Title

The Effects of Inter-annual Climate Variability on the Departures of Leatherback Marine Turtles from the California Current Ecosystem

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The Effects of Inter-annual Climate Variability on the Departures of Leatherback Marine Turtles from the California Current Ecosystem

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Keywords: *Dermochelys coriacea*, El Niño/Southern Oscillation, La Niña, Leatherback Conservation Area, Adaptive Management

ABSTRACT

The Pacific Ocean is a highly variable environment, and changes in oceanographic conditions impact the distributions of many organisms. Inter-annual climate variability, especially the El Niño/Southern Oscillation, is known to have wide-ranging impacts on organisms in the California Current. Understanding the factors that drive changes in the spatial ecology of organisms, such as inter-annual climate variability, is essential in many cases for effective conservation. Leatherback marine turtles are endangered, and many populations, especially in the Pacific, are declining due to anthropogenic impacts. This study demonstrates that during positive phases of the El Niño/Southern Oscillation, there is a southward bias to Western Pacific leatherback tracks as they depart the California Current. During autumn when leatherbacks frequent the California Current, the US National Marine Fisheries Service institutes a large time-area closure for the drift gillnet fishery to minimize leatherback bycatch. During positive phase autumn months, this study reveals that much of the leatherback activity occurs south of the time-area closure's southern boundary where drift gillnet fishing is still permitted. With the southward movements of leatherbacks during positive phase autumn months, this study suggests seasonal dynamic adaptive management measures may be warranted.

INTRODUCTION

The leatherback marine turtle, *Dermochelys coriacea*, is the most widely distributed and oceanic of the marine turtles, yet it is also one of the most threatened. Leatherbacks were one of the first species listed in 1970 on the US Endangered Species List prior to the passing of the Endangered Species Act of 1973 (ESA) (USFWS 1970). They are also listed as an Annex 1 species through the Convention on International Trade in Endangered Species (UNEP-WCMC 2013). Although they have been afforded protection for several decades, many leatherback marine turtle populations are still in trouble. Indeed, some populations such as the Western Pacific population have declined by as much as 78% in the last 27 years (Tapilatu et al. 2013; Figure 1). As long-lived, slow reproducing creatures, marine turtles are particularly vulnerable to anthropogenic-induced mortality. Species with long lifespans and low fecundity are often unable to sustain steady populations under the pressures of anthropogenic-induced mortality (Congdon et al. 1993). The main factors of decline affecting leatherback populations include fisheries bycatch, plastic pollution, and human-induced low recruitment (e.g. nest poaching, light pollution, and subsidized predator nest depredation) (Tomillo et al. 2008; Mrosovsky et al. 2009; Wallace and Saba 2009; Santos et al. 2012; Welicky et al. 2012).

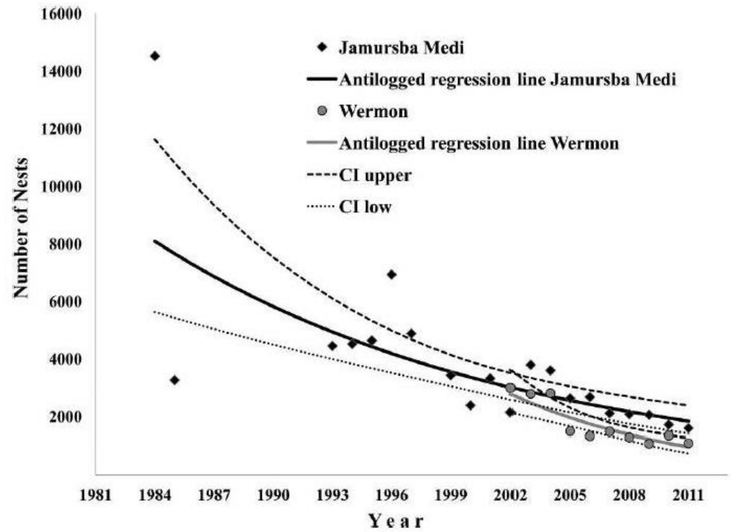

Figure 1. The declining trend of Western Pacific leatherback annual nesting abundances from Bird's Head Peninsula, Papua Barat, Indonesia from 1984-2011. Graph from Tapilatu et al. 2013.

In the California Current Ecosystem, understanding the factors that affect the spatial ecology of leatherback turtles is particularly pertinent to their conservation as turtle concentrations in late summer/early autumn often spatially coincide with fisheries operations.

Bycatch in one of these fisheries, the California/Oregon drift gillnet fishery for swordfish and thresher shark, is a major source of adult leatherback mortality (Spotila et al. 2000; Carretta et al. 2004; Lewison et al. 2009). One such factor that affects the spatial ecology of many organisms in the California Current is inter-annual climate variability (Caselle et al. 2010; Menge et al. 2011; Allen et al. 2013). This research investigates how the El Niño/Southern Oscillation, one of the most important sources of inter-annual climate variability, affects the migrations of Western Pacific leatherbacks as they depart the California Current Ecosystem. Furthermore, this project provides insight into potential adaptive management measures that can be implemented to minimize seasonal leatherback bycatch while maintaining some of the current operations of the California/Oregon drift gillnet fishery.

Western Pacific Leatherback Marine Turtle Ecology

The leatherback marine turtle is a highly migratory species that has been reported throughout the world's oceans (Figure 2). Additionally, it has the most extensive range (both horizontally and vertically) of any living reptile. Nesting is limited to tropical and subtropical latitudes, and in the Pacific Ocean, nesting aggregations occur mostly in Mexico, Costa Rica, Indonesia, the Solomon Islands, and Papua New Guinea (NOAA NMFS and USFWS 1998). However, leatherbacks are frequently found in temperate regions of the oceans (Goff and Lien 1988; Benson et al. 2011). Leatherback marine turtles have several physiological adaptations that enable them to inhabit cold waters within their extended geographical range. These

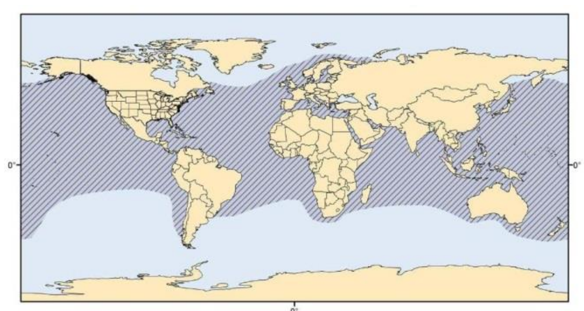

Figure 2. Worldwide distribution of leatherback marine turtles. The shaded area represents the known range of leatherback turtles. Map from NOAA NMFS: http://www.nmfs.noaa.gov/pr/species/turtles/leatherback.htm

adaptations include a countercurrent circulatory heat exchange system (Greer et al. 1973), a thick layer of insulating fat (Goff and Lien 1988; Davenport et al. 1990), ectothermic homeothermy due to their low surface area to volume ratio (Paladino et al. 1990), and an increased ability to elevate their body temperature from metabolic activity (Southwood et al. 2005; Bostrom and Jones 2007). These factors enable leatherback marine turtles to undergo extensive migrations to forage in distant, yet oftentimes cold waters.

