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Is climate change modifying the behavior of sea turtles? The particular case of the loggerhead turtle in the Alboran Sea

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Sporadic sea turtle nesting within the western Mediterranean Sea

The loggerhead turtle, a predominant species in the Mediterranean Sea (DiMatteo et al., 2022), exhibits a diverse migratory behavior throughout its life history, with females showing a strong tendency toward philopatry during the nesting period (Omeyer et al., 2021); returning to the same locations where they were born. There is thus a convergence of individuals from eastern Mediterranean and Atlantic nesting areas in the western Mediterranean (Camiñas and de la Serna, 1995; Monzón-Argüello et al., 2010; Carreras et al., 2011; Camiñas et al., 2021).

In recent years there has been an unprecedented surge in nesting activities outside the traditional eastern Mediterranean nesting grounds. This unexpected occurrence of sporadic nesting events in the western Mediterranean has prompted hypotheses that it might signify an early stage of colonization (Carreras et al., 2018; Hochscheid et al., 2022). Despite the surge in nesting outside established areas, albeit one not extensively documented currently, recent genetic studies have revealed past instances of colonization (Santidrián Tomillo et al., 2023). Present climatic conditions in the western Mediterranean basin, though comparatively cooler than their eastern counterparts, have proven conducive for nesting (Santidrián Tomillo et al., 2023). In fact, medium and long-term forecasting models suggest the suitability of the western Mediterranean as a climatic refuge for loggerhead sea turtles (Witt et al., 2010; Pike, 2014). The empirical evidence suggests that sea turtle individuals nesting along the Spanish coast originate from distant populations in the Atlantic and eastern Mediterranean regions (Carreras et al., 2018; Luna-Ortiz et al., 2024), underscoring the occurrence of a long-range colonization process. Furthermore, the absence of remigrant individuals implies that nesting females are likely colonizers rather than residents (Luna-Ortiz et al., 2024). These findings have important implications for the conservation of loggerhead turtles, highlighting a notable expansion of nesting range from east to west

within the Mediterranean basin (Mancino et al., 2022). Additionally, there has been a shift from a nesting window previously viable only in exceptional years to one now viable annually (Cardona et al., 2023). In this context, several authors have postulated that the observed behavioral alterations reflected in the heightened occurrence of sporadic sea turtle nesting within the western Mediterranean Sea might be attributed to climate change (Carreras et al., 2018; Hochscheid et al., 2022; Santidrián Tomillo et al., 2023).

The increase in sporadic loggerhead sea turtle nests could also be attributed to the rising density of loggerhead turtles in the Mediterranean. Despite the global threatened status of loggerhead turtles, conservation policies in the Mediterranean have led to its designation as a species of least concern on the IUCN Red List since 2015. Due to mounting pressures from tourism and rising temperatures, an increase in loggerhead sea turtles in the Mediterranean could lead turtles in the region to seek new nesting beaches.

The particular case of Alboran Sea

The Alboran Sea is a marine bridge that connects the Mediterranean and the Atlantic sea turtle populations. According to many studies based on stranding and by-catch data, loggerhead sea turtles from Atlantic nesting beaches migrate to the Mediterranean Sea through the Alboran Sea during the spring and summer seasons, while returning to the Atlantic Ocean during the winter season (Camiñas and de la Serna, 1995; Báez et al., 2011, Báez et al., 2017; Bellido et al., 2018). Moreover, Revelles et al. (2007) propose the presence of a permeable barrier within the Strait of Gibraltar which influences the dispersal patterns of juvenile loggerhead sea turtles. Consequently, juveniles originating from the Atlantic are unable to traverse the inward surface current, compelling them to reside in the Mediterranean until they attain a minimum size to overcome the flow of Atlantic waters. The delineation of the Alboran Sea is contingent upon the presence of distinct geographical boundaries flanking its longitudinal expanse, principally embodied by the Strait of Gibraltar and the hydrographic interface spanning from Oran to Cape Gata. These demarcations not only serve as geographical confines but also exert a discernible influence on species distribution, effectively demarcating the confines of a biogeographical domain. The easternmost sector is characterized by the Alboran Sea Frontal System. Under optimal conditions, the easternmost extension of this frontal system spans from Cape Gata to Oran, Algeria. However, this barrier may experience attenuation, permitting a restricted flux of species. Consequently, the Alboran Sea's boundary exhibits permeability, with the eastern expanse of the province of Almería being attributable to the Alboran Sea in function to oceanography context at a moment (Vargas-Yáñez et al., 2002; Real et al., 2021; Vargas-Yáñez et al., 2021).

It is of interest that although the first loggerhead turtle nesting site detected in the Iberian Peninsula was found on the Andalusian coast (Tomás et al., 2002; Báez et al., 2021a), located proximate to the Alboran Sea border (in a broader biogeographical context, it might be considered part of the Alboran Sea), and despite the rise of sporadic nesting phenomena across the western Mediterranean, only four instances of loggerhead turtle nestings have been documented in or in close proximity to the Alboran Sea: Vera (Almería) on July 27, 2001; Pulpi (Almería) on July 17, 2015; Fuengirola (Málaga) on August 4, 2020; and Marbella (Málaga) on July 8 and Mojacar (Almería) on 29 August 2023 (Figure 1). There are no records of such nesting sites on the coast of Morocco (Báez et al., 2021a).

The Alboran Sea represents the viable threshold for loggerhead turtle nesting, with conducive climatic conditions being essential for nesting occurrences. To validate this proposition, it becomes imperative to establish a correlation between sporadic nestings and short-term climatic indices. Such an association would provide crucial insights into the potential impact of immediate climatic variables on the irregular nesting events observed, thereby strengthening the hypothesis of climate change's influence on sea turtle nesting behavior within the Alboran Sea.

