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Promise or peril in a warming ocean? An emergent pathway leads North Pacific loggerhead sea turtles into the northern California Current System

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Over recent decades, the eastern North Pacific Ocean (ENP) has undergone significant climate-driven change, characterized by rising sea surface temperatures (SSTs), a northward expansion of the North Pacific Transition Zone (NPTZ), and more frequent marine heatwaves. Juvenile North Pacific loggerhead sea turtles (*Caretta caretta*), a highly mobile species sensitive to environmental variability, have emerged as a sentinel species within the region. When North Pacific loggerheads migrate from the eastern subtropical gyre to coastal habitat, they do so offshore of the Baja California Peninsula, Mexico. Analysis of an extensive satellite tracking data set (n=285,1997–2023) revealed no prior observations of juveniles entering the colder, nutrient-rich waters of the northern California Current System (CCS). However, the gradual northward shift of loggerhead foraging habitat has been observed in parallel with an increasingly oligotrophic NPTZ. In 2024, four of 28 satellite-tracked individuals deviated from historic migratory routes and entered the northern CCS. To understand the physical mechanisms that enabled these novel movements, we integrated SST, chlorophyll-a concentrations, and surface current conditions experienced by these individuals and compared them to historical records within the region. During September-October 2024, these turtles reached 45°N latitude, where they encountered strong eastward flow within the North Pacific Current (NPC), thermally suitable conditions, and enhanced productivity. These conditions created a transient, high-latitude migratory corridor into the northern CCS. While three of these turtles benefited from reaching enhanced forage habitat in the California Current System, one likely suffered cold-stunning upon entry into suboptimal waters. The other 24 turtles remained south of the NPC, in the subtropical gyre. Our study represents the first confirmed use of a new, northern CCS migratory corridor by juvenile North Pacific loggerhead sea turtles. These findings expand on the conceptual framework of the 'thermal corridor hypothesis,' which suggests that sea turtles opportunistically exploit anomalously warm conditions to reach foraging habitats along the North American coast. They also emphasize the role of additional environmental drivers, such as advective current systems, in these movements. Under accelerated climate change, such transient pathways may become increasingly prevalent, with significant implications for conservation planning and fisheries management.

KEYWORDS

climate change, loggerhead sea turtle, migration, North Pacific Current, North Pacific Ocean, ocean currents, sea surface temperature

Introduction

Climate change is rapidly altering oceanic ecosystems. Rising sea surface temperatures (SSTs), shifts in circulation, and more frequent marine heatwaves (MHWs) are significantly reshaping habitats and modifying both the structure and function of ecosystems (Pinsky et al., 2020; Gomes et al., 2024; Wernberg et al., 2025). These changes are complex and particularly disruptive to mobile marine species that depend on stable environmental cues (e.g., thermal gradients, current systems, and prey availability) for critical life history phases such as foraging, reproduction, and long-distance migration (Robinson et al., 2009). Such cues enable individuals to synchronize their movements with the seasonally predictable conditions that emerge along their migratory pathways.

As climate change accelerates, the reliability of environmental cues has become increasingly unstable, prompting individuals to adjust their spatial distributions in search of more suitable habitats. These adjustments may create novel ecological opportunities for some species to access previously inaccessible environments. However, the capacity to monitor and respond to these environmental changes varies among taxonomic groups and within populations (Burrows et al., 2011), often being influenced by ecological traits, life history strategies, and dispersal abilities (Robinson et al., 2009). Therefore, factors such as phenological shifts, physiological limitations, and increased energetic demands can significantly impact the ability to adapt, especially for species with narrow ecological tolerances (Evans and Bearhop, 2022; Kuletz et al., 2024). In the context of a rapidly changing oceanic environment, not all species are expected to successfully adapt, underscoring the complex and uncertain ecological outcomes involved (Cavole et al., 2016; Lezama-Ochoa et al., 2024).

These changes have had a particularly significant impact on the eastern North Pacific Ocean. Known as a biodiversity hotspot for many ecologically and commercially important highly migratory taxa such as sea turtles, sea birds, marine mammals, and pelagic fishes (Brodeur et al., 1999; Polovina et al., 2001, 2017; Ichii et al., 2009; Block et al., 2011; Whitney, 2015; Clay and Brooke, 2024), the region has experienced significant biophysical transformations in recent decades. The expansion of the subtropical gyre and poleward shift of the North Pacific Transition Zone (NPTZ), a key oceanographic boundary and forage habitat (Polovina et al., 2001), have reduced productivity and thus altered species distributions (Polovina et al., 2008; Le et al., 2019; Yang et al., 2020; Briscoe et al., 2025; Chen et al., 2025). The California Current System (CCS) has experienced some of the most prolonged and intense MHWs on record (Oliver et al., 2018), with substantial restructuring of food-web dynamics (Green et al., 2022; Gomes et al., 2024) and species redistributions (Jacox et al., 2020; Welch et al., 2023). Against the backdrop of long-term climate change, the recurrence of these extreme events has reshaped the eastern North Pacific in ways that suggest these novel conditions may become the new baseline (Weber et al., 2021; Gomes et al., 2024). As a result, there is substantial concern that ocean warming across the North Pacific will present new challenges and risks to species conservation and fisheries management strategies (Jacox et al., 2020; Green et al., 2022; Welch et al., 2023; Farchadi et al., 2024).

Given these concerns, the vulnerable North Pacific loggerhead sea turtle (*Caretta caretta*) has emerged as an important sentinel species (Hazen et al., 2019; Early-Capistrán et al., 2024) for detecting ecosystem changes within the eastern North Pacific (ENP). The 28-year-long (1997–2025) electronic tagging dataset of North Pacific loggerheads represents the most comprehensive, long-term population-level dataset of any vertebrate marine species. Individuals from this population are genetically distinct, as Japan represents the sole nesting ground across the entire North Pacific population (Bowen et al., 1995). Juveniles undergo a multi-year migration within the subtropical gyre, foraging throughout the Central North Pacific (CNP) (Polovina et al., 2004, 2006; Kobayashi et al., 2008; Abecassis et al., 2013; Briscoe et al., 2016b), in the East China Sea (Kobayashi et al., 2011), and in the eastern North Pacific off the Baja California Peninsula (BCP), Mexico (Peckham et al., 2011; Wingfield et al., 2011; Allen et al., 2013; Seminoff et al., 2014; Eguchi et al., 2018). Upon maturity, these turtles return to their natal beaches in Japan to reproduce, residing in the western Pacific for the remainder of their lives (Nichols et al., 2000; Watanabe et al., 2011).

Decades of research on the North Pacific loggerhead population have provided exceptional insight into the seasonal foraging movements, diet, and patterns of active dispersal across the North Pacific Ocean (Polovina et al., 2000, 2001, 2004, 2006; Parker et al., 2005; Howell et al., 2008, 2010; Kobayashi et al., 2008; Abecassis et al., 2013; Briscoe et al., 2016b, 2016a, 2025; Gaspar et al., 2025). Juveniles exhibit a well-established meridional (north-south) migration between 30° - 40°N latitudes that closely follows the seasonal displacement of the 18°C-SST isotherm (Polovina et al., 2001). Broadly, the isotherm serves as a proxy for the forage habitat associated with the Transition Zone Chlorophyll Front (TZCF). This dynamic feature marks the sharp surface chlorophyll-a gradient between the oligotrophic subtropical waters with surface chlorophyll-a less than 0.2mg/m^3 to the south and the temperate waters with surface chlorophyll-a exceeding 0.2mg/m^3 to the north (Polovina et al., 2001, 2017). Herein, we refer to the 18°C-SST isotherm as an indicator of the northern latitude of juvenile North Pacific loggerhead habitat. Loggerheads move with the TZCF from its southernmost position towards the end of the winter (February-March) to its northernmost position at the end of the summer (September-October).