Based on genetic studies, $^{\delta}$15N amino acid stable isotope analysis, and satellite tracking data, two distinct populations of leatherbacks in the Pacific Ocean have been identified: the Eastern Pacific nesting population and the Western Pacific nesting population (NOAA NMFS 2000; Shillinger et al. 2008; Benson et al. 2011; Seminoff et al. 2012; Figure 3). Many Western

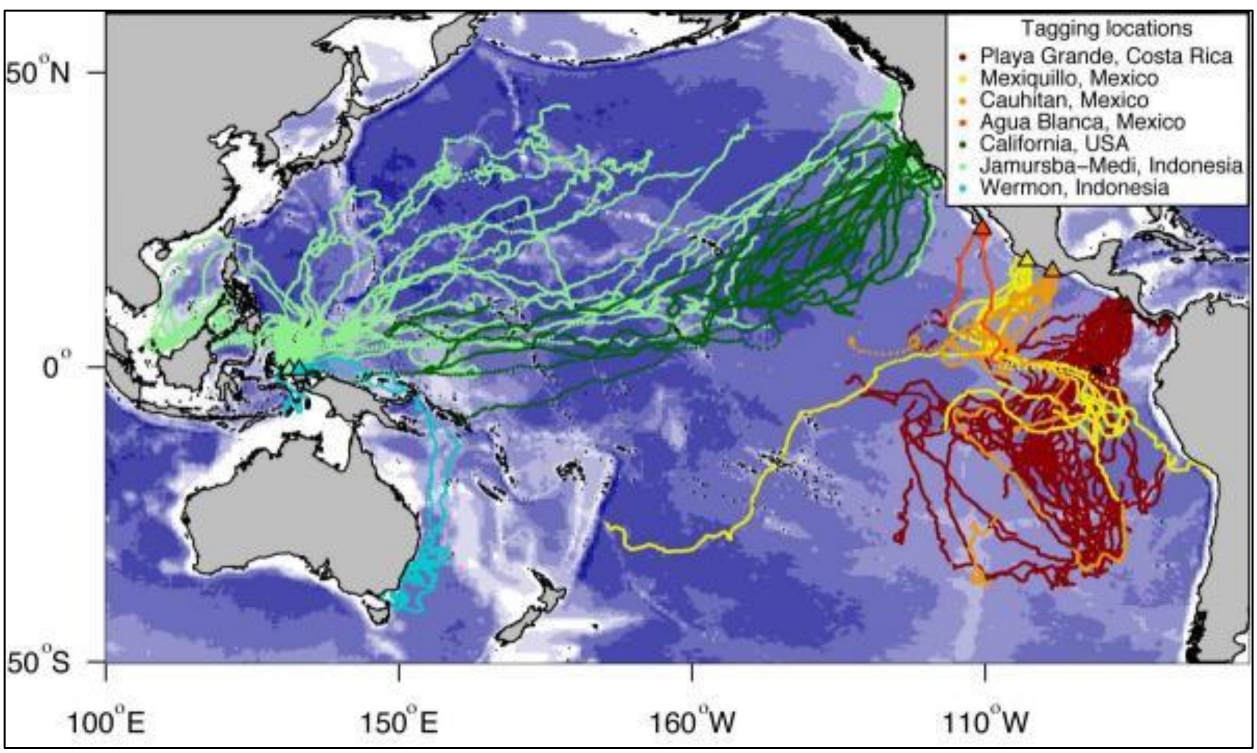

Figure 3. Tracks of Western Pacific and Eastern Pacific leatherback marine turtles. Turtle tracks are color coded by original tagging location. Many individuals of the Western Pacific population (dark and light green tracks) migrate across the Pacific Ocean from breeding grounds in Indonesia to feed in the California Current Ecosystem. Map from Bailey et al. 2012a.

Pacific leatherbacks nesting in boreal summer undergo trans-Pacific migrations from breeding grounds in the Indo-Pacific to foraging grounds off the west coast of North America (Benson et al. 2011; Figure 3). Migrating to these distant foraging grounds requires approximately 10 to 12 months one direction and may involve multiple years of migrating to high-latitude foraging grounds in summer and low latitudes in winter before returning to the Western Pacific (Benson et al. 2011).

In the California Current Ecosystem off the west coast of North America, strong northwesterly winds blow parallel to the coast during April and May, resulting in strong spring upwelling events along this eastern boundary current (Hickey and Royer 2001). These spring upwelling events bring cold nutrient-rich waters to the surface making the area highly biologically productive (Hickey and Royer 2001). The rich supply of nutrients also encourages gelatinous prey blooms, to which Western Pacific leatherbacks are drawn in the summer and fall (Graham 2009). Leatherbacks feed mainly on cnidarians such as jellyfish and siphonophores, squid, and to lesser extent on tunicates such as salps and pyrosomas (NOAA NMFS and USFWS 1998; Graham 2009). In the California Current, leatherbacks frequently forage on brown sea nettles, and the distribution of this prey species is considered critical for their foraging success in this region (NOAA NMFS 2012).

Inter-annual Climate Variability

El Niño/Southern Oscillation

The Pacific Ocean is a highly variable environment with large-scale inter-decadal and inter-annual oscillations in ocean conditions. The El Niño/Southern Oscillation (ENSO) is one of the most important inter-annual oscillations in oceanic and atmospheric conditions, and its effects can be seen in oceanic and weather fluctuations around the globe (Chang and Zebiak

2003). Originating in the Eastern Tropical Pacific, it is a cyclical climate phenomenon triggered every 2 to 7 years by interactions between the atmosphere and oceans (Chang and Zebiak 2003). There are three main ENSO phases: the neutral phase (normal oceanic conditions), the positive phase (atypically warm conditions), and the negative phase (atypically cool conditions) in the Eastern Tropical Pacific Ocean. Warm positive phases are commonly called El Niño conditions, while cool negative phases are typically called La Niña conditions.

During neutral phases in the tropical Pacific Ocean, easterly trade winds along the surface of the equatorial Pacific drive a strong upwelling of deep, cold water within the Peruvian Current along the South American coast (Chang and Zebiak 2003; Figure 4). This region of cool water is known as the Eastern Equatorial Pacific Cold Tongue, and it is characterized by high atmospheric surface pressure and low precipitation (Chang and Zebiak 2003). Temperatures in the Eastern Equatorial Pacific Cold Tongue are typically < 21ºC (Kayano et al. 2005). In contrast, in the Western Pacific, some of the warmest waters of the oceans (> 29ºC) can be found (Kayano et al. 2005; Sun et al. 2013). This region is called the Western Pacific Warm Pool, and low atmospheric surface pressures over this area cause high precipitation. This sharp gradient in sea surface temperatures across the equatorial Pacific drives the Pacific Walker Circulation. This circulation system consists of rising warm, wet air in the Western Pacific and sinking cool, dry air in the Eastern Pacific, which are cyclically

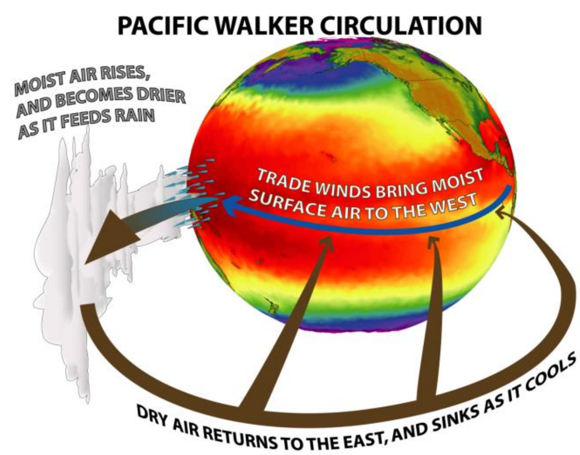

Figure 4. A schematic of the Pacific Walker Circulation. Image from NOAA Geophysical Fluid Dynamics Laboratory: http://www.gfdl.noaa.gov/tropical-atmospheric-circulation-slowdown

interconnected in the lower troposphere by surface easterly trade winds and upper westerly winds (Held and Hou 1980; Chang and Zebiak 2003; Sohn et al. 2013).

