannot be simulated with passive drift. In nature, this switch from active to passive drift is indeed gradual and depends on the health status of the individual turtle; therefore, we examine three threshold temperatures (T_c : 10°C, 12°C and 14°C) in this analysis. Our approach differs from other studies where a single temperature (10.5°C) was selected to consider turtles as cold-stunned[26], or where it was assumed that young turtles in the first year of their drift die if the temperature drops below 10°C[36].

3 Results

The southern North Sea, bounded on the east by the Dutch coastline, is predominantly a shallow sea (depth less than 100 m). The flow in this region is influenced largely by tides and seasonal winds. In winter, the average ocean temperature in the southern North Sea can reach below 10°C (Figure 1), creating conditions for cold stunning and potential strandings of juvenile Kemp's ridley turtles present in this region. Due to the sea surface temperature of 8–9°C to the east of the United Kingdom, it is unlikely that the turtles could have survived the transport from the north. Relatively higher temperatures are observed south of the Strait of Dover due to the transport of subtropical heat via the Gulf Stream and North Atlantic Current. In particular, the lowest temperatures in the southern North Sea are observed along the coastlines and the effect of influx of warmer water from the North Atlantic Current is visible away from the coasts. In addition, ocean currents, Stokes drift, and wind are predominantly south-westerly in December (Figure 1). As can be seen in the animations[53], these environmental factors result in the transport of passive particles via the English Channel and through the Strait of Dover, before stranding on the Dutch coast. However, since turtles that are not cold-stunned are active swimmers, we focus on their transport once the ocean surface temperatures along the trajectories drop below selected critical thresholds.

Simulations without windage

In the simulations due to currents and Stokes drift only (i.e., with a windage of 0.0%), particle trajectories always drop below threshold temperatures (T_c) of 10°, 12°and 14°C within the southern North Sea region (Figure 2) except the stranding at IJmuiden, where particles experienced temperatures below 14°C even before crossing the English Channel (Figure 2a). As expected, the distance from the stranding location decreases as the lower thresholds are crossed (Figure 2). The continuous - and in the case of the strandings at Monster and Westkapelle steep - decrease in ocean surface temperature along the trajectories as particles approach the stranding location can also be observed in the temperature time series (Figure 3a–e *(left)*).

In most cases, stranding occurred once the T_c = 10°C threshold was crossed by particles. For IJmuiden, Monster, and Den Helder, temperatures of approximately 8°C were experienced by particles a few days before strandings (Figure 3a,c,d). However, for the stranding at Westenschouwen, the ocean surface temperature along the trajectories never dropped below T_c = 10°C (Figure 3b *(left)*). Most particles crossed the lowest T_c = 10°C a few days (Monster and Westkapelle) to almost two weeks (IJmuiden and Den Helder) before stranding (Figure 3a,c–e *(right)*). Particles crossed T_c = 12°C approximately a few days to a month before stranding. Finally, particles crossed T_c = 14°C three to six weeks before stranding.

Simulations with windage

Simulations from all the stranding locations are combined to investigate the additional effect of four different percentages of 10 m atmospheric wind on the transport of particles: 0.1%, 1.0%, 2.0%, and 3.0%. For each windage setting across all the strandings, the time and distance between cold-stunning and stranding increases with the T_c ; a similar trend to the case without windage (Figure 4). For the particles that cross the T_c = 10°C threshold, the mean time between