The position and structure of this habitat are shaped by the basin-scale circulation that frames the Transition Zone. The Kuroshio Extension supplies the eastward-flowing North Pacific Current (NPC) (Qiu, 2002; Cummins and Freeland, 2007), which creates retention and convergence zones that can elevate prey encounter rates (Polovina et al., 2006). As the NPC reaches the North American coast, it bifurcates into a subpolar branch (i.e., the Alaska Current) and a subtropical branch that feeds into the CCS (Hickey, 1979; Chelton and Davis, 1982; Cummins and Freeland, 2007) (Figure 1, inset). Although it is a well-defined feature centered around 45°-47°N latitude (Batten and Freeland, 2007; Auad et al., 2011), its core intensity and latitudinal position vary seasonally and interannually, driven by wind forcing and fluctuations in the broader-scale circulation of the subarctic and subtropical gyres (Qiu, 2002; Douglass et al., 2006; Batten and Freeland, 2007; Cummins and Freeland, 2007). Embedded within the NPC are eddies and meanders, where cool nutrient-rich waters mix with warm subtropical waters, creating forage habitat for loggerhead sea turtles and other marine predators, similar to oceanic mesoscale features observed within the Kuroshio Extension Bifurcation Region (*see* Polovina et al. (2006).

In addition to temperature and prey availability, ocean currents are known to contribute to the dispersal of these individuals (Briscoe et al., 2016a; Gaspar et al., 2025). However the degree to which these drivers shape ontogenetic shifts into critical habitats remains unclear. Although the proportion of individuals transitioning from oceanic to neritic habitats is unknown, an estimated 43,000 juveniles forage along the coastal waters of the BCP at any given time, highlighting the importance of this developmental habitat (Peckham et al., 2007; Seminoff et al., 2014). Recruitment to this coastal habitat is thought to be facilitated by the formation of a thermally suitable corridor, with juveniles following anomalously warm waters eastward and into the southern end of the CCS.

In recent years, sightings of loggerheads within the central (Early-Capistrán et al., 2024) and northern CCS (Parker et al., 2024) have prompted questions about the migratory routes and environmental drivers underlying these northerly occurrences. Historically, loggerheads have not been observed using the NPC

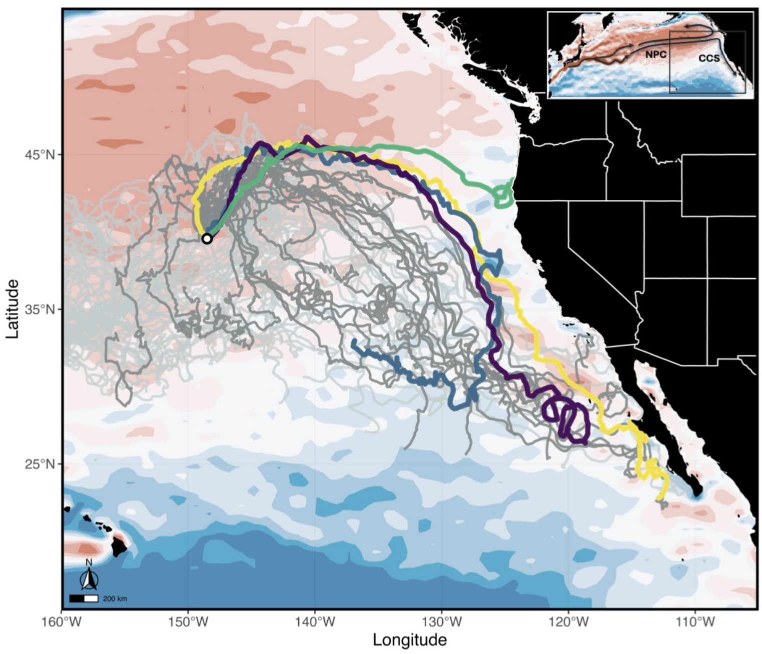

FIGURE 1
Study area of juvenile North Pacific loggerhead sea turtles (n = 98), spanning 15°N–50°N and 160°W–105°W during 1997–2025. Historical tracks are shown in grey. In July 2024, 28 turtles were released (dark grey lines; release site indicated by a white circle), of which four individuals (Mei: yellow; Fumi: blue; Anacapa: purple; Kanna: green) traversed into the northern California Current System (CCS). The background and inset map depict the long-term mean zonal current (u, m/s) for September–October, averaged over 1997–2024 and resampled to a 0.5° x 0.5° spatial grid, across the North Pacific. Within the study region (black box), the core flow of the North Pacific Current (NPC) is shown in dark red, and the solid black lines indicate the general path of the NPC and its bifurcation into the northward Alaska Current and southward flowing CCS.

to enter into the colder, more productive waters of the northern CCS. Instead, upon approaching the North American coast, they typically move southwards, remaining within warmer oligotrophic waters before entering productive neritic habitat at lower latitudes (~ 30°N). In recent decades, warming trends have driven a progressive poleward shift in the northern bounds of juvenile North Pacific loggerhead habitat (Briscoe et al., 2025). Significantly, the recent deployments of a total of 53 juvenile loggerheads across 2023 (n=25) and 2024 (n=28) have provided new insights into this shift, revealing that individuals are now able to reach latitudes that overlap with the NPC (Figure 1). In particular, a subset of individuals released in 2024 (n = 4) displayed unprecedented movements at higher latitudes (40–45° N), progressing eastward in the NPC into the northern CCS, rather than following historically observed southward migratory routes. While three of these individuals navigated through the CCS, one likely suffered cold-stunning upon entry into cold nearshore CCS upwelled waters. These movements represent a marked departure from known migratory patterns, raising new questions about the role of environmental cues, the accessibility of novel habitats, and their associated ecological consequences. Moreover, the contrasting outcomes among individuals underscore both the emerging opportunities and potential risks marine species face in a rapidly changing ocean. While there were several other tracked loggerheads that entered the CCS north of Baja, we focus on the 4 animals that were the furthest north and were the only ones to use the novel NPC pathway. Further, as previously mentioned, since the NPC bifurcates with a southern branch feeding into the CCS, and a norther branch feeding into the Alaska Current, the potential exists for loggerheads to be transported into much colder waters.

Building on these observations, this study examines the oceanographic conditions that facilitated the movement of the four juvenile loggerheads into the northern CCS in 2024, relative to other loggerheads within the region. Specifically, we compare oceanographic conditions across years to assess whether anomalously warm waters and enhanced eastward advection supported the formation of a transient, dynamic corridor extending into higher latitudes. As a sentinel species for environmental change, loggerheads provide a unique lens to elucidate mechanisms enabling access to previously inaccessible habitat, and highlight the ecological trade-offs associated with such movements. More broadly, these insights advance our understanding of how climate-driven changes are reshaping habitat connectivity, with significant implications for the conservation and management of highly migratory species that utilize these pathways in the eastern North Pacific Ocean.