El Niño or La Niña conditions arise from fluctuations in the coupled oceanic-atmospheric Pacific Walker Circulation System. During El Niño conditions, the trade winds in the Pacific weaken, reducing the intensity of upwelling in the equatorial Peruvian Current, leading to anomalously warm waters across latitudinal gradients in the Eastern Pacific (Chang and Zebiak 2003). Furthermore due to this weakening of the Pacific Walker Circulation System, the Western Pacific experiences cooler than average sea surface temperatures and decreased precipitation. El Niño's counterpart, La Niña, is a strengthening of the Walker Circulation System, and it is characterized by cooler than average waters with high productivity in the Eastern Pacific and warmer and wetter than average conditions in the Western Pacific (Chang and Zebiak 2003). During both cycles of ENSO, sea surface temperature, sea surface height, ocean productivity, upwelling, precipitation, currents, and sea surface fronts change across the Pacific, affecting how organisms interact with their environment (Kayano et al. 2005).

Known Effects of ENSO on Other Pacific Populations

Leatherbacks are known to alter behavior based on changing oceanographic conditions (Saba et al. 2008a; Wallace and Saba 2009). For example, nesting Eastern Pacific female leatherbacks show strong sensitivity to the effects of El Niño/Southern Oscillation events (Saba et al. 2007, Saba et al. 2008b). During cool regimes in the Eastern Tropical Pacific, Eastern Pacific females exhibit shorter remigration intervals (time spent between nesting seasons). These shorter remigration intervals mean that Eastern Pacific leatherbacks are nesting more frequently and annual egg production increases during La Niña conditions. Saba et al. (2007) and (2008a) suggests that productivity transitions (and thus limits on the availability of food) at leatherback foraging areas in the Eastern Tropical and Southeastern Pacific during these cycles likely are the cause of these variable remigration intervals. For example, Eastern Pacific leatherback female locations are positively correlated with large-scale equatorial phytoplankton blooms that were most likely induced by iron enrichment following the termination of an El Niño event (Saba et al. 2008a). To date, no papers have investigated the effects of ENSO on remigration intervals or inter-nesting intervals (time spent between nesting events of one season) for females of the Western Pacific population.

In-water Management and Protections for Western Pacific Leatherbacks

In September 2012, the leatherback became California's state marine reptile (CA 2012). As part of this measure, California has designated October 15 annually as Pacific Leatherback Conservation Day (CA 2012). Although not afforded any special protections beyond those that it already receives as an endangered species under the ESA, this move raises awareness for leatherback conservation within California waters and may serve to better engage local public in leatherback conservation issues.

Under Section 4 of the Endangered Species Act of 1973, the National Oceanic and Atmospheric Administration (NOAA) National Marine Fisheries Service (NMFS) is required to designate areas of critical habitat for endangered and threatened species under its jurisdiction (United States 1973). In 2012, the NMFS revised its leatherback critical habitat designation to include an additional 41,914 miles^2 in the Pacific Ocean off the coasts of California, Oregon, and Washington (NOAA NMFS 2012; Figure 5A). Prior to this revision, only habitat off St. Croix, US Virgin Islands was designated as critical habitat for Atlantic leatherback populations (NOAA NMFS 1979). As a protection measure, critical habitat designations only affect federal projects

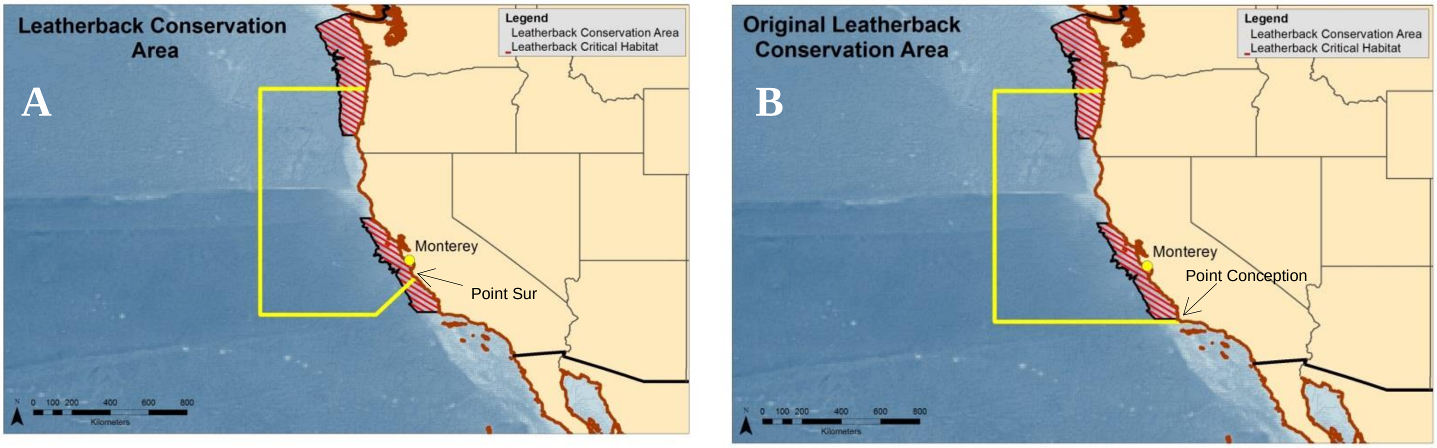

Figure 5. Maps showing the boundaries of Western Pacific leatherback critical habitat (red dashed polygons) and the current (A) and biologically recommended (B) boundaries for the Leatherback Conservation Area (yellow polygon).

that may “adversely modify or destroy critical habitat” (NOAA 2012). These designations do not affect private endeavors such as boating or fishing.

One of the main sources of mortality for Western Pacific leatherbacks in the California Current is a result of fishery bycatch. Although leatherback bycatch is a rare event, when it does occur, it can have a significant impact on the population (NOAA NMFS 2000). Because of this, the NMFS implemented the Leatherback Conservation Area (LCA) in 2001 (NOAA NMFS 2001a; Figure 5A). The LCA is a time-area closure for the California/Oregon drift gillnet fishery off the west coast of the United States. This is an annual closure of all drift gillnet fishing within designated boundaries from August 15 to November 15 in order to reduce leatherback marine turtle bycatch (NOAA NMFS 2001a). Prior to the LCA’s implementation, the California/Oregon drift gillnet fishery was estimated to entangle approximately 13 to 27 leatherbacks per year, with approximately 8 to 17 of these takes resulting in mortality (NOAA NMFS 2000). The initial NMFS biological opinion recommended the LCA be bounded by straight lines connecting the geographic coordinates of Point Conception, CA (34°27 N) to (34°27’ N, 129° W), to (45° N, 129° W), to the 45° N intersection with the Oregon coast (NOAA NMFS 2000; Figure 5B). However, due to pressure from the drift gillnet fishing community to fish north of Point

Conception in order to remain economically viable, an alternative southern boundary was designed (NOAA NMFS 2001a). The NMFS adjusted the eastern part of the southern boundary at (34°27’ N, 123°35’ W) and angled the boundary line north to the intersection with land just south of Point Sur (36°18.5’ N) (NOAA NMFS 2001a; Figure 5A). The NMFS chose to implement this alternate design for the Leatherback Conservation Area, and it is this angled design for the LCA that has been in effect annually since 2001.

MATERIALS AND METHODS

Argos Satellite Telemetry Data

Leatherback marine turtle tracking data were obtained from the NOAA Southwest Fisheries Science Center (SWFSC) courtesy of NOAA researcher Scott Benson. Turtles were tracked via satellite telemetry using Service Argos. Details of tracking and the methods of platform animal attachment are available in Benson et al. (2011).