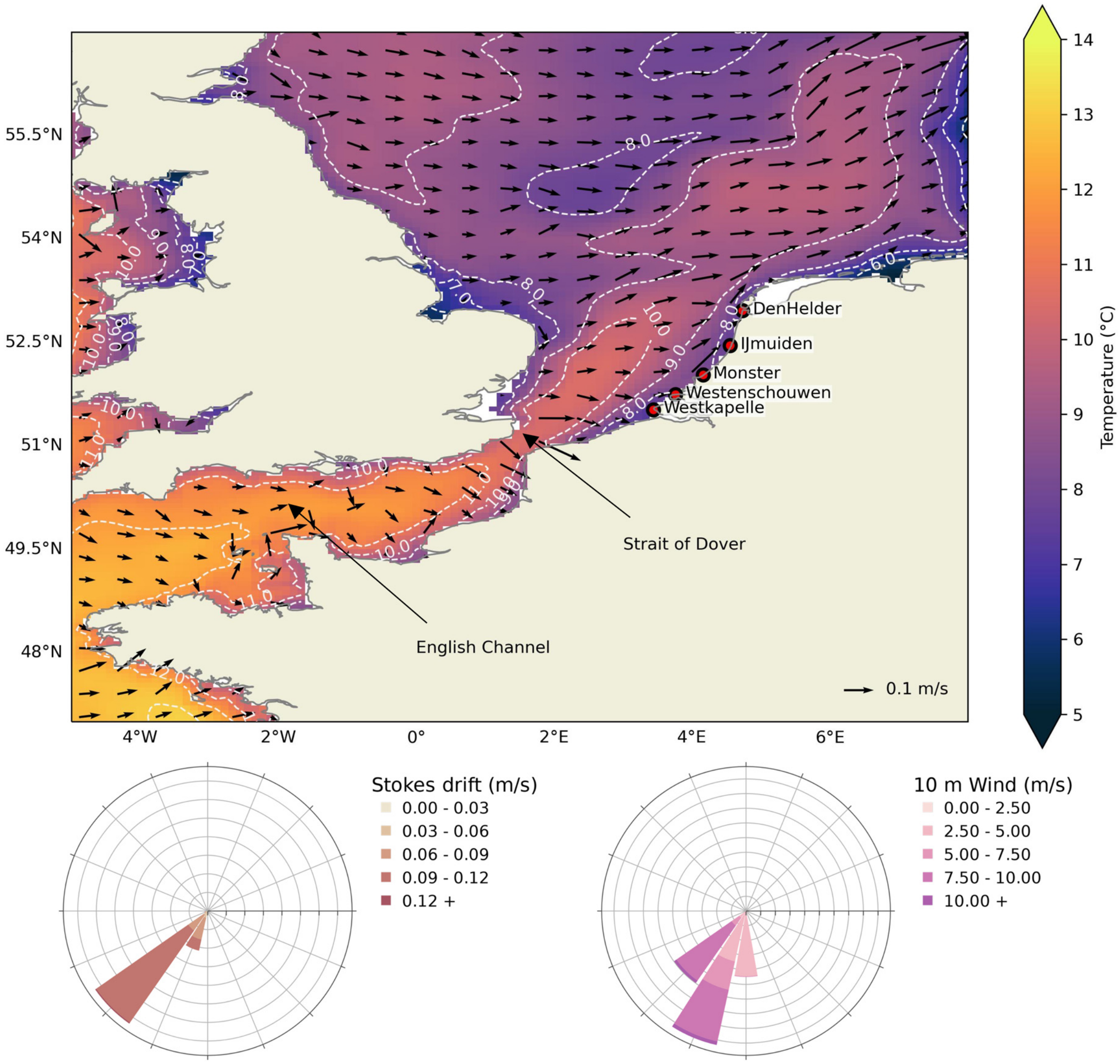

Figure 1. Study region of the European Northwest Shelf. *top:* Mean surface currents *(arrows)* and temperature *(colormap)* for the December months of years 2006, 2008, 2011, 2014, and 2021[44] close to the stranding dates of Kemp's ridley turtles in the Netherlands, and stranding locations are also marked with *red circles* (Table 1). The *dashed* lines show the temperature contour. *bottom:* Wind-rose diagrams show the mean Stokes drift *(left)* and 10 m wind *(right)* for the same months and for the region shown here. Land and coastlines are obtained from python package *cartopy*[54].

cold-stunning and stranding varies marginally with increasing windage and ranges between 5.4 and 6.9 days (Figure 4a). In addition, the mean distance of the stranding location from the cold-stunning locations shows an increase from 71.4 to 117.1 km with increasing windage (Figure 4d). In the Westenschouwen stranding, particles did not cross the T_c = 10°C threshold for any windage setting (see Figure3b *(left)*), therefore they were excluded from the statistics in Figure 4a,d. At the higher T_c = 12°C threshold, the time between cold-stunning and stranding shows a small decrease in the mean from 17.7 to 12.4 days for increasing windage (Figure 4b), while it marginally varies for T_c = 14°C (Figure 4c), similar to T_c = 10°C. The mean distance from the stranding location increased with windage from 115.8 to 283.1 km and from 229.7 to 377.5 km for T_c = 12°C and 14°C, respectively, and was considerably for higher windage of 2.0% and 3.0% (Figure 4e,f). Similar to Figure 4, a summary of the windage effect on cold-stunning events for each stranding location is provided in Supplementary Information[53].

Ideally, particles should cross the threshold temperatures faster as the windage increases due to stronger drift, but no clear signature is observed in Figure 4a-c. This can be explained