Methods

Loggerhead satellite tracking

This study analyzes satellite telemetry data from juvenile North Pacific loggerhead sea turtles, encompassing a total of 285 released and tracked individuals between January 1997 and June 2025. Of these individuals, 251 were raised at the Port of Nagoya Public Aquarium in Nagoya, Japan. Polovina et al. (2006) and Gaspar et al. (2025) discussed the movements and activity of captive-reared and wild-caught North Pacific juvenile loggerhead sea turtles. The inclusion of 53 turtles covering the period July 2023-June 2025 is part of the Sea Turtle Research Experiment on the Thermal Corridor Hypothesis (STRETCH) 2023–2027 initiative (www.loggerheadstretch.org).

Detailed methods on animal care, tagging, and release locations can be found in Abecassis et al. (2013) and Balazs et al. (2016). Briefly, Argos-linked satellite transmitters were attached to the carapace of all juveniles, following the procedures recommended in Balazs et al. (1996) with modifications as described by Calder (2024). Argos-derived surface locations were collected by the National Oceanic and Atmospheric (NOAA) Pacific Islands Fisheries Science Center (PIFSC), Marine Turtle Research Program, Hawaii (1997–2013), and by Stanford University, California (2023–2025). All raw Argos turtle positions were fitted to a move persistence state space model using the 'aniMotum' package (Jonsen et al., 2023). This approach provides time-regularized estimates (12-h intervals) of animal location while accounting for observation error and irregularity.

Median latitude by year-groups (180°-130°W)

The tracking data from 1997 to 2024 were not uniformly distributed across this entire period but fell into three discrete groupings: 1997–2004 (n=16), 2005–2013 (n=79), and 2023–2024 (n=52). Uneven sample sizes resulted from tagging efforts and multi-year transmissions across different years. To examine potential latitudinal shifts in habitat by eastward-only turtle movement during our study period, we calculated the median latitude of turtles moving eastward between 180°-130°W longitude for September and October within each year group. Any westward movements were not considered in this analysis because their westward migratory routes due to homing (Gaspar et al., 2025) are less defined. This approach was similar to the methodology in Briscoe et al. (2025). We also quantify the degree of individual variability around the median within each year group.

Turtle movements within the eastern North Pacific (150°W-130°W)

Because loggerheads were observed entering the NPC and CCS during September and October 2024, our study focused on 66 individuals that utilized the waters of the eastern North Pacific (150° W - 130°W) during September and October (1997-2024). This subset included 14 captive-reared individuals tracked during September and October of 2006 and 2007, and 52 individuals during September and October of 2023 and 2024. One individual (Ayame) from the STRETCH 2023 data set was excluded because its transmission ended prematurely, on 10 August 2023 (Supplementary Table 1).

Environmental data collection

Given the range of the 2024 tracks, we defined our spatial domain as 35°N - 50°N, 150°W - 130°W (Figure 1) for the collection of environmental data. This region encompasses the NPC as it extends across the North Pacific and provides source waters for both the poleward and equatorward flows along the North American coastline (Cummins and Freeland, 2007). We focused on its subtropical extension into the CCS, which has been defined as the region within 800 km-1,000 km from shore (Hickey, 1979; Auad et al., 2011; Kahru et al., 2018).

To characterize the oceanographic conditions during the months of September and October and compare them with historical variability, we analyzed surface current fields for the same months across all years with turtle observations in the eastern North Pacific between 2006 and 2024. Monthly and daily zonal (u) and meridional (v) surface current velocities were obtained from the Copernicus Marine Environmental Monitoring Service (CMEMS) eddy-resolving GLORYS12v1 reanalysis product, which provides a spatial resolution of 1/12° and is based on global ocean and sea ice circulation simulations using the NEMO platform (Lellouche et al., 2021; CMEMS EU Copernicus Marine Service, 2025c). Surface Stokes drift vectors, used to incorporate wave-induced drift into turtle velocities, were obtained from the WAVERYS reanalysis of the global wave field produced with the MFWAM model (Law-Chune et al., 2021; CMEMS EU Copernicus Marine Service, 2025a). Monthly and daily sea surface temperatures were obtained from NOAA's Coral Reef Watch Program at a 5-km spatial resolution (NOAA, 2024). Monthly and daily chlorophyll-a concentrations were obtained at a 4-km spatial resolution from the Copernicus Marine Environmental Monitoring Service's Global Ocean-Colour blended product (CMEMS EU Copernicus Marine Service, 2025b).

Because NOAA surveys have previously documented loggerhead sea turtles in the Southern California Bight during the 2014–2015 El Niño and the 2015–2016 marine heatwave (Allen et al., 2013; Eguchi et al., 2018; Welch et al., 2019), we also examined conditions from September to October 2014 to assess whether they were similar to those in 2024 and might have enabled a similar loggerhead pathway into the northern CCS.

Turtle-environment analyses

To characterize the environmental conditions experienced by turtles *in situ*, daily location data were temporally matched to gridded daily surface data, including zonal and meridional current components, SSTs, and chlorophyll-a concentrations, extracted underneath each corresponding turtle position. Across years, comparisons of September-October conditions were made by mapping the monthly mean zonal surface velocities, SST (including the 18°C isotherm) and chlorophyll-a fields, and relating CCS-entry tracks to nearshore conditions. Turtle-drift velocities of the four turtles of interest from 2024 were estimated using the methodologies described in Gaspar et al. (2025). Briefly, the daily mean turtle velocity over the ground ($\hat{V}_t$) was computed as the great-circle distance between successive state-space-model estimated turtle positions at 0:00 UTC, divided by the time interval (24h) and decomposed into zonal (u_t) and meridional (v_t) components (see Gaspar et al., 2025). The time-matched estimates of a γ parameterized Stokes drift ($\hat{V}_{sto}$) were added to the surface currents ($\hat{V}_{co}$) to calculate drift velocity ($\hat{V}_d$):

$$\hat{V}_d = \hat{V}_{co} + \gamma \hat{V}_{sto}$$

where γ is 0.28, as used in Gaspar et al. (2025) to optimize drift impacts on turtle movements.

All data processing and analyses were performed using R (version 4.2.2) and Python (version 3.9.6). Results are reported as mean ± standard deviation unless otherwise noted.

Results

Figure 2 builds upon results from Briscoe et al. (2025) and shows a progressive northward shift in the average habitat of eastward-moving juvenile loggerheads in the eastern North Pacific, from 38.6°N ± 2.5° to 43.2°N ±0.9° latitude (n=147 individuals during September and October 1997–2024, between 180°-130°W longitude). Since 1997, the mean habitat during September and October has shifted northward, while the overall extent of the seasonal migration of about 1,000 km has remained unchanged.

Prior to the 2024 turtles, there were satellite-tracked turtles in 2006, 2007, and 2023 that traveled east of 140°W longitude but did not enter the northern CCS. Between September and October 2006–2007, the eastward flow associated with the NPC was positioned north of 40°N latitude, with the strongest velocities concentrated between 45° and 50°N latitude and west of 140°W longitude (Figures 3A, B). The broader clockwise circulation of the North Pacific Subtropical Gyre was noticeable, with the equatorward flow of the CCS situated along the eastern boundary, and the westward flow of the subtropical gyre at lower latitudes, as shown in blue. Thirteen individuals migrated through the eastern North Pacific during this period, broadly tracking the 18°C-SST isotherm, which reached its maximum extent around 40°N latitude in September (Figure 3A), before shifting southward in October (Figure 3B). Both the turtles and the isotherm remained south of the strongest NPC flow during this period. The turtles remained in the oligotrophic, subtropical gyre waters as they migrated eastward and then southeastward until reaching the coastal waters of the Baja California Peninsula, Mexico.