A sample size of 41 satellite tracked leatherback marine turtles tagged near Monterey Bay, CA from 2000-2011 was used in this analysis. Filters were applied to Argos satellite telemetry data to remove erroneous fixes using the Douglas-Argos Filter available online (Wikelski and Kays 2013). The Douglas-Argos Filter uses the Douglas-Argos Algorithm as described in Douglas et al. (2012). Running the Douglas-Argos Algorithm selects between Argos locations 1 and 2 and filters out erroneous point locations using a distance-angle-rate algorithm. A maximum redundancy of 10 km, a maximum realistic rate of movement of 10 km/hr, and a rate coefficient of 40° were chosen as biological plausibility thresholds following examples in the literature (Witt et al. 2011; Bailey et al. 2012b). All Z Location Classes were removed from analysis. Because the distance-angle-rate filter does not filter the last location of a track, these points were manually removed from further analysis. After application of the filter, additional erroneous points, such as those intersecting land, were removed manually.

Geographic Information System Data

All maps were created using ArcGIS 10.0.0. Bathymetry data were obtained as an ETOPO1 global 1-minute gridded elevation dataset (ice sheet surface) at 0.0166667 degrees resolution from the NOAA BloomWatch 360 browser (NOAA CoastWatch 2013). US maritime boundary shapefiles were obtained from the NOAA Office of Coast Survey website (NOAA OCS 2012). High resolution land and geopolitical layers were obtained from the NOAA National Geophysical Data Center's Global Self-consistent, Hierarchical, High-resolution Geography Database (GSHHG) version 2.2.2 (NOAA NGDC 2013). A description of the processing and assembly of the GSHHG data can be found in Wessel and Smith (1996).

Additionally, leatherback critical habitat shapefiles were obtained from NOAA Fisheries Geographic Information Systems (NOAA NMFS 2013). Leatherback Conservation Area point data were obtained from the federal register (NOAA NMFS 2001a). Using ArcGIS, these point data were converted into polygon feature classes to display the leatherback conservation areas' boundaries. Drift gillnet set and leatherback take point data were obtained as tabular data courtesy of Jim Carretta at NOAA SWFSC and then converted into a point feature class for use in ArcGIS.

The geographic coordinates 37° N, 122° W (Benson et al. 2011) were used as the location of leatherback tagging events that occurred in Monterey Bay, California.

El Niño/Southern Oscillation Data

Values from the Multivariate ENSO Index (MEI) were used to assign ENSO phase in this analysis (NOAA ESRL 2013). Although a measure of tropical ENSO anomalies, the MEI is commonly adopted as a tool for investigating ENSO effects in temperate Pacific climates (Wharton et al. 2009; Menge et al. 2011; Bollens et al. 2011; Tremblay et al. 2011; Hallack-Alegria et al. 2012). These values are calculated as 1/1000 of standard deviations and are based off six main variable forcings over the tropical Pacific: sea surface temperature, sea-level pressure, surface air temperature, zonal and meridional components of surface wind, and total cloudiness fraction of the sky (Wolter 1987; Wolter and Timlin 1993; NOAA ESRL 2013). Since the values for the MEI are calculated on a sliding bi-monthly scale (e.g. Jan-Feb, Feb-Mar, Mar-Apr), and there is approximately a week-long lag in the response of the global atmosphere to tropical sea surface temperature anomalies (NOAA ESRL 2013), monthly MEI values were assigned to the first month of the sliding scale. For example, the Jan-Feb value was assigned to January and the Feb-Mar value was assigned to February.

A ±0.8 standard deviation cutoff was selected for positive and negative phases of the oscillation. All monthly MEI values ≥ 0.8 were assigned as positive phase months, all monthly MEI values ≤ –0.8 were assigned as negative phase months, and all monthly MEI values which fell in between were assigned as neutral phase months for analyses.

Statistical Analysis

Analyses were conducted in R 3.0.0 (R Core Team 2013). Each animal's monthly mean location was calculated by taking the means of the monthly values for each animal's longitude and latitude. Using these mean locations, each animal's mean bearing and distance traveled from Monterey Bay, CA was calculated for the month of September using the function 'bearing' in the package 'argosfilter' and the function 'rdist.earth' in the package 'fields' respectively (Frietas 2012; Furrer et al. 2013). September was chosen as it is during the height of when leatherbacks are in the California Current, during an important time when the leatherback conservation area is in effect, and when the animals used in this analysis were tagged and began their migration out of the California current. A total of 38 animal track segments from 2000-2007 were used for September analyses. For animals for which there are data for multiple Septembers, only data from the September in which they were tagged were used in order to control for a possible tagging effect on turtle movements.

Bearing and distance values were tested for normality via an Anderson-Darling test using the function 'ad.test' in the package 'nortest' (Gross and Ligges 2012). Monthly ENSO phase and each animal's monthly mean bearing and mean distance were compared using nonparametric Kruskal-Wallis Rank Sum tests with the function 'kruskal.test' in R (R Core Team 2013). A Nemenyi-Damico-Wolfe-Dunn post-test was run to elucidate significant group comparisons as described in Hollander and Wolfe (1999) using the function 'oneway_test' and following the example on page 28 in the package 'coin' (Hothorn et al. 2008).

RESULTS

Autumn Departure Trends

From September to December 2000-2011, there were 6 ENSO positive months, 7 ENSO negative months, and 20 ENSO neutral months (Table 1). There were no satellite tracking data available for the autumns of 2008, 2009, and 2010. Across all seasons, there were 9 individual turtles tracked during ENSO positive seasons, 5 individual turtles tracked during ENSO negative seasons, and 27 individual turtles tracked during ENSO neutral seasons.

Mapping leatherback departures from the California Current by ENSO phase reveal an interesting trend in leatherback movements from September to December. Animals in all three groups start in September near Monterey Bay, CA (their tagging site), and then most travel progressively southwest to lower latitudes by December (Figure 6A-D). However, when plotting tracks by ENSO phase, it appears that animals departing during warm and cold phase months are moving farther south than turtles departing during neutral months (Figure 7). There is spatial overlap between all three groups near the southern edge of neutral month tracks and the northern edges of positive and negative month tracks; however, it visually appears that turtles departing in neutral phase months travel farther north along this wide migratory corridor while animals departing during negative and positive phases are traveling farther south. This separation of tracks by ENSO phase can be further seen by taking the mean of the mean monthly location for each turtle and plotting these locations by ENSO phase (Figure 8).

Autumn Multivariate ENSO Index Values and Number of Turtle Tracks/Month								
Year	September	n	October	n	November	n	December	n
2000	-0.247	2	-0.381	2	-0.755	2	-0.581	1
2001	-0.126	1	-0.276	1	-0.18	1	0.003	2
2002	0.808	8	0.952	8	1.059	8	1.11	7
2003	0.441	7	0.509	7	0.519	7	0.315	8
2004	0.524	10	0.467	15	0.786	12	0.643	8
2005	0.255	6	-0.166	9	-0.407	3	-0.585	2
2006	NTD				1.292	1	0.951	1
2007	-1.162	4	-1.142	4	-1.177	4	-1.168	4
2008	NTD							
2009	NTD							
2010	NTD							
2011	NTD		-0.965	1	-0.978	1	-0.978	1
Total Tracks		38		47		39		34

Table 1. A table of the Multivariate ENSO Index (MEI) values for each month of turtle tracking data. Red numbers indicate values above the 0.8 standard deviation cutoff and are considered positive (warm) phase months. Blue numbers are less than the -0.8 cutoff and are considered negative (cold) phase months. Black values fall in between the cutoff values and are considered neutral months. NTD: No Tracking Data.