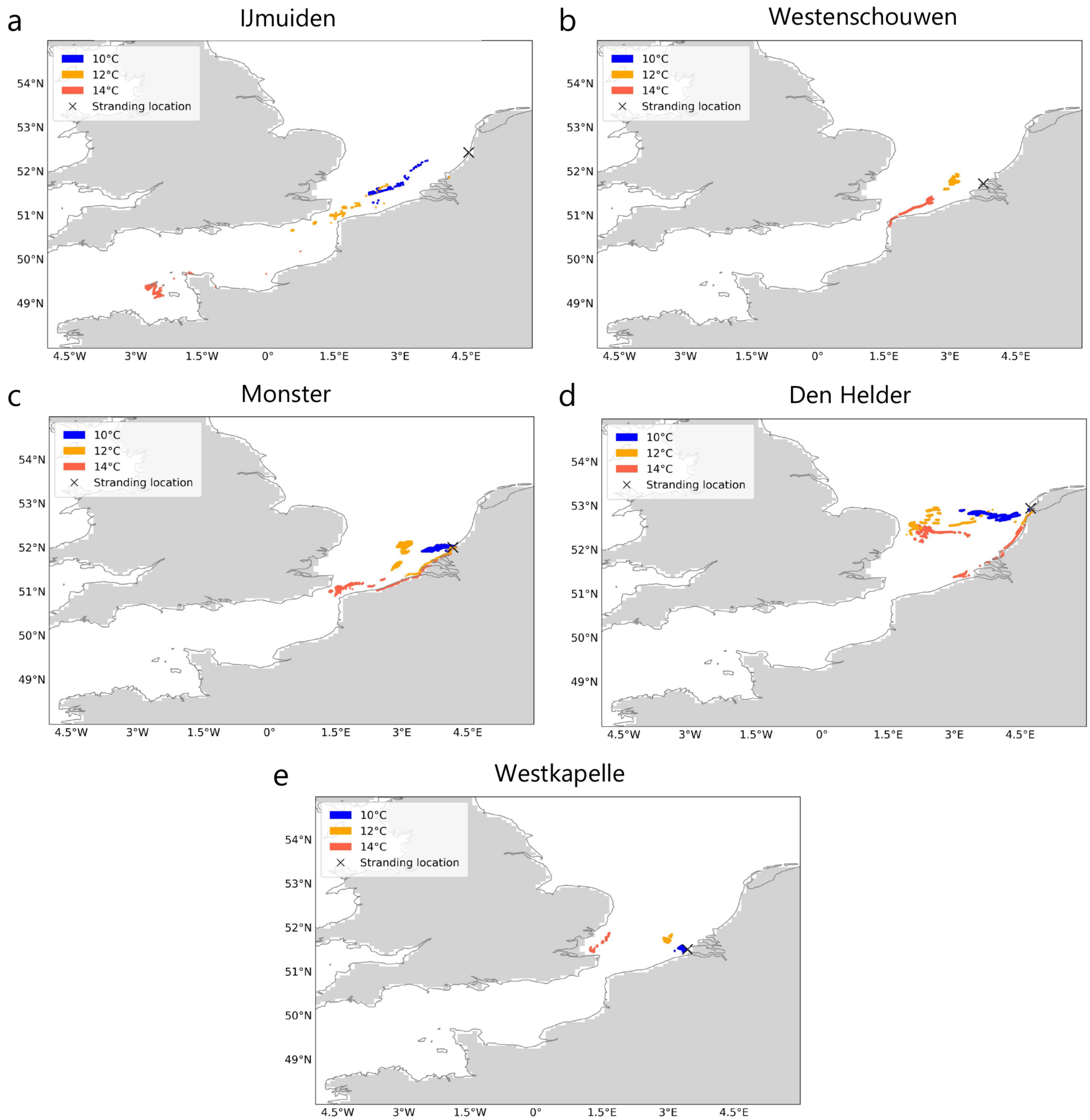

Figure 2. Locations where threshold temperatures were crossed before stranding. For five recent Kemp's ridley strandings in the Netherlands between 2007 and 2022 (**A**–**E**), locations where threshold ocean surface temperatures (T_c : 10°, 12° and 14° C) were crossed by particles during Lagrangian simulations with currents and Stokes drift only (i.e., no windage) are shown. Stranding locations are marked for reference. The land mask is obtained from the ocean model[44] and coastlines from python package *cartopy*[54]. The animations of the back-tracked particles are provided in 53.

by the variable effect of windage on cold-stunning events with different temperature thresholds even for the individual strandings[53]. For example, a clear decrease in time is visible for the IJmuiden stranding from 9.8 to 2.3 days in case of T_c = 10°C, while it is variable for T_c = 12°C and 14°C. For the same stranding, we also observe that the distribution of particle distance did not increase linearly with increasing windage for different temperature thresholds. We speculate that this variability results from the differences in the hydrodynamics of the study region over different stranding

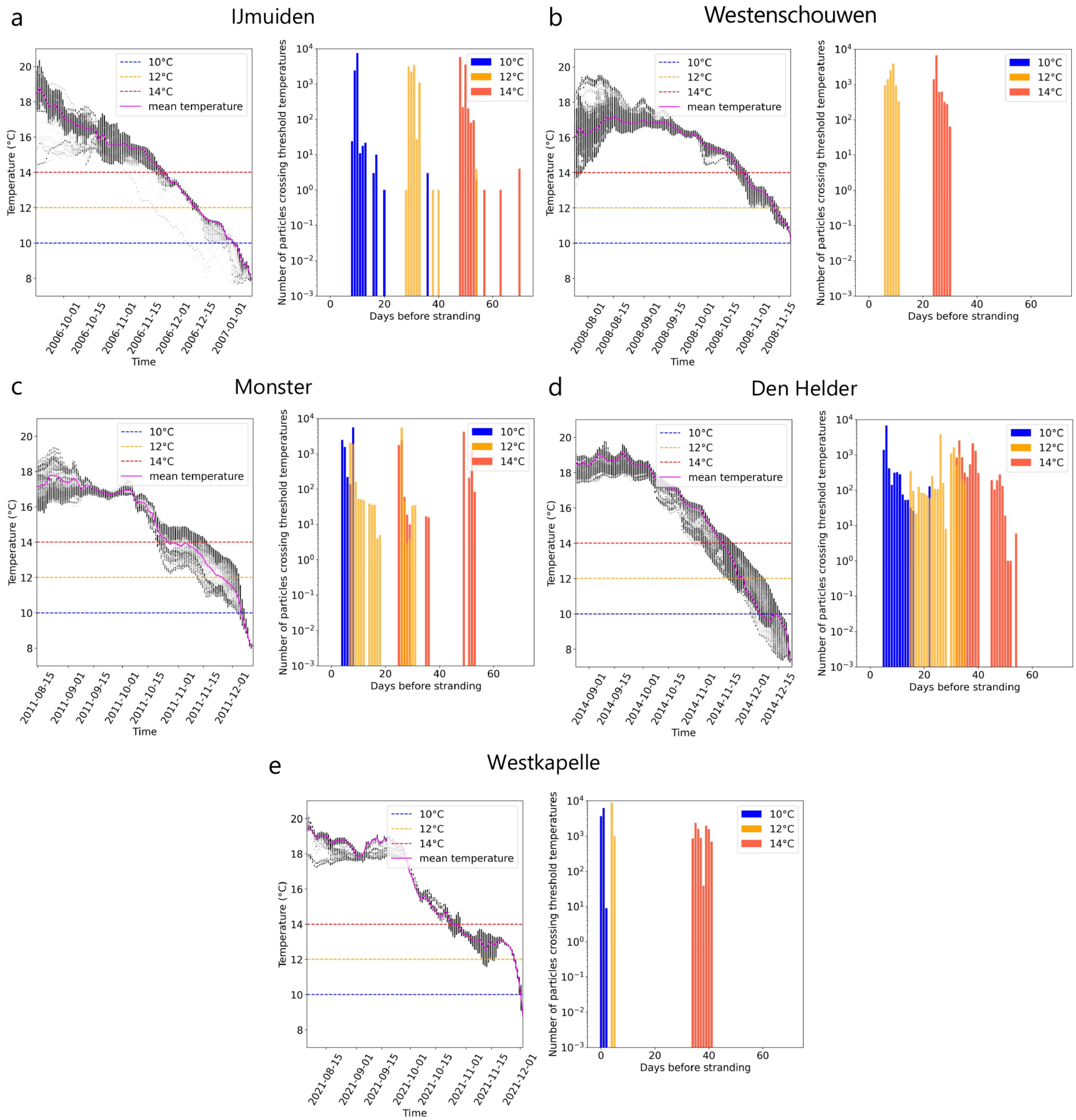

Figure 3. Days before stranding when threshold temperatures were crossed. For five recent Kemp's ridley strandings in the Netherlands between 2007 and 2022 (**A**–**E**), *(left)* the temperature distribution of all drifting particles *(black dots)* and temperature mean *(pink line)* over time before arriving at the stranding location using Lagrangian simulations with currents and Stokes drift only (i.e., no windage) are shown. Critical threshold temperatures analysed in this study (T_c: 10°, 12° and 14° C) are marked for reference *(dashed line)*. *(right)* Number of particles crossing threshold temperatures for the last time before stranding.