In 2023, both the 18°C-SST isotherm and turtle positions extended farther north, reaching latitudes above 45°N in September (Figure 3C). By October (Figure 3D), the eastward zonal flow remained strongest to the west of 140°W, and shifted south of 45°N latitude, creating intensified conditions in the central North Pacific but weakened east of 140°W longitude. All individuals began to shift south-southeast with the seasonal migration of the 18°C SST isotherm.

During September 2023, 2024, and October 2024, the eastward flow of the North Pacific Current (NPC) was stronger than in 2006–2007 (Figures 3, 4; Supplementary Figure 2A). During these periods, zonal velocities were consistently stronger, east of 140°W. Notably, in September and October 2024, the mean position of the 18°C isotherm east of 140°W stayed north of 40°N latitude. While September 2024 turtle distributions resembled those in 2023 (i.e., at or above 45°N latitude), the combined strength of the zonal

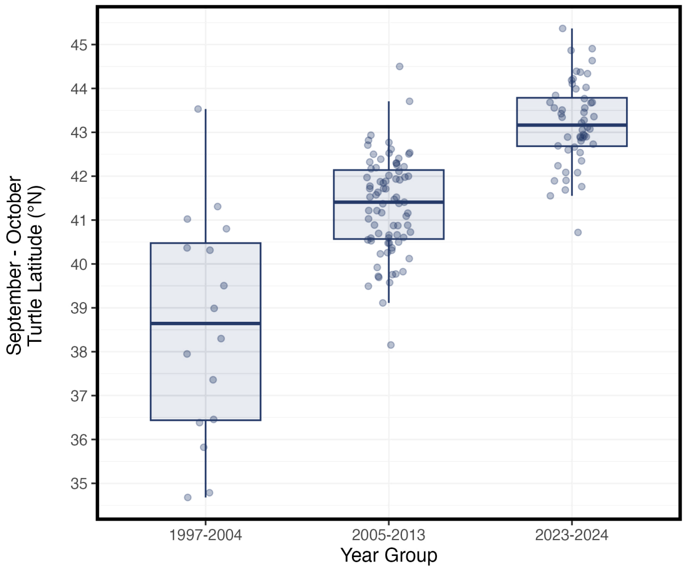

FIGURE 2
Distribution of median September–October turtle latitudes (°N) for juvenile North Pacific loggerhead sea turtles (n = 147) across three year groups (1997–2004, 2005–2013, and 2023–2024) between 180–130°W longitude. Each point represents the median latitude of an individual turtle. The boxplots show the interquartile range (IQR) with the group median (horizontal line).

currents and the more northerly position of the 18°C isotherm east of 140°W allowed turtle positions to stay further north in October 2024. Although all turtles moved south or southeast with the isotherm, the four individuals that entered the CCS showed a more pronounced eastward movement from September to October 2024.

Total daily turtle velocities over ground (ut, vt; dark blue) and drift velocities (ud, vd; light blue) during September and October 2024 differed among the four individuals that entered the CCS, Anacapa Fumi, Kanna, and Mei (Figure 5). Positive zonal velocities (Figure 5A) denote eastward turtle movements or current flow. Figure 5B indicates northward and southward movements. Periods

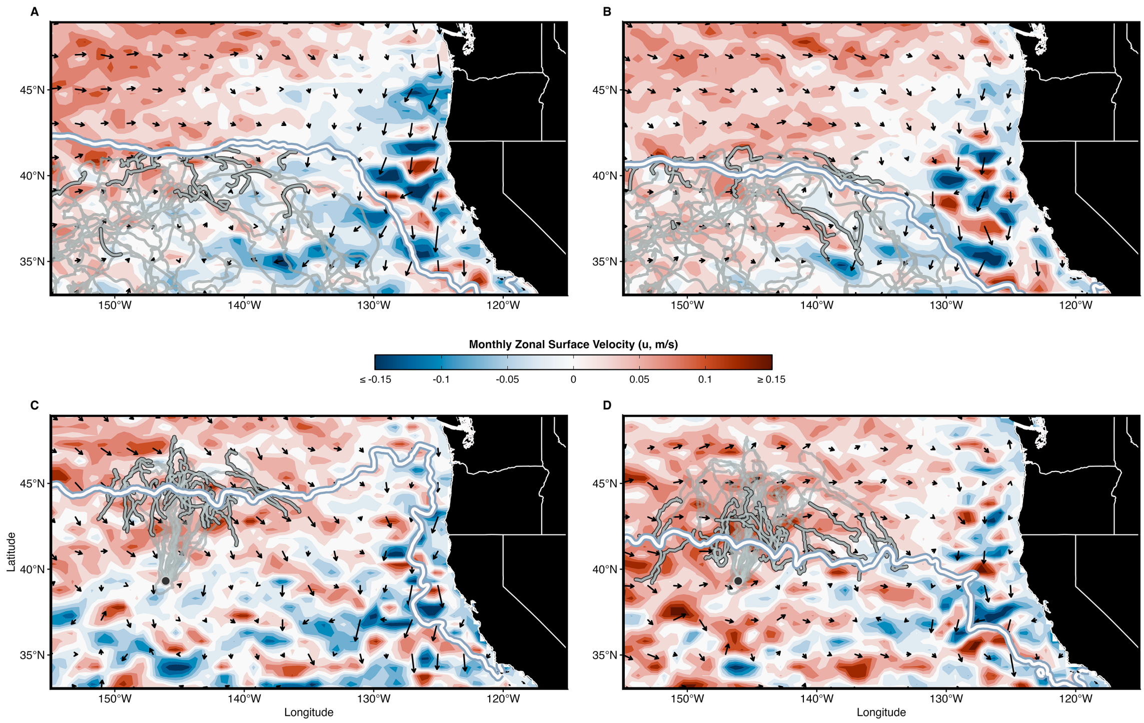

FIGURE 3
Monthly mean zonal currents (u, m/s) overlaid with current vectors for **(A)** September 2006–2007, **(B)** October 2006–2007, **(C)** September 2023, and **(D)** October 2023, resampled to a 0.5° x 0.5° spatial grid. Vector arrows represent 0.1 m/s. Full loggerhead turtle tracks are shown in grey, with the September and October segments highlighted in darker shades. The white line indicates the average monthly position of the 18 °C SST isotherm.