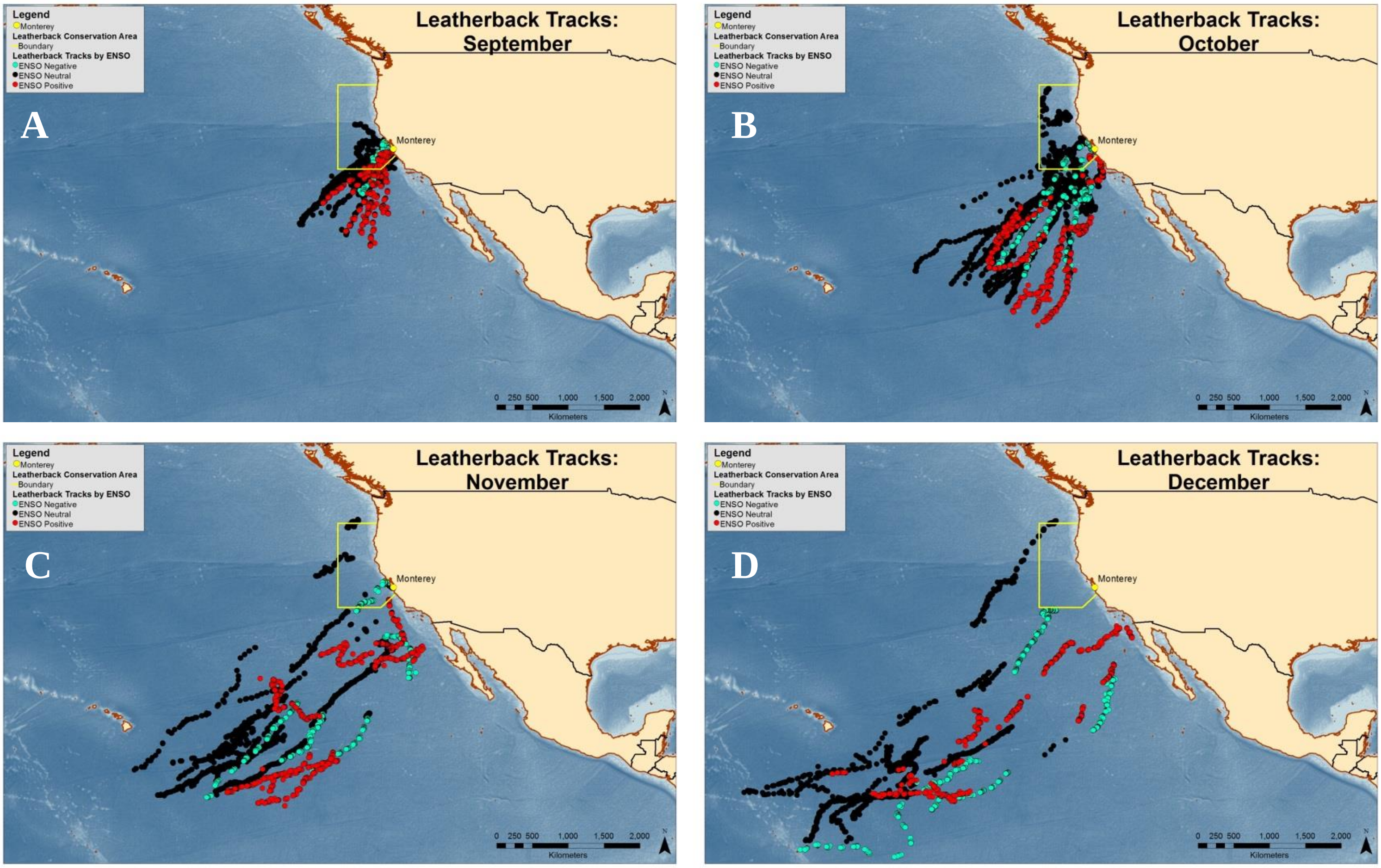

Figure 6. Maps of leatherback turtle departures from the California Current in September (A), October (B), November (C), and December (D). Leatherback turtles used in the study were tagged in September near Monterey Bay, CA. Points in red indicate leatherback locations during ENSO positive phase months. Points in blue indicate leatherback locations during ENSO negative phase months. Points in black indicate leatherback locations during ENSO neutral phase months. The leatherback conservation area boundary is shown in yellow.

September Angles of Departure

For all Septembers, there were 8 individual turtles tracked during ENSO positive events, 4 individual turtles tracked during ENSO negative events, and 24 individual turtles tracked during ENSO neutral events. A Kruskal-Wallis test comparing each animal's mean bearing in September to the corresponding monthly ENSO phase (i.e. positive, negative, and neutral) produced significant results (alpha = 0.05, $p < 0.003$). Upon further investigation, a

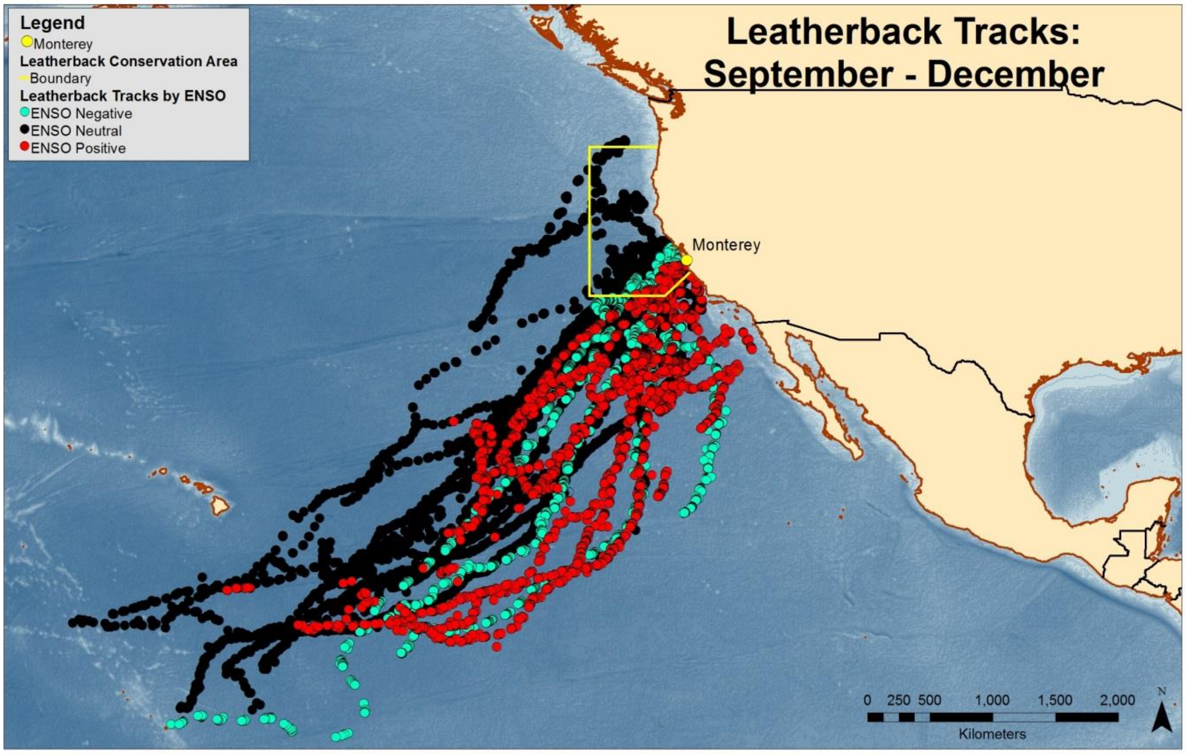

Figure 7. Tracks of satellite tagged leatherback marine turtles departing the California Current from September to December during the three phases of El Niño/Southern Oscillations. Tracks during positive (warm) phases are displayed in red, tracks during negative (cold) phases are displayed in blue, and tracks during neutral phases (normal conditions) are displayed in black. The boundary of the Leatherback Conservation Area is displayed in yellow.

