Phenological Shifts in Loggerhead Sea Turtle (Caretta caretta) First Nesting Dates

by

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Abstract

In 2007, the newest report of the Intergovernmental Panel on Climate Change (IPPC) stated that warming of the global climate system is now occurring at an unprecedented rate. Scientists have observed significant temperature changes in both the air and ocean, and predict that there is more warming yet to come. Sea turtles may be sensitive to global warming due to two features of their life history: temperature dependent sex determination (TSD), and high nesting site fidelity. With TSD the temperature of incubation determines the sex of the hatchlings with high temperatures yielding females and low temperatures yielding males. Local temperature shifts in turtle-nesting regions may affect the gender balance of one or several sea turtle species. Sea turtles might prevent sex skewing by nesting earlier in the season. I looked for a