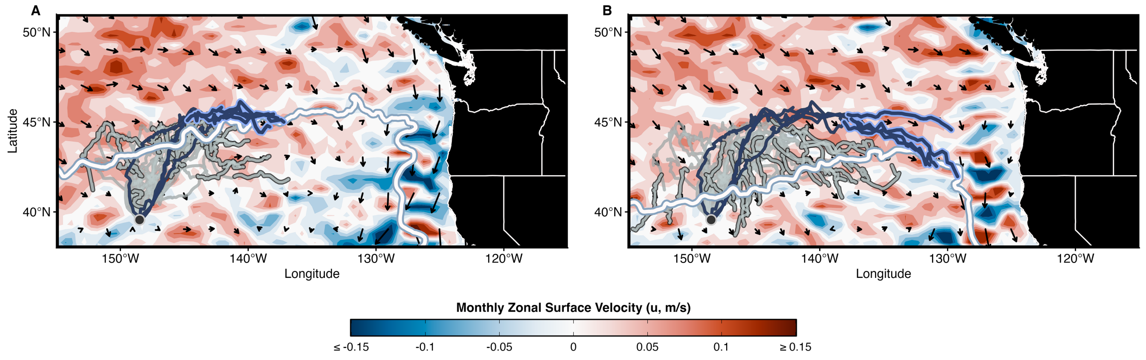

FIGURE 4
Monthly mean zonal currents (u, m/s) overlaid with current vectors for **(A)** September 2024 and **(B)** October 2024, resampled to a 0.5° x 0.5° spatial grid. Vector arrows represent 0.1 m/s. Full loggerhead turtle tracks are shown in grey, with the September and October segments highlighted in darker shades. The white line indicates the average monthly position of the 18 °C SST isotherm.

exceeding the current flow indicated active swimming with it. Given the inherent mesoscale variability within the NPC (White, 1982), individual turtle trajectories exhibited slight differences in movement speed. However, movement analyses indicated that these turtles were not passively advected by the NPC, but rather swam eastward with a directed velocity of about 0.1 m/s (0.36 km/h) above the underlying current, which was also approximately 0.1 m/s (Figure 5A), while their southward movement appeared to be drifting with the southward flow of the meridional flow, following expected seasonal trends northward in September and then southward in October 2024 (Figure 5B), while maintaining thermally suitable conditions (Figures 6A, B). Further work to extend Gaspar et al. (2025) is underway to examine the effect of the optimization parameter γ on eastward drift as individuals approach the coastline and grow in size.

Monthly SSTs experienced by the four eastward-moving turtles along their migratory routes in 2024 are shown in Figure 6. The white region shows SSTs between 17.5°C – 18.5°C, consistent with established habitat preferences in Howell et al. (2008). Although all four individuals reached latitudes above 45°N during September and October, they remained within SSTs ranging from 15.4°C to 18.4°C (mean: 17.2°C ± 0.5°C; Figures 6A, B). Three individuals subsequently migrated southward through the CCS, briefly encountering cooler waters off the central California coast in November and December (15.3°C ± 1.1 °C between 35° and 40°N latitude, Figures 6C, D). However, these conditions were within a suitable range for a juvenile loggerhead sea turtle (Coles & Musick, 2000). As these individuals moved into lower latitudes (< 35°N) in December 2024, SSTs increased to 14.9 °C – 18.3°C. In contrast, the northernmost individual, Kanna, experienced a notable decrease in SSTs (12.3°C ± 1.5°C) as the turtle continued eastward. Ultimately, this turtle encountered much colder waters along the North American coast, where Argos transmissions eventually ended in December 2024, likely due to cold-stunning (Schwartz, 1978).

Monthly mean chlorophyll-a concentrations experienced by all tracked turtles during (A) September, (B) October, (C) November, and (D) December 2024 are shown in Figure 7. Consistent with published literature, elevated chlorophyll-a concentrations were observed within the eastern boundary waters of the CCS, where the upwelled, high-nutrient waters converge with the oligotrophic waters (Hickey, 1979). During September and October 2024, the position of the 18°C-SST isotherm extended north (see Figures 3, 6A, B) and coastal upwelling produced elevated chlorophyll-a concentrations beyond 45°N latitude. The four individuals that moved into the CCS were closer to the coast than the rest of the cohort, which remained in oligotrophic offshore waters. The three individuals transiting through this region encountered median daily chlorophyll concentrations of 0.13 mg/m³ ± 0.04 mg/m³ in September-October 2024. By November-December 2024, these three began to move southward within the CCS, however they remained in higher chlorophyll-a concentrations than the rest of the turtle tracks (median: 0.15 of 0.13 mg/m³ and 0.10 of 0.13 mg/m³, respectively, Figures 7C, D).

Comparison of environmental conditions in September-October 2014 and 2024 showed that both the NPC and CCS displayed comparatively weaker zonal flows in September 2014 than those observed in September 2024 (Figures 4A, 8A, respectively). Conversely, the conditions in October 2024 (Figure 4B) more closely resembled those observed in October 2014 (Figure 8B), with both years characterized by enhanced zonal transport within the NPC. Furthermore, during September and October of 2014 and 2024, the 18°C SST isotherm extended north of 40°N latitude and east of 140°W longitude, indicating the presence of anomalously warm SSTs in the northern CCS. Such conditions likely facilitated access into the CCS, potentially contributing to the unusually high numbers of juvenile loggerheads observed in the Southern California Bight waters in 2015.

Discussion

This study presents the first empirical evidence of satellite tracked juvenile North Pacific loggerhead sea turtles entering the northern CCS, representing a significant deviation from their historic migratory routes. The trajectories of four ‘sentinel’ individuals revealed the emergence of this novel pathway connecting oceanic movements to established developmental foraging habitats. Our observations suggest that these movements were associated with the northward trend in the September and October loggerhead