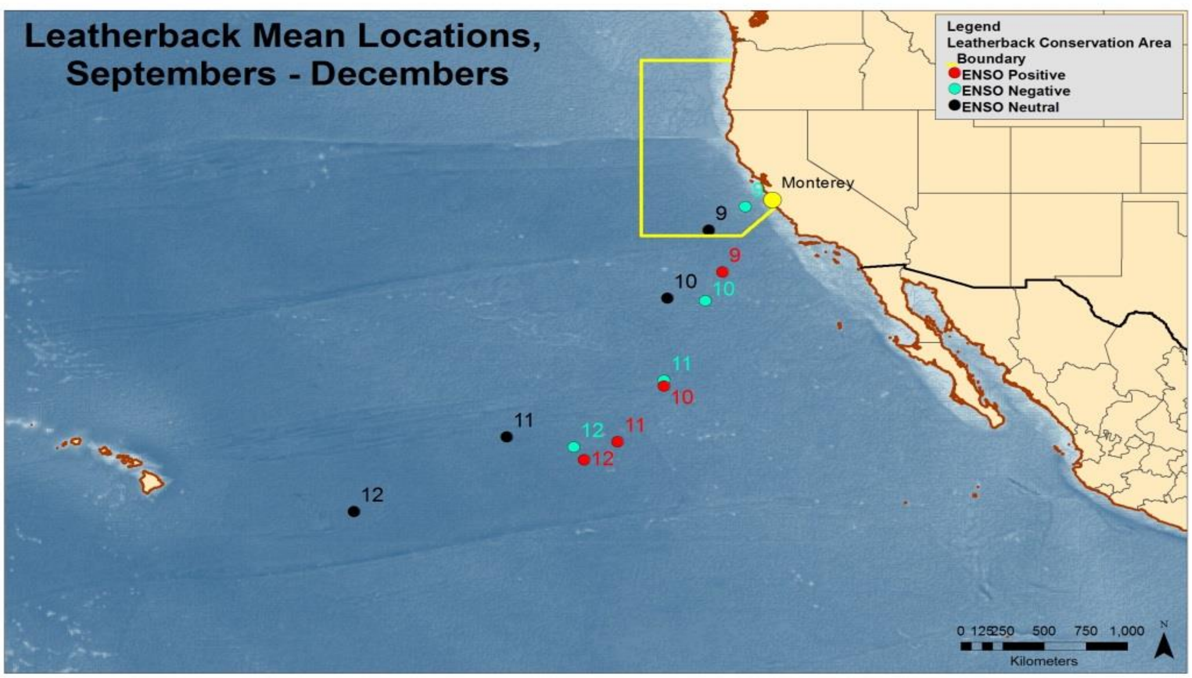

Figure 8. Mean Monthly leatherback locations by ENSO phase. Leatherback mean locations are labeled by numeric month. Locations in red represent positive (warm) ENSO phases. Locations in blue represent negative (cold) ENSO phases. Locations in black represent neutral ENSO phases. The boundary of the Leatherback Conservation Area is displayed in yellow.

Nemenyi-Damico-Wolfe-Dunn post-test yielded significant results between two of the three group comparisons: the ENSO Positive – ENSO Negative group and the ENSO Positive – ENSO Neutral group (Table 2). Mapping these tracks in light of these results reveals that leatherbacks departing the California Current in ENSO positive phase Septembers bear farther south than do turtles departing during negative or neutral phases (Figure 9).

September Distances Traveled

A Kruskal-Wallis test comparing each animal's mean distance traveled in September to the corresponding monthly ENSO phase yielded significant results (alpha = 0.05, $p < 0.008$). Upon further analysis, a Nemenyi-Damico-Wolfe-Dunn post-test yielded significant results between one of the three group comparisons: the ENSO Positive – ENSO Negative group (Table 2). Mapping these tracks reveals that leatherbacks departing the California Current in ENSO positive phase Septembers travel a greater distance southeast than do turtles departing during cool phase Septembers (Figure 9).

Nemenyi-Damico-Wolfe-Dunn Post-test for September		
Departure Factor	ENSO Phase Comparisons	p-value
Bearing	Neutral - Negative	0.674
	Positive - Negative	0.002
	Positive - Neutral	0.007
Distance	Neutral - Negative	0.728
	Positive - Negative	0.003
	Positive - Neutral	0.296

Table 2. A Nemenyi-Damico-Wolfe-Dunn post-test was run after Kruskal Wallis tests yielded significant results for both the animals' bearing and distances traveled. Numbers in red indicate significant results with alpha = 0.05.

Southern Movements and the Leatherback Conservation Area

While a certain amount of autumn leatherback activity outside of the Leatherback Conservation Area boundary is to be expected, there is a substantial portion of leatherback activity during warm phase ENSO months occurring south of the LCA southern boundary (Figure 10). Additionally, much of this activity is within the boundaries of the United States Exclusive Economic Zone (EEZ), meaning that it is within US federal jurisdiction (Figure 10). Standardizing ENSO positive turtle locations to one point/day per turtle yields 89 turtle locations in September, October, and November within the EEZ. Of these 89 locations, the majority (69%) are located outside the current LCA southern boundary, meaning that only 31% of ENSO positive turtle locations in this study lie within the LCA's protections. Furthermore, leatherback takes in the California/Oregon drift gillnet fishery have occurred in this region (Figure 11). These takes have primarily occurred within the waters northwest of Point Conception within the region initially bounded by the LCA southern boundary that was proposed in the 2000 NOAA NMFS biological opinion.