years. Note that the fraction of particles that crossed a certain T_c also decreases with high windage at higher T_c (see Figure 4). This can be primarily attributed to the increasing number of beached particles in the complex coastal regions and islands in the simulations: ~2–4% and ~50% of n = 50, 000 particles beached at low and high windage, respectively. High windage (in addition to currents and Stokes drift) can transport particles further into the land which cannot be successfully displaced to the sea by the anti-beaching kernel. In the case of the strandings at Monster

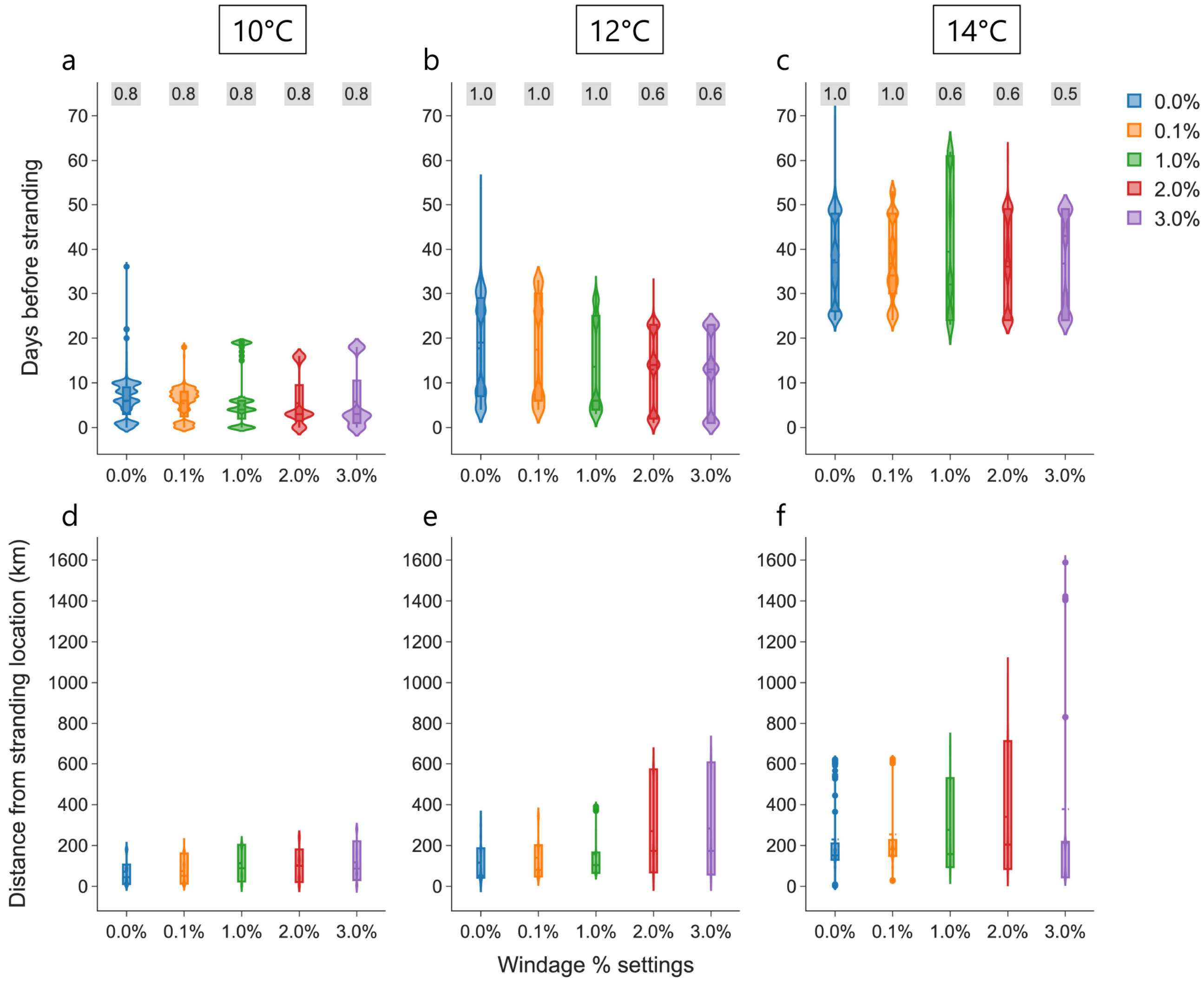

Figure 4. Effect of windage settings. Violin plots of days before stranding (**a**–**c**) and distance of each particle from the respective stranding locations (**e**–**f**) when a threshold temperature is crossed under the influence of currents, Stokes drift and different windage settings (0.0%, 0.1%, 1.0%, 2.0%, and 3.0%) considered in the analysis is shown. The text in *grey* box on top represents the proportion of total number of particles (n = 50,000) crossing the threshold at a windage setting.

and Westkapelle with 2.0–3.0% windage, particles originating from the UK coast with low ocean temperatures arrived at the stranding locations within a few days, without encountering temperatures above 10°C (see the animations and analysis output in 53).

4 Discussion

In all the seven historical strandings on the Dutch coast until 2022, juvenile Kemp's ridley turtles were found alive at the time of reporting. However, only two turtles could be successfully rehabilitated and released in the Gulf of Mexico, while the others didn't survive for more than a few days[10–12,39]. The initial condition of the turtle at the time of stranding, the first response by observers, and the time lag in arriving at a rehabilitation facility add to the complexity of implementing rehabilitation protocols, particularly in locations far from their native habitat, where such occurrences are rare[10]. While the role of wind and waves is suggested for the drift of floating cold-stunned turtles[23,24,26], we are the first to use Lagrangian simulations to model their backward in time drift with the surface currents including the effect of tides, waves, and wind from the stranding location along with temperature sampling to study the five recent Kemp's ridley strandings in the Netherlands. Although we focus only on Kemp's ridleys, we encourage the use of this method for strandings of other turtle species and/or regions, considering their species- and age-specific thermal constraints[22].