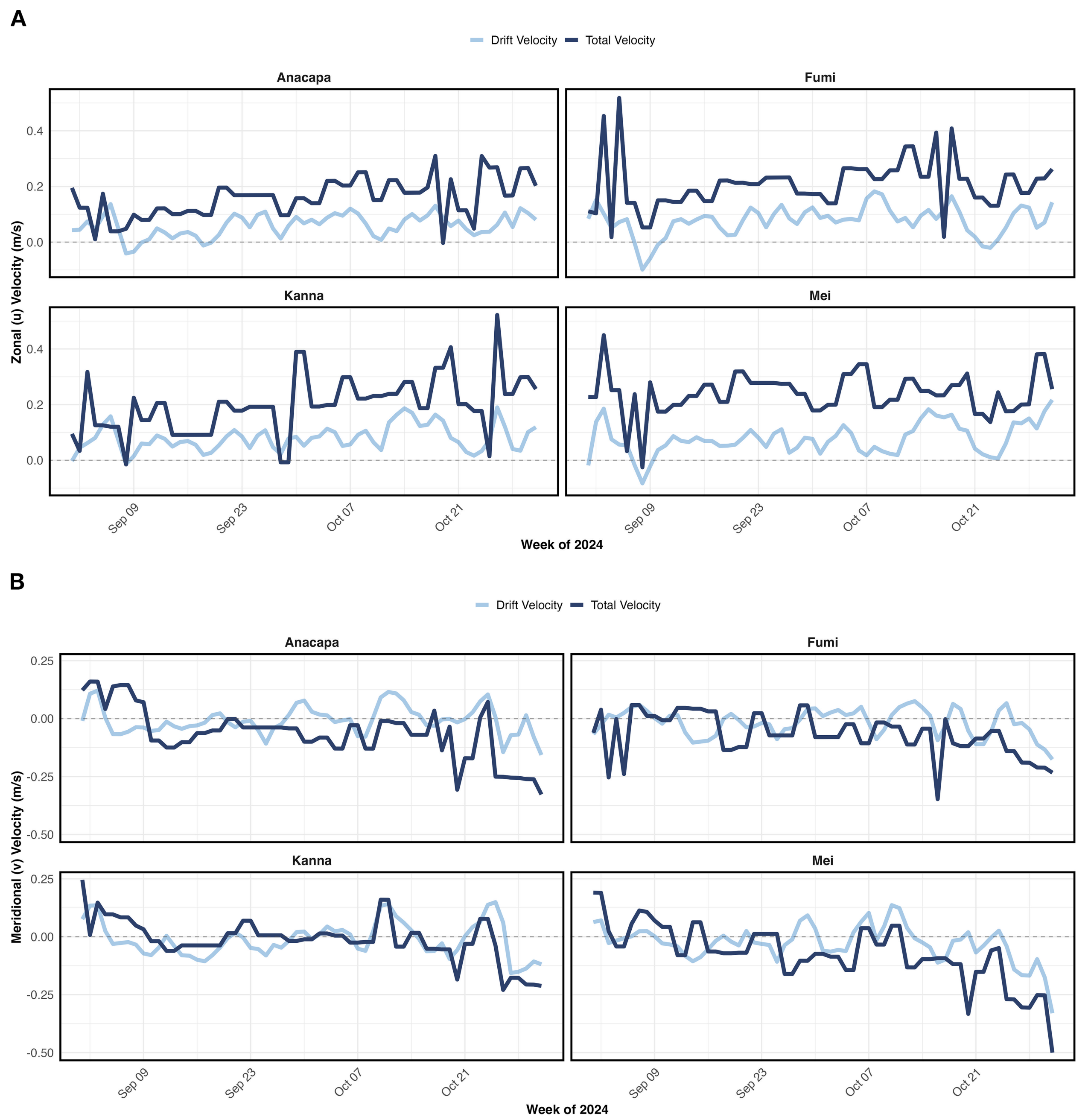

FIGURE 5
Total daily **(A)** zonal and **(B)** meridional turtle velocities over ground (dark blue) and drift velocities (light blue) during September and October 2024 for the four individuals that entered the northern CCS: Anacapa, Fumi, Kanna, and Mei. Positive and negative values of zonal velocities **(A)** indicate eastward and westward movement, respectively. Positive and negative meridional velocities **(B)** indicate northward and southward movement.

forage latitude and its intersection with the eastward flow of the North Pacific Current. These conditions created a thermally suitable and productive migratory corridor that facilitated access into the highly productive waters of the CCS. These findings further advance the conceptual framework of the ‘thermal corridor hypothesis’, by showing that anomalously warm SSTs and a northward displacement of the 18°C SST isotherm can produce an extension of an existing thermal corridor, which sea turtles opportunistically exploit favorable conditions to access forage habitat (Briscoe et al., 2021). Significantly, our results underscore the role of additional environmental processes in the development of these ephemeral pathways, such as advective current systems. We propose that under future warming scenarios, this emerging pathway may develop into a recurrent corridor, with potentially important conservation and management implications for this vulnerable population. In this context, our results highlight the importance of sustained adaptive management strategies, including the periodic re-evaluation and modification of high-effort fishing zones, as well as the refinement of dynamic bycatch mitigation tools in areas where loggerhead occurrence is likely to increase.

For nearly three decades, juvenile North Pacific loggerhead migratory movements have closely followed the seasonal latitudinal shifts of the 18°C isotherm, which aligns with the

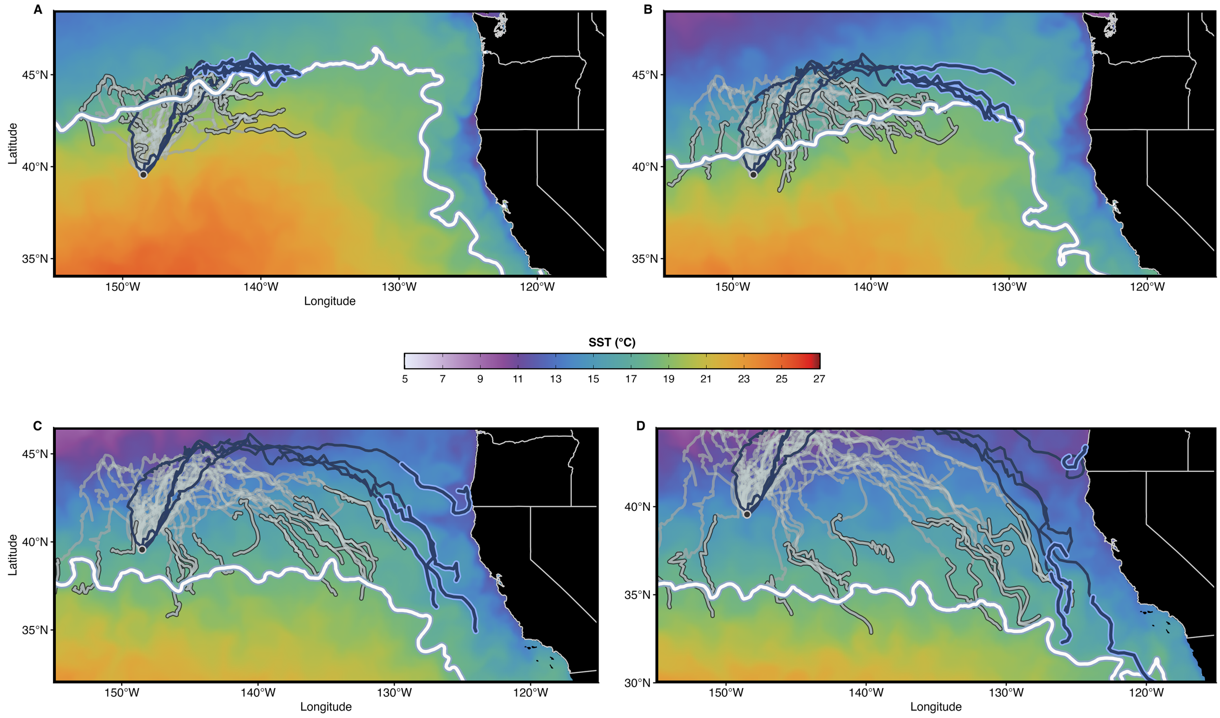

FIGURE 6
Monthly sea surface temperatures (SSTs) for **(A)** September, **(B)** October, **(C)** November, and **(D)** December 2024. Complete turtle tracks are shown in grey; portions of tracks for the four individuals that entered the CCS are highlighted in dark purple, with positions corresponding to each month. The white line indicates the average monthly position of the 18 °C SST isotherm.