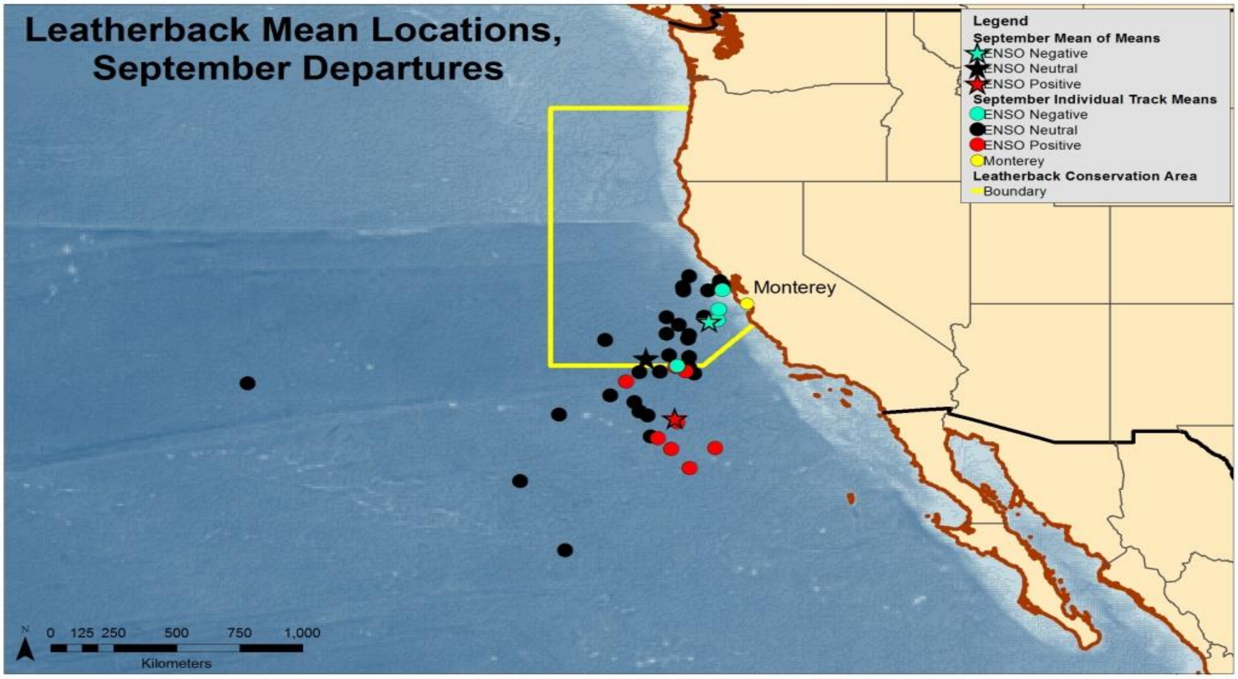

Figure 9. Map of individual turtle track means plotted by ENSO phase for the month of September. Red dots represent turtles during positive (warm) ENSO phases. Blue dots indicate turtles during negative (cold) ENSO phases. Black dots represent turtles during neutral ENSO phases. Stars represent the mean location for all turtles during each ENSO phase.

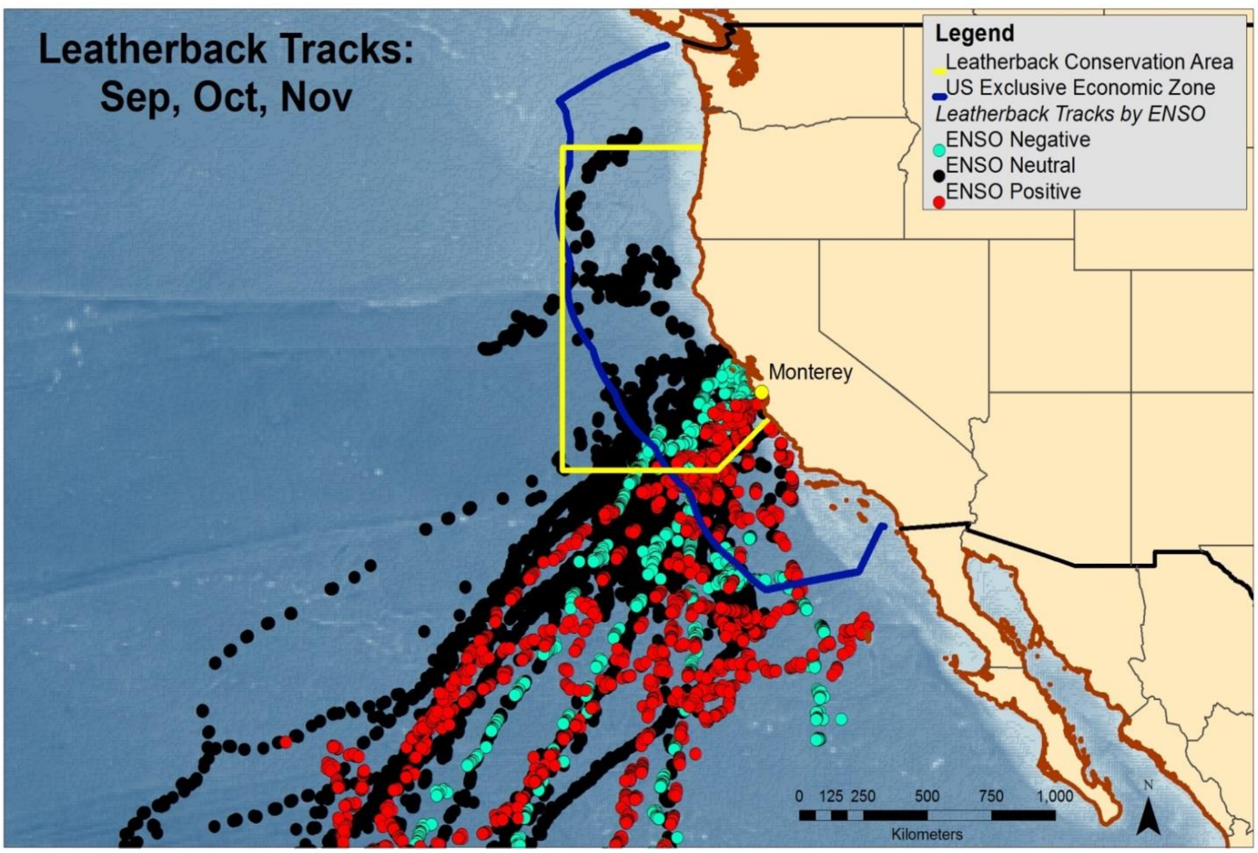

Figure 10. Map of leatherback tracks during the September, October, and November, which is when the Leatherback Conservation Area is in effect. August tracks are not included since all turtles in this study were tagged in September. The dark blue polygon represents the boundary of the US exclusive economic zone. During warm phase months, the majority of leatherback activity is observed south of the southern LCA boundary.

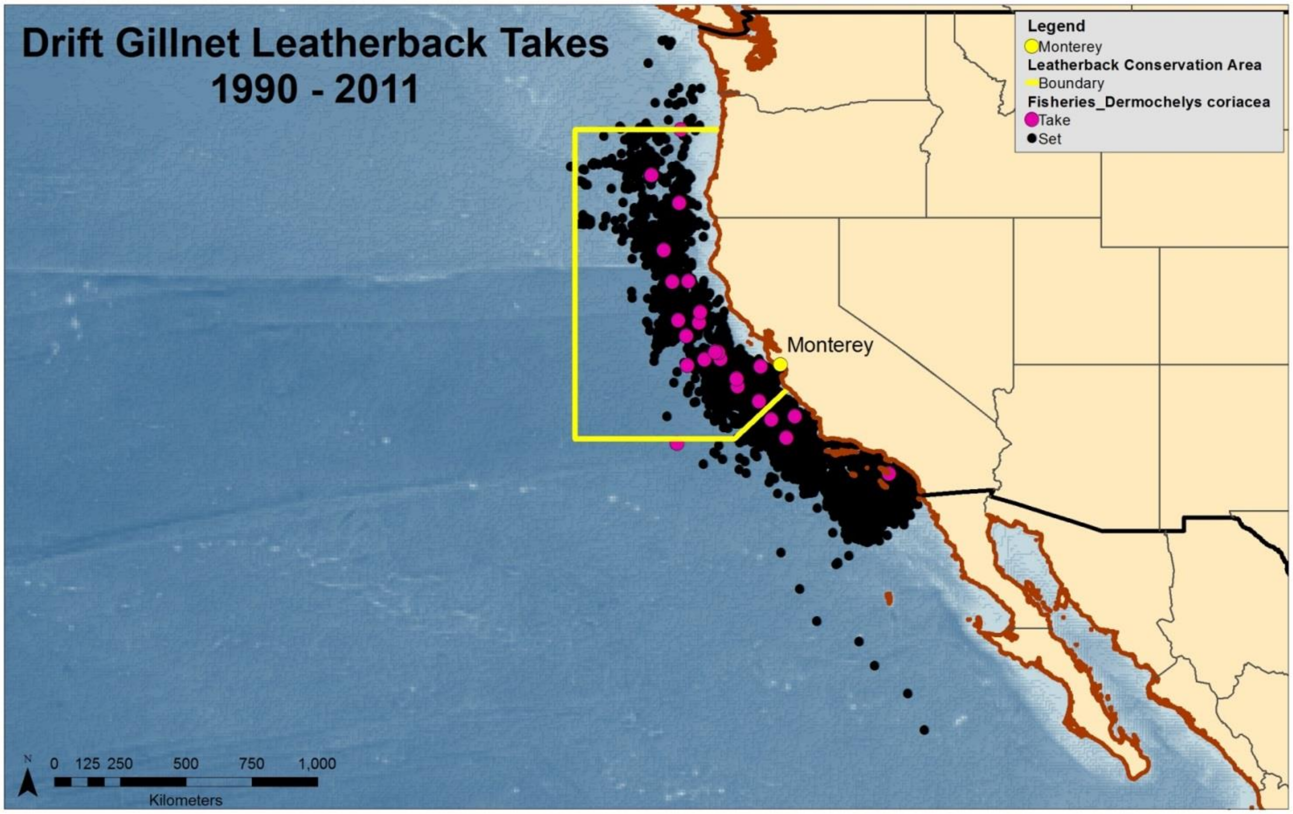

Figure 11. Map of drift gillnet sets (black dots) and sets with leatherback bycatch (pink dots) from 1990-2011. The Leatherback conservation area (yellow polygon), a time-area closure for the drift gillnet fishery went into effect in 2001. Four leatherback takes have occurred south of the LCA southern boundary, with three of them located between Point Sur and Point Conception, CA.

DISCUSSION

El Niño/Southern Oscillation

The El Niño/Southern Oscillation events that occurred during the timeframe of this study were relatively weak to moderate in strength. For reference, the two strongest El Niño events in the past three decades occurred in 1982-83 and 1997-98 and had positive MEI values ranging from 1 to 2 standard deviations higher than those experienced here (NOAA ESRL 2013). It may be likely that during stronger ENSO events, the differences in turtle movements between ENSO phases may be more exaggerated. This is an area where further research is suggested.

Furthermore, values from the Multivariate ENSO Index are not necessarily linearly related to the intensity of ENSO events in mid-latitudes where the leatherbacks in this study range (van Beynen et al. 2007). ENSO is primarily a tropical process, and the MEI measures tropical Pacific anomalies (NOAA ESRL 2013). ENSO's global effects are felt outside the equatorial Pacific through its teleconnected impacts on the ocean and atmosphere, and these teleconnections do not necessarily manifest identically across all ENSO events (He et al. 2013). ENSO can affect sea surface temperatures, thermocline structure, upwelling, and currents, as well as other ecologically-important oceanographic variables (Kayano et al. 2005). Therefore, correlating leatherback tracks directly with changing inter-annual oceanographic conditions in the California Current is recommended as a next step to this study. Benson et al. (2011) has already showed that area restricted search (ARS) behavior, which is indicative of turtle foraging, is positively correlated with several oceanographic conditions within Western Pacific leatherback foraging grounds; therefore, it may be a worthwhile addition to this study to further investigate if turtle departures from the California Current are also influenced directly by these conditions on an inter-annual timescale.

Warm Phase Southern Movements

The results of this study demonstrate that Western Pacific leatherback turtles departing the California Current bear farther southwest during autumn warm phases of the El Niño/Southern Oscillation. Why leatherbacks bear farther southwest during these periods is unknown. Potential reasons could be that turtles are tracking convergence patterns that aggregate prey, turtles are following certain oceanographic conditions, or turtles are tracking conditions that may cue either returning to the California Current for further feeding or cue embarking on a trans-Pacific migration to nesting grounds. Many of these reasons are speculative and further research into their plausibility is recommended.

Another explanation for this behavior may lie just south of Hawaii. In this area, an additional foraging ecoregion, called the Equatorial Eastern Pacific (EEP) foraging ground, has been identified (Benson et al. 2011). Many of the turtles in this study arrived in this ecoregion by December, and Benson et al. (2011) noted that ARS behavior in this ecoregion by California-tagged turtles occurs from December through spring, indicating the likely presence of a food source during this time. Furthermore, ARS behavior in the EEP appears to primarily occur along the southern edge of the California leatherbacks' migratory route (Figure 1 in Benson et al. 2011), which is where most ENSO-positive and ENSO-negative tracks are observed (Figure 7). One possible explanation for the southern movements of turtles during autumn ENSO warm phases may be that a food source appears in the southern EEP due to changing oceanographic conditions during ENSO events, and that leatherbacks departing the California Current Ecosystem may be migrating preferentially toward this food source during ENSO warm phases. Further research into this potential explanation would be an additional valuable next step to this research.

Moreover, the results of this study demonstrate that the majority of the warm phase leatherback locations within US federal jurisdiction are found south of the Leatherback Conservation Area's southern boundary. Given this southward bias and documented mortality from fisheries bycatch in this region, it may be worthwhile to consider seasonally-dynamic adaptive management measures.

Adaptive Management

Adaptive management measures are management policies with built-in flexibility for implementation based on specified triggers (US DOI 2009). These types of measures are particularly pertinent for management decisions that need to be made on short time scales since the regulatory and public review process typically takes a year or more to complete. For leatherback turtles in the California Current, inter-annual climate variability affects movements at seasonal and annual time scales. A seasonally-mobile southern boundary for the Leatherback Conservation Area triggered by ENSO positive conditions may be an appropriate adaptive management measure to ensure minimal leatherback bycatch in the future. For example, during ENSO neutral and negative phases, it may be suitable for the LCA's southern boundary to remain unchanged as shown in Figure 5A. However, when the Eastern Pacific appears to be entering El Niño conditions in autumn, expanding the southern boundary farther south to encompass the area bounded by Point Conception may be the most prudent option to protect the species (Figure 5B). Point Conception is recommended since the majority of fishing and turtle activity spatially coincide within this region.

Dynamic Time-Area Closures

Amending the current LCA regulation to change the southern boundary every time it appears that the Pacific may be entering an El Niño season would be both impractical and costly. However, amending the LCA regulation once to include the flexibility of a dynamic southern boundary is possible. In fact, a seasonally-dynamic time-area closure for turtles in the California Current already exists. For loggerhead marine turtles, the NMFS currently implements a time-area closure in the Southern California Bight for the drift gillnet fishery during January and August of El Niño seasons (NOAA NMFS 2007). This dynamic time-area closure was initiated based on bycatch data from the fishery where it was noted that the only times loggerhead sea turtles were observed taken by drift gillnetting operations were during warm phase ENSO months in Southern California's waters.

Conclusion

In summary, endangered Western Pacific leatherback marine turtles in the California Current face many barriers to recovery. Current management measures are designed to minimize mortality to leatherbacks so that populations may recover. However, managers must also balance the needs of all stakeholders in their decisions regarding the management of a protected species. Initially, it was recommended that the Leatherback Conservation Area drift gillnet fishing closure should have a southern boundary extending east to Point Conception, CA. However, due to fishing industry pressures, this boundary was moved north to Point Sur, CA. This study demonstrates that leatherback turtles bear farther southwest when departing the California Current during ENSO positive phase months. These southerly movements mean that a disproportionate number of leatherback locations are found outside the Leatherback Conservation Area's Point Sur southern boundary during warm phase months. Adopting an adaptive management approach for leatherback conservation, like the one currently in place for loggerhead conservation, may help better conserve the species while balancing fishery needs.

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Dedication

I would like to dedicate this work to my father, Terry R. Van Zerr (July 10, 1943 - May 17, 2013), without whom none of this would have been possible. His compassion, guidance, and financial and emotional support will not be forgotten.

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