We show that turtles might have continuously encountered ocean surface temperatures below 14°C from locations most likely in the southern North Sea and up to the English Channel (Figure 2). As previously noted in 10, these simulations further support the notion of Kemp's ridley juvenile turtles reaching the North Sea via the English Channel. For the stranding at Westenschouwen in November 2008, it was observed that the juvenile Kemp's ridley turtle might not have faced temperatures below 10°C indicating that temperatures between 10–12°C can also result in stranding. Differences in physiological conditions can also be responsible for stranding in this case but its analysis is beyond the scope of this study.

The decreasing distance from the stranding location and temperature as particles approached the stranding location (Figure 2 and Figure 3) indicates that if the turtles start developing symptoms of cold stunning at 14°C, they are likely to face even lower temperatures, which could deteriorate their condition even more. Hence, turtles are unable to escape from the southern North Sea region to the relatively warmer Atlantic waters (Figure 1). For each threshold temperature and all the strandings, increasing windage values resulted in an increase in distance; however, it did not have much effect on the time between cold-stunning and stranding (Figure 4). This timescale between crossing the threshold temperatures and the stranding on the Dutch coast varied in different stranding events from (i) a day to three weeks for T_c = 10°C, (ii) a few days to a month for T_c = 12°C, and (iii) three weeks to two months for T_c = 14°C. We note that minimum temperatures of approximately 8°C were sampled in the simulations, as also indicated in the mean temperature field shown in Figure 1. Hence, lethal temperatures (5-6.5°C)[22] were not encountered by particles across all the windage scenarios, and low metabolism in cold temperatures[18] might explain how these turtles survived this transport over several days. However, it is unclear how long juvenile turtles can endure these conditions in the natural environment.

The possible timescales of turtles drifting in a cold-stunned state for a few days to two to three weeks (below 10°C) might indicate similar physiological conditions to those in multiple strandings reported within a day to up to a few weeks of temperatures between 8° and 11°C in the east US coast, e.g. as observed in 24 and 25. This suggests similar protocol requirements for the rehabilitation of Kemp's ridley turtles in the Netherlands. Therefore, it is recommended that rehabilitation protocols are adequately implemented and individuals are further tracked upon release to assess the long-term impact of rehabilitation[32,33,55]. For future strandings, the approach used in this study can even be applied to obtain real-time insights on the individual's history in the cold-stunned state and accordingly take necessary steps for rehabilitation. Post-rehabilitation, the released turtles can be monitored for movement, feeding, diving, and interaction behaviour with other turtles, when equipped with satellite transmitters[34,55]. In addition, these rehabilitation opportunities should be used to raise awareness about threats faced by wild species and, educate and engage the local public towards collaborative conservation efforts[33].

Even though Kemp's ridley juveniles are known to forage in the northeast Atlantic Ocean[28,55], their transport into the North Sea is considered an occasional drift[10]. Additional research could investigate the seasonal food availability in the southern North Sea to assess if these turtles were possibly feeding in this region before the onset of winter. This is particularly relevant for assessing changes in species distribution due to a warming climate[56] and is likely to impact cold-stunning-induced strandings[29]. Furthermore, it remains to be investigated if conclusions drawn from this study also apply to juvenile Kemp's ridley strandings on other western European coasts.

Ethics and consent

Ethical approval and consent were not required.

Data and software availability

Source data

The Copernicus Marine Service ocean data used in this study can be downloaded from https://doi.org/10.48670/moi-00059[44] and https://doi.org/10.48670/moi-00060[46]. The ERA 5 wind data can be downloaded from https://doi.org/10.24381/cds.adbb2d47[48].

Underlying data

Data publication platform of Utrecht University: kemps_ridleys_dutch_strandings. https://doi.org/10.24416/UU01-6NPX5Y[53].

This project contains the following underlying data:

- File **simulation_output_files.zip**:Simulation outputs for different windage setting analysed in this study. Windage settings: 0.0%, 0.1%, 1.0%, 2.0% and 3.0% are abbreviated as 0pWind, 01pWind, 1pWind, 2pWind and 3pWind, respectively. Same structure is used in the folders below.
- Folder **animations/xpWind**: Animations of simulations are available in this folder within subfolders of each windage setting.
- Folders **analysis/xpWind**: Analysis of cold stunning event for each particle per simulation are available in subfolders for each windage setting.
- Folder **analysis/windage_effect_per_station**: Effect of each windage setting on the extracted cold stunning event is shown for each station.

Extended data

Analysis code available from: https://github.com/OceanParcels/Kempsridley_turtle_strandings

Archived analysis code at time of publication: https://zenodo.org/doi/10.5281/zenodo.10450425[49]

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Open Peer Review

Current Peer Review Status: ✔ ✔

Version 2

Reviewer Report 20 September 2024

https://doi.org/10.21956/openreseurope.19879.r42948

✔ **Lesley Stokes**
Southeast Fisheries Science Center,, NOAA/National Marine Fisheries Service,, Miami,, Florida,, USA

The authors have addressed all relevant feedback, and the manuscript is ready for acceptance.

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: sea turtle biology

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Reviewer Report 27 August 2024

https://doi.org/10.21956/openreseurope.19879.r42949

✔ **Casper Van de Geer**
Centre for Ecology and Conservation, University of Exeter (Ringgold ID: 151752), Penryn, Cornwall, UK

The authors have addressed feedback to where the paper is ready for acceptance.

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Sea turtle ecology and conservation

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Version 1

Reviewer Report 28 June 2024

https://doi.org/10.21956/openreseurope.18278.r41256

?

Casper Van de Geer
Centre for Ecology and Conservation, University of Exeter (Ringgold ID: 151752), Penryn, Cornwall, UK

Overall:
An interesting paper that investigates strandings of a critically endangered species of sea turtle, Kemp's ridley (Lk), a long way from their usual range.

It would be good to know why the authors chose to only look at Kemp's ridley turtles (Lk), when there are also strandings data from other species, e.g., loggerhead turtles (as seen on waarneming.nl).

Certain parts of the paper could use some copyediting.

Abstract:
Consider editing the Background section of the Abstract to (1) remove repetition that there are Lk strandings on the Dutch coast and (2) clarify how your research could help improve the rehabilitation process.

Introduction:
Suggest indicating the year of the population estimate cited in text.

Methods:
Were the data from waarneming.nl or from literature sources 10-12 and 35? Are the strandings reported in these literature sources captured in the waarneming.nl database? If so, then a brief recognition of the usefulness of waarneming.nl will suffice and this paragraph can be made clearer and shorter.

CCL stands for "curved carapace length", please correct the mistake in the definition. Also please specify what type of CCL was taken. If this is unknown, please note that in the text.
For reference, please see: Bolten AB (1999)

Please report resolutions of data that were used in both degrees and kilometers, for ease of interpretation.

Section “Defining cold stunning events” contains information that should be, or already is, in the introduction. This section can be made shorter and merged with the previous methods section.

Python package “cartopy” is used, so it should be added to the references. The same goes for other analysis software that was used.

I am not familiar with the technicalities of Lagrangian modelling and as such cannot comment on whether the methods used are appropriate.

Results:
In the discussion, the authors note that the magnitude of windage did “not have much effect on the time between cold-stunning and stranding.” Can a statistical test be done to investigate where the magnitude becomes a significant factor?

Discussion:
Please check statements are underpinned with literature. For instance, the last sentence of the second paragraph should be supported by findings from other studies.

The authors mention that individuals should be monitored post-release to assess survival rates and possible contribution to the Lk population, which is a point well-made. However, this is not further elaborated in the paper.

Comparison to other similar studies would be beneficial, especially to compare methods. For instance: Hart et al. (2006)
Figures:
Figure 1: suggest making the place markers (red dots) more clear. Perhaps change to something more colour-blind friendly (I am colour blind) or add black outline to the dots.
Also suggest adding reference to the animated particles in the legend.

References
1. Hart K, Mooreside P, Crowder L: Interpreting the spatio-temporal patterns of sea turtle strandings: Going with the flow. *Biological Conservation*. 2006; **129** (2): 283-290 Publisher Full Text
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Is the work clearly and accurately presented and does it cite the current literature?
Partly

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?

I cannot comment. A qualified statistician is required.

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Sea turtle ecology and conservation

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 02 Jul 2024
Darshika Manral

Thank you for your review comments. I am on a research cruise currently and will take at least 3-4 weeks to respond with the next version.

Competing Interests: No competing interests were disclosed.

Author Response 05 Aug 2024
Darshika Manral

Dear Reviewer, We thank you for your feedbacks on the manuscript. They were of great help in improving the manuscript. We have submitted the updated manuscript along with responses to each comment given below. Please note some additonal changes that have been made:

- Throughout: We clarify that we are investigating Kemp's rdidley strandings only until 2022.
- In the conclusion: We have added a statement to emphasize on the need for understanding changes to species distribution.
  "Additional research could investigate the seasonal food availability in the southern North Sea to assess if these turtles were possibly feeding in this region prior to the onset of winter. This is particularly relevant for assessing changes in the species distribution with a warming climate[52] and is likely to imapct cold-stunning induced strandings[29]."
- Grammar corrections and some sentences have been reformed for clarity

We look forward to your further comments. Best regards, Darshika Manral and co-authors
Overall:
An interesting paper that investigates strandings of a critically endangered species of sea turtle, Kemp's ridley (Lk), a long way from their usual range.

It would be good to know why the authors chose to only look at Kemp's ridley turtles (Lk), when there are also strandings data from other species, e.g., loggerhead turtles (as seen on waarneming.nl).

Certain parts of the paper could use some copyediting.

Response: We have addressed the point on choice of turtle species in the introduction (last paragraph): "The strandings of juvenile Kemp's ridley turtles in the Netherlands are unique, though rare, as they always stranded alive, unlike loggerhead, green, and leatherback turtles, which arrive at different life stages and are often dead or in various stages of decomposition [10]. This higher survival rate may be attributed to the observed higher tolerance of Kemp's ridleys to lethal temperatures of 5-6.5°C for 20-24 hours compared to loggerhead or green turtles [22]. Secondly, Kemp's ridleys stranding in the Netherlands belong to a single population originating from the Gulf of Mexico [2], while species such as loggerhead turtles, which have multiple subpopulations in the Atlantic Ocean [54], can arrive in the Netherlands from different regions. This conclusion is based on an analysis of loggerhead turtles that stranded in the Netherlands in 2023 and 2024, conducted by the Gendika B.V. laboratory in Veendam (Netherlands), using the method described in 56 (unpublished)."

Abstract:

Consider editing the Background section of the Abstract to (1) remove repetition that there are Lk strandings on the Dutch coast and (2) clarify how your research could help improve the rehabilitation process.

Response: We have updated the abstract where we removed some of the repetitions. For the second point we added the following sentence: "The estimate of cold-stunned drift duration of the turtles provides additional knowledge about their health status at the time of stranding." **Introduction:**

Suggest indicating the year of the population estimate cited in text.

Response: We have updated the text: "With 22,341 mature individuals of a single known population and declining numbers over the past three generations, they are critically endangered according to the latest International Union for Conservation of Nature (IUCN) assessment in 2019 [2]."

Methods:

Were the data from waarneming.nl or from literature sources 10-12 and 35? Are the strandings reported in these literature sources captured in the waarneming.nl database? If so, then a brief recognition of the usefulness of waarneming.nl will suffice and this paragraph can be made clearer and shorter.

Response: Some clarifications have been made to the sources and the paragraph has been edited: "Seven strandings of Kemp's ridley turtles have been reported in the Netherlands until 2022 [11, 12, 35]. Two of those strandings took place in December of 1954 and 1970, while the others happened in this century (Table 1). The 2007 stranding location was obtained from 53 and the rest from waarneming.nl, a citizen-science-based online platform where different flora and fauna observations in the Netherlands are curated. These strandings were also confirmed in the literature, with details about turtles' status[10–12]. All the stranded turtles were alive at the time of reporting, which might reflect the accessibility of flat and sandy Dutch beaches from nearby population centers, increasing the likelihood that these turtles were not stranded for long before being found."

CCL stands for "curved carapace length", please correct the mistake in the definition. Also

please specify what type of CCL was taken. If this is unknown, please note that in the text. For reference, please see: Bolten AB (1999)
Response: The text has been updated to: The curved carapace length notch to tip (CCLn-t) (see Figure 1b in 55) of these individuals was between 20–30 cm [10–12, 35] and were identified as juveniles [36].
Please report resolutions of data that were used in both degrees and kilometers, for ease of interpretation.
Response: The text has been updated: "Daily mean ocean surface currents that include the effect of tides are obtained from the reanalysis data for the European North West Shelf along with ocean surface temperatures, all available since 1993 at the spatial resolution of 0.111° × 0.067° (~ 7 km) [38]. In addition, the effect of Stokes drift (a net transport in the direction of wave propagation due to surface waves) [39] on the transport of these particles is accounted for using three-hourly data from 40, available since 1980 at ~1.5 km resolution (0.0135° × 0.0303°). Since floating turtles might be partially exposed to the atmospheric wind, the effect of wind on their transport is also investigated [41]. Three-hourly wind at 10 m above sea level is obtained from ERA5 reanalysis data at 0.25° × 0.25° resolution (~17.51 km × 27.83 km, computed at 51° N) [42]." Section "Defining cold stunning events" contains information that should be, or already is, in the introduction. This section can be made shorter and merged with the previous methods section.
Response: The repetitive part has been removed. However, we would like to keep the remaining text in a separate subsection as it highlights a key aspect of our analysis: selected temperature thresholds. The updated paragraph is as follows: "**Extracting the cold-stunning event** Due to the floating behaviour of the cold-stunned Kemp's ridley turtles, their movement is simulated as passively drifting virtual particles at the ocean's surface (also suggested in 23 and 26). The most recent event before stranding when the interpolated ocean surface temperature on a particle trajectory drops below a threshold temperature is extracted from its trajectory and marked as a cold-stunning event, similar to the approach used in 26. We assume that turtles can swim above the threshold temperature and hence, their movement cannot be simulated with passive drift. In nature, this switch from active to passive drift is indeed gradual and depends on the health status of the individual turtle; therefore, we examine three threshold temperatures (T_c : 10°C, 12°C and 14°C) in this analysis. Our approach differs from other studies where a single temperature (10.5°C) was selected to consider turtles as cold-stunned [26], or where it was assumed that young turtles in the first year of their drift die if the temperature drops below 10°C [51]." Python package "cartopy" is used, so it should be added to the references. The same goes for other analysis software that was used. **Response:** cartopy citation is now added at #49 and is referenced in Figure 1 and 2. The updated text is as follows: "The land mask is obtained from the ocean model [38] and coastlines from python package cartopy [49]. " Reference for Parcels framework is already available at #37.

I am not familiar with the technicalities of Lagrangian modelling and as such cannot comment on whether the methods used are appropriate.
<u>**Results:**</u>
In the discussion, the authors note that the magnitude of windage did "not have much effect on the time between cold-stunning and stranding." Can a statistical test be done to investigate where the magnitude becomes a significant factor?
Response: The selected range of windage used in our study is more practical for our use-

case here, therefore, we don't think we should test for higher windages. Higher percentages of 4-5% are used for buoys or robust empty bottles like objects (reference-45,46 in the manuscript). Instead, we have improved the description of the results elaborating on the wingage effects: "Simulations from all the stranding locations are combined to investigate the additional effect of four different percentages of 10 m atmospheric wind on the transport of particles: 0.1%, 1.0%, 2.0%, and 3.0%. For each windage setting across all the strandings, the time and distance between cold-stunning and stranding increases with the T_c; a similar trend to the case without windage (Figure 4). For the particles that cross the T_c = 10°C threshold, the mean time between cold-stunning and stranding varies marginally with increasing windage and ranges between 5.4 and 6.9 days (Figure 4a). In addition, the mean distance of the stranding location from the cold-stunning locations shows an increase from 71.4 to 117.1 km with increasing windage (Figure 4d). In the Westenschouwen stranding, particles did not cross the T_c = 10°C threshold for any windage setting (see Figure3b (left)), therefore they were excluded from the statistics in Figure 4a,d. At the higher T_c = 12°C threshold, the time between cold-stunning and stranding shows a small decrease in the mean from 17.7 to 12.4 days for increasing windage (Figure 4b), while it marginally varies for T_c = 14°C (Figure 4c), similar to T_c = 10°C. The mean distance from the stranding location increased with windage from 115.8 to 283.1 km and from 229.7 to 377.5 km for T_c = 12°C and 14°C, respectively, and was considerably for higher windage of 2.0% and 3.0% (Figure 4e,f). Similar to Figure 4, a summary of the windage effect on cold-stunning events for each stranding location is provided in Supplementary Information [47]. Ideally, particles should cross the threshold temperatures faster as the windage increases due to stronger drift, but no clear signature is observed in Figure 4a-c. This can be explained by the variable effect of windage on cold-stunning events with different temperature thresholds even for the individual strandings [47]. For example, a clear decrease in time is visible for the IJmuiden stranding from 9.8 to 2.3 days in case of T_c = 10°C, while it is variable for T_c = 12°C and 14°C. For the same stranding, we also observe that the distribution of particle distance did not increase linearly with increasing windage for different temperature thresholds. We speculate that this variability results from the differences in the hydrodynamics of the study region over different stranding years.

Discussion:

Please check statements are underpinned with literature. For instance, the last sentence of the second paragraph should be supported by findings from other studies.

Response: Reference(#18) has been added.

The authors mention that individuals should be monitored post-release to assess survival rates and possible contribution to the Lk population, which is a point well-made. However, this is not further elaborated in the paper.

Response: The following text has been added: "Post-rehabilitation, the released turtles can be monitored for movement, feeding, diving, and interaction behaviour with other turtles, when equipped with satellite transmitters [34, 48]."

Comparison to other similar studies would be beneficial, especially to compare methods. For instance: Hart et al. (2006)

Response: We have compared our method to other studies including Hart et al. (2006)

(references- 50, 26, 51) in the introduction: "Previously, pathways of cold-stunned or dead turtles have been studied using different methods like tracking of drift bottles experiment and satellite-tracked drifters released offshore, and forward and backward in time virtual particle simulations using ocean data [50, 26,51]. In addition, these studies then analyse environmental factors like temperature, wind, and currents data to interpret the stranding patterns of cold-stunned turtles. Here, we combine these approaches to model the drift of cold-stunned turtles from their observed stranding locations and dates using surface currents, waves, and wind data, along with temperature sampling along the trajectory of virtual particles in a previously unstudied region."

Figures:

Figure 1: suggest making the place markers (red dots) more clear. Perhaps change to something more colour-blind friendly (I am colour blind) or add black outline to the dots.

Response: Updated the Figure with black edges to the markers. Also suggest adding reference to the animated particles in the legend.

Response: We have added the following sentence to the caption of Figure 2: "The animations of the back-tracked particles are provided in 47."

Competing Interests: No competing interests were disclosed.

Reviewer Report 28 May 2024

https://doi.org/10.21956/openreseurope.18278.r39323

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Lesley Stokes
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Introduction: One comment is in reference to the line: "In order to enhance the survival prospects of endangered and threatened species like Kemp's ridley sea turtles, it is crucial to have every individual, particularly those nearing reproductive age, released back into the wild to maximize the potential for species preservation." We don't have evidence that rehabilitation of a relatively few number of stranded individuals will make a difference at a population level, so this statement may be controversial. I suggest a less definitive tone, stating that releasing individuals, particularly those nearing reproductive age, may be beneficial for species preservation, but not going so far as to suggest that it is crucial to have every individual rehabilitated and released. The last line in the paragraph addressing sea turtle welfare and outreach is a much stronger supporting argument for the expense and effort of rehabilitation.

Discussion: It may not be appropriate to say "However, only two... raising questions about the shortcomings in rehabilitation protocols or their adequate implementation." There are many factors that could influence whether a turtle was successfully rehabilitated and transported back to the native habitat (a major undertaking). The condition of the turtle at stranding is the most critical component, as the best rehabilitative care cannot overcome some cases where the turtle was in very poor condition at intake. No information was given about the reasons that the other 5 turtles were not successfully released. Did they die in rehabilitation? Were they kept as unreleasable permanent residents due to logistical constraints preventing release back to the Gulf of Mexico? Was there not a facility with the resources or knowledge to properly care for the turtles? A bit of context would make this a stronger section if you want to bring up shortcomings in the protocols, even just to introduce these factors influencing rehabilitation success and note that further description is beyond the scope of this manuscript.

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
I cannot comment. A qualified statistician is required.

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: sea turtle biology

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 02 Jul 2024

Darshika Manral

Thank you for your review remarks. We will incorporate the suggested changes in the next version.

Competing Interests: No competing interests were disclosed.

Author Response 05 Aug 2024

Darshika Manral

Dear Reviewer, We thank you for your feedbacks on the manuscript. They were of great help in improving the manuscript. We have submitted the updated version along with responses to each comment given below. Please note some additonal changes that have been made:

- Throughout: We clarify that we are investigating Kemp's rdidley strandings only until 2022.
- In the conclusion: We have added a statement to emphasize on the need for understanding changes to species distribution.
  "Additional research could investigate the seasonal food availability in the southern North Sea to assess if these turtles were possibly feeding in this region prior to the onset of winter*. This is particularly relevant for assessing changes in the species distribution with a warming climate*[52] *and is likely to imapct cold-stunning induced strandings*[29]."
- Grammar corrections and some sentences have been reformed for clarity

We look forward to your further comments. Best regards, Darshika Manral and co-authors
Comment 1 Introduction: One comment is in reference to the line: *"In order to enhance the survival prospects of endangered and threatened species like Kemp's ridley sea turtles, it is crucial to have every individual, particularly those nearing reproductive age, released back into the wild to maximize the potential for species preservation."* We don't have evidence that rehabilitation of a relatively few number of stranded individuals will make a difference at a population level, so this statement may be controversial. I suggest a less definitive tone, stating that releasing individuals, particularly those nearing reproductive age, may be beneficial for species preservation, but not going so far as to suggest that it is crucial to have every individual rehabilitated and released. The last line in the paragraph addressing sea turtle welfare and outreach is a much stronger supporting argument for the expense and effort of rehabilitation.
Response: We have updated the text to the following: "Rehabilitating and releasing endangered or threatened species like Kemp's ridley sea turtles into the wild may enhance their survival prospects and contribute to species conservation[34] , especially in the case of individuals nearing reproductive age."
Comment 2 Discussion: It may not be appropriate to say "However, only two... raising questions about the shortcomings in rehabilitation protocols or their adequate implementation." There are many factors that could influence whether a turtle was successfully rehabilitated and transported back to the native habitat (a major undertaking). The condition of the turtle at stranding is the most critical component, as the best rehabilitative care cannot overcome some cases where the turtle was in very poor condition at intake. No information was given about the reasons that the other 5 turtles were not successfully released. Did they die in rehabilitation? Were they kept as unreleasable permanent residents due to logistical constraints preventing release back to the Gulf of Mexico? Was there not a facility with the resources or knowledge to properly care for the turtles? A bit of context would make this a stronger section if you want to bring up shortcomings in the protocols, even just to introduce these factors influencing rehabilitation success and note that further description is beyond the scope of this manuscript.
Response: We have updated the text to the following: "However, only two turtles could be

successfully rehabilitated and released in the Gulf of Mexico, while the others didn't survive for more than a few days[10-12, 35]. The initial condition of the turtle at the time of stranding, the first response by observers, and the time lag in arriving at a rehabilitation facility add to the complexity of implementing rehabilitation protocols, particularly in locations far from their native habitat, where such occurrences are rare[10]."

Competing Interests: No competing interests were disclosed.