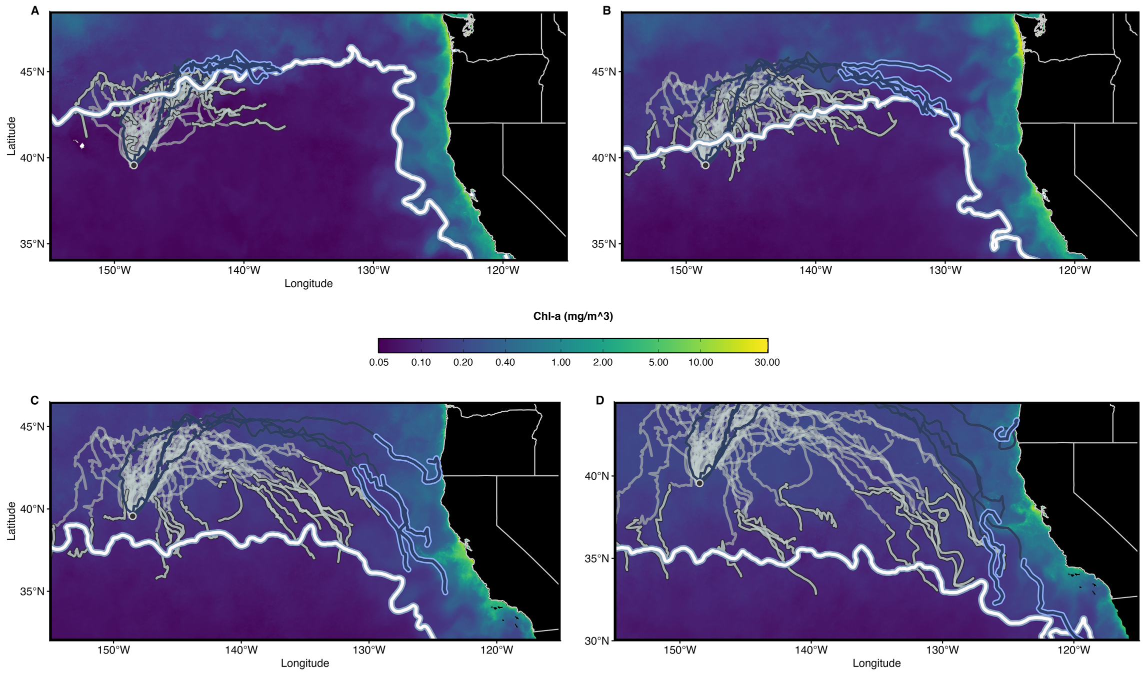

FIGURE 7
Monthly mean chlorophyll-a concentrations for **(A)** September, **(B)** October, **(C)** November, and **(D)** December 2024. Complete turtle tracks are shown in grey; portions of tracks for the four individuals that entered the CCS are highlighted in dark purple, with positions corresponding to each month. The white line indicates the average monthly position of the 18 °C SST isotherm.

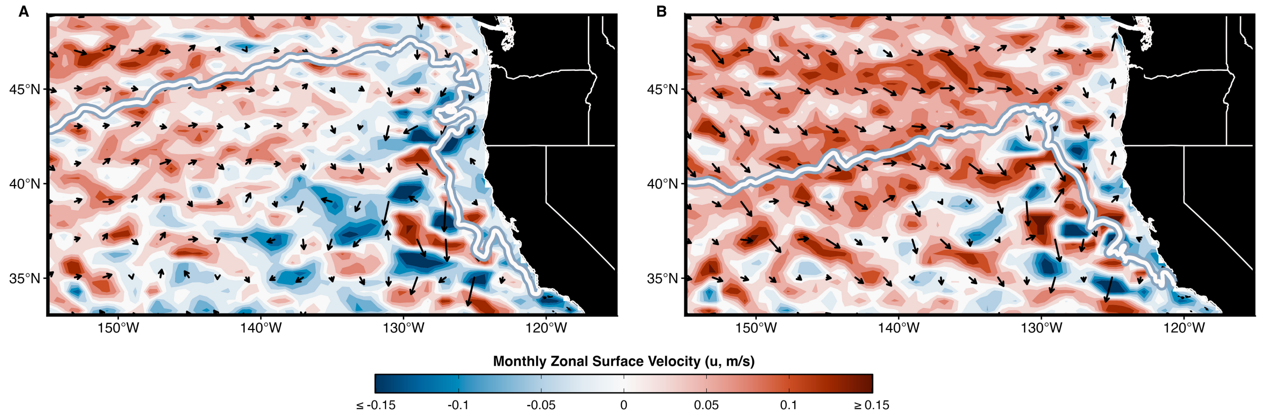

FIGURE 8
Monthly mean zonal currents (u, m/s) overlaid with current vectors for **(A)** September 2014, **(B)** October 2014, resampled to a 0.5° x 0.5° spatial grid. Vector arrows represent 0.1 m/s. The white line indicates the average monthly position of the 18 °C SST-isotherm.

highly productive TZCF (Polovina et al., 2001). In 2024, anomalous oceanographic conditions shifted the 18°C isotherm farther north, causing it to overlap with the NPC (Figure 4). This intersection altered historic environmental cues that turtles have historically followed and facilitated access to novel foraging opportunities at higher latitudes. While most turtles in the region shifted south with the seasonal migration of the 18°C isotherm, four individuals entered into the northern CCS, a habitat not previously documented for this population. Not only does the NPC provide eastward transport, it also contains eddies and current meanders where cool nutrient-rich, enhanced chlorophyll waters mix with warm subtropical waters to create forage habitat for loggerhead sea turtles (Figure 7). The movements of these four individuals coincided with the intensification of the NPC's zonal flow, and the occurrence of thermally suitable, productive waters, supporting the hypothesis that strong eastward advection combined with an expanded thermal envelope temporarily opened a high-latitude migratory corridor into the CCS.

Conditions in October 2024 were most similar to those observed in 2014 (Figure 8, Supplementary Figure 2), as a strong MHW developed east of 150°W longitude (Mercator Ocean, 2025) and resembled the oceanographic conditions that preceded the previously mentioned 2014–2015 El Niño and 2015–2016 MHW events, which resulted in overlapping juvenile loggerheads and fisheries activities within the Southern California Bight (Eguchi et al., 2018; Welch et al., 2019). Given these parallels, the 2014 conditions serve as a historical example for assessing whether similar processes, such as elevated SSTs, enhanced currents, and behavioral flexibility, may facilitate forage opportunities for juvenile loggerheads within the CCS. Their northern positioning coincided with SST and chlorophyll gradients, suggesting they actively targeted the biologically productive frontal features, while their cohort counterparts remained in more oligotrophic waters (Figures 7A, B). These conditions, shaped by upwelling and offshore advection, would be advantageous, exposing them to enhanced prey availability and foraging opportunities. The divergence of these four individuals into the northern CCS in 2024 under similar conditions further suggests that these thermal and advective features could expand the habitat range of juvenile North Pacific loggerhead sea turtles, increasing the likelihood of their longer-term presence within the region. Taken together with our drift analysis, these patterns suggest that the four individuals entering the northern CCS exhibited eastward swimming behavior, facilitated by favorable advection, to exploit a transient migratory corridor, while the majority of their cohort remained in offshore, oligotrophic habitat following the shift of the 18°C SST isotherm. Furthermore, the movements of these four 'sentinel' individuals offer valuable insights into potential redistributions for this population in response to future environmental changes within the region.

Our findings highlight the importance of elevated water temperatures and altered currents in shaping the eastward trajectories of four juvenile North Pacific loggerheads along a newly identified migratory route. However, the ecological outcomes of this corridor were variable. Three of the four exhibited adaptive responses, moving south within the CCS during November and December 2024 (Figures 6C, D, 7C, D). These movements reflect the need to balance thermal constraints and foraging, which are critical for ectothermic organisms (Huey, 1991; Epperly et al., 1995). While they encountered a range of SSTs, their southward trajectories ultimately connected them to established juvenile foraging habitats in the eastern North Pacific (Kobayashi et al., 2008; Seminoff et al., 2014). Two individuals, Mei and Rosa, successfully entered neritic waters along the Baja California Peninsula, while Fumi remained oceanic waters, consistent with the juvenile's oceanic habitat phase (Kobayashi et al., 2008; Abecassis et al., 2013). Further analysis is underway to identify whether Fumi initiated homing (*see* Gaspar et al., 2025). Regardless, this ability to exploit both oceanic and neritic environments is characteristic of juvenile loggerheads. It has been recorded in populations from the western North Atlantic (McClellan and Read, 2007; Mansfield et al., 2009) and the Mediterranean (Revelles et al., 2007; Casale et al., 2008). However, such shifts have been challenging to observe in the North Pacific population (Abecassis et al., 2013; Briscoe et al., 2021), yet the adaptability of these individuals underscores their behavioral plasticity and the importance of maintaining habitat connectivity across pelagic and neritic zones in the eastern North Pacific. Given our limited understanding of individuals experiencing ontogenetic habitat shifts between pelagic and neritic zones, documenting alternative life history strategies through a migratory corridor is a significant contribution.