North Atlantic oscillation a short-term climate index affecting on sea turtles

The North Atlantic Oscillation (NAO) stands as the preeminent large-scale climatic fluctuation, exerting influence over the North Atlantic region in short-term periods. Its variability significantly impacts diverse meteorological parameters encompassing wind speed, direction, disparities in air temperature, and precipitation, notably during the boreal winter. Beyond its atmospheric effects, the

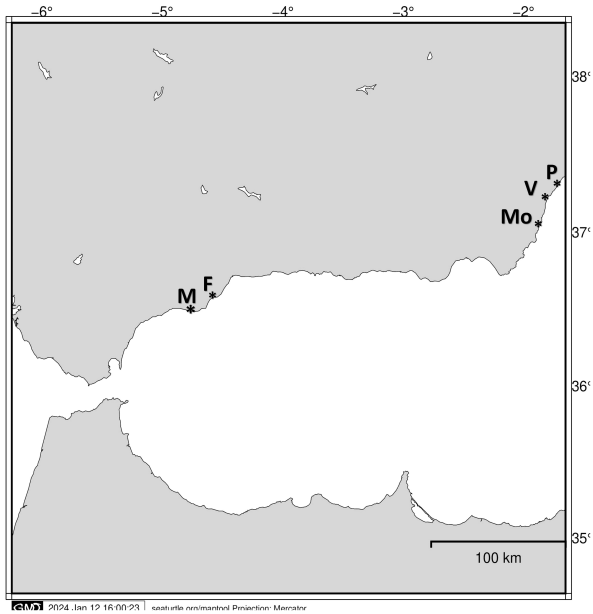

FIGURE 1
Location of the four sporadic nesting sites from the Alboran Sea and nearby areas. Key: V, Vera (Almería) on July 27, 2001; P, Pulpi (Almería) on July 17, 2015; F, Fuengirola (Málaga) on August 4, 2020; M, Marbella (Málaga) on July 8, and Mo, Mojacar (Almería) on 29 August, 2023. *Loggerhead sea turtle nesting activity location.

NAO extends its influence to the ocean, instigating alterations in heat distribution, sea surface temperature, gyre circulation, mixed layer depth, salinity levels, high-latitude deep water formation, and sea ice coverage (reviewed in Báez et al., 2021b). Consequently, the NAO has garnered extensive attention in the analysis of marine ecosystems' variability. Various studies have established a teleconnection between NAO fluctuations and migration of sea turtles through the Alboran Sea (Báez et al., 2011; Báez et al., 2017; Bellido et al., 2018).

The North Atlantic Oscillation (NAO) assumes positive and negative values, each eliciting distinct meteorological repercussions. The positive phase of the NAO induces above-average westerly winds across the northern mid-latitudes and fosters arid climatic conditions in the Mediterranean region whereas the negative phase leads to substantial precipitation in southern Europe. Beyond the directional implications of the NAO on storms and the qualitative meteorological conditions within the North Atlantic, the quantitative magnitude of this oscillation holds significant importance (reviewed in Báez et al., 2021b). Employing a binary logistic regression (using the software SPSS 17.0) to correlate the presence by year (i.e. 2001, 2015, 2020 and 2023 corresponding to the nests of Vera, Pulpí, Fuengirola and Marbella/Mojacar, respectively) or absence (i.e. 19 years without nests detected in or around the Alboran Sea) of nests with the observed mean July NAO for each year yields a statistically significant function (Omnibus Test= 5.252; df= 1; P= 0.022; Nagelkerk R2 = 0.338; AUC= 0.803). Therefore, despite the limited number of nests within the Alboran Sea region, evidence supports a causal relationship between loggerhead sea turtle nestings in the Alboran Sea and the state of the North Atlantic Oscillation.

Discussion

Over the nesting of 23 years, ranging from the initial recorded turtle nest in Vera 2001 to the most recent one in 2023, there is a prevalence of 14 years characterized by a mean negative North Atlantic Oscillation (NAO) during the month of July, while 9 years exhibit a mean positive July NAO. Notably, all four instances of turtle nestings occurred during years featuring a mean negative July NAO. Three specific occurrences, the Pulpi nesting in 2015 and the most recent in Marbella and Mojacar in 2023, align precisely with the years showcasing the most extreme negative July NAO values. NAO in negative phase favours the sporadic laying of loggerhead turtles in the Alboran Sea. Báez et al. (2013) found that the negative NAO could help to increase sea surface temperature from Alboran Sea.

Sea turtle are threat rising sea levels drive by climate change and severe storms under climate change, potentially diminishing available nesting beaches crucial for egg laying by sea turtles (Maneja et al., 2021). In addition, sea turtles exhibit temperature-dependent sex determination raising the possibility that climate-induced temperature increases could influence sex ratios in these populations (Tezak et al., 2020). Therefore, climate change may impact the ecology of sea turtles, as elucidated above, where the extremely negative North Atlantic Oscillation (NAO) in July could directly influence this process. Climate change is a global phenomenon on a broad scale, yet there is limited evidence of cases akin to the rise in sporadic nesting outside the western Mediterranean. A citizen science project indicated that despite Peru not being considered to have nesting beaches, at least two species were observed nesting and on the rise (Zavala and Kelez, 2015). However, this instance might stem from inadequate beach surveys rather than a shift in sea turtle behavior. Consequently, the absence of similar occurrences outside the Mediterranean might suggest the involvement of additional factors beyond climate change. However, the NAO is very sensitive to climate change, with periods of predominantly negative NAO, and more extreme oscillations (Báez et al., 2013). Therefore, the phenomenon of sporadic nesting on the beaches of the Alboran Sea will increase over time.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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