However, not all individuals achieved successful outcomes. The fourth, northernmost individual, Kanna, experienced a notably different result. Upon entering into the colder waters of the CCS, Kanna was likely transported northward as the NPC bifurcated near the coast and as it branched northward to form the Alaska Current. This trajectory would have resulted in suboptimal thermal conditions that exceeded its lower thermal tolerance limits (Figure 6). This turtle likely suffered from cold stunning and potential mortality. Our interpretation is supported by several independent lines of evidence of stranded or cold-stunned wild turtles in the northern CCS. In 2023, a cold-stunned loggerhead sea turtle, presumed to have followed a similar route to Kanna, was rescued by the staff of the Vancouver Aquarium (pers. comm Vancouver Aquarium). Similar occurrences have been documented by media, including the rescues of cold-stunned loggerheads (Williams, 2021; Buchanan, 2024) and an increase in stranded loggerheads along the Oregon coast in 2024 (Ehrlich, 2025), as well as similar occurrences along the California coast (Early-Capistrán et al., 2024, Harris et al., in prep). The satellite tracking of these 53 turtles as part of the STRETCH Project has highlighted the ability of juvenile loggerheads to reach coastal foraging grounds within southern California (https://www.loggerheadstretch.org/map.html), however the four individuals in this study represent the first evidence of their emergence within the northern CCS. While the other three turtles successfully adapted, Kanna's trajectory underscores the physiological risks associated with a novel migratory pathway and highlights the vulnerability of juvenile loggerheads to oceanographic change.

The emergence of this dynamic corridor raises significant ecological and management concerns related to climate-driven changes to the ENP. The accelerated rate of oceanographic change in the region has been documented among highly mobile marine species (*see* Welch et al. (2023); Lezama-Ochoa et al. (2024); Tanaka et al. (2021); Briscoe et al. (2025), and has contributed to the poleward expansion of tropical and subtropical taxa, altering the composition and distribution of prey species within the NPTZ and CCS (Cheung et al., 2015; Cavole et al., 2016; Gomes et al., 2024). This biogeographic restructuring, a phenomenon known as 'tropicalization' (Osland et al., 2021; Zarzyczny et al., 2023), has contributed to the increasing occurrence of warm-water organisms such as *Vella vella*, pyrosomes (*Pyrosoma atlanticum*), and Pacific sardines (*Sardinops sagax*) within the northern CCS (Lindegren et al., 2013; Brodeur et al., 2018; Sutherland et al., 2018; Morgan et al., 2019; Jones et al., 2021; Gomes et al., 2024). Most recently, the genetic confirmation of Japanese sardines (*Sardinops melanosticata*) within the region in response to MHW events represents an independent example of intermittent corridor development within the NPC (Longo et al., 2024), enabling species to access previously restricted habitat. Such shifts may present foraging opportunities for many higher trophic level species in addition to juvenile loggerheads, however they also risk creating a spatial mismatch between suitable thermal conditions, prey availability, and energetic demands, with clear winners and losers (Cavole et al., 2016; Venegas et al., 2023). Our four sentinel turtles illustrate both the potential promises and perils of accelerated climate change: while some individuals will successfully exploit new resources, others will struggle to navigate shifting habitats associated with environmental extremes.

These ecological changes have significant consequences for the conservation and management of this vulnerable species. As loggerheads migrate through the CCS, they could be exposed to increased commercial fisheries, including operations that historically posed a bycatch risk to highly migratory species (Hazen et al., 2018). Welch et al. (2019) documented the overlap of large numbers of juvenile loggerheads off Southern California, coinciding with increased fishing activity—indicating a potential rise in fisheries interactions under warming scenarios. As ocean temperatures continue to rise, this migratory corridor may become more persistent, resulting in a higher abundance of loggerheads in the northern and central CCS that may increase their exposure to fishing efforts. Recent data indicate that pelagic fishing efforts in the region have shifted in response to warming events, as productive zones migrate and species redistribute (Farchadi et al., 2024; Muhling et al., 2025). Additionally, the recently NOAA-approved expansion longline fisheries in California waters (NOAA, 2025a), combined with the proposed increased aquaculture within the Southern California Bight (NOAA, 2025b), may further elevate interaction rates and will require adaptive management strategies. Consequently, the increased presence of loggerheads in these high-effort fishing areas raises concerns about incidental capture, posing new challenges for conservation and management.

Conclusions

Our study provides the first confirmed evidence of juvenile North Pacific loggerhead sea turtles using a northern CCS migratory corridor, developed under anomalous warm-water intrusions and an intensified NPC flow. Building on the Thermal Corridor Hypothesis (Briscoe et al., 2021), our findings emphasize the dynamic nature of corridor development and the integral contribution of other environmental variables, such as current patterns, in shaping ephemeral migratory pathways. While our results illustrate the capacity of North Pacific loggerheads to adaptively respond to oceanographic variability and exploit novel eastern migratory routes, they also highlight the variability in survival outcomes. Future research will be necessary to more comprehensively assess the conservation and management implications of the increased presence of this species within the region. This will be particularly important as accelerated ocean conditions continue to reshape the region. Understanding the emergence and variability of such dynamic corridors will be fundamental for improved predictions of redistributions and range expansions, evaluation of associated risks, and the development of dynamic management strategies that ensure the resilience of this vulnerable population in the face of a changing ocean.

Data availability statement

This study has been conducted using publicly available environmental data from NOAA Coral Reef Watch Version 3.1 (https://coralreefwatch.noaa.gov) and E.U. Copernicus Marine Service (https://marine.copernicus.eu/). The datasets presented in this article are not yet readily available because data collection is ongoing but may be available upon request. Requests to access the datasets should be directed to Denise Parker (denise.m.parker@outlook.com) and Larry Crowder (lbcrowder@stanford.edu).

Ethics statement

The animal study was approved by Stanford University Protocol APLAC-34400. The study was conducted in accordance with the local legislation and institutional requirements.

Author contributions

DB: Writing – review & editing, Formal analysis, Writing – original draft, Methodology, Conceptualization, Visualization, Investigation, Data curation. LC: Project administration, Investigation, Writing – review & editing, Conceptualization, Funding acquisition, Resources. GB: Conceptualization, Writing – review & editing, Investigation, Resources, Data curation, Methodology. JS: Conceptualization, Investigation, Writing – review & editing. FA: Writing – review & editing, Data curation. PG: Writing – review & editing, Formal analysis, Methodology. CL: Methodology, Writing – review & editing. LJ: Resources, Writing – review & editing, Methodology. MK: Resources, Writing – review & editing, Methodology, Data curation. MM: Writing – review & editing, Resources, Data curation, Methodology. DP: Writing – review & editing, Data curation. MR: Writing – review & editing, Data curation, Resources, Methodology. TS: Resources, Writing – review & editing, Methodology, Data curation. BS: Methodology, Writing – review & editing. JT-B: Methodology, Writing – review & editing, Formal analysis. CT: Writing – review & editing, Data curation. NY: Methodology, Writing – review & editing. JP: Investigation, Writing – original draft, Writing – review & editing, Conceptualization, Formal analysis, Data curation, Methodology.

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Conflict of interest

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

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2026.1733784/full#supplementary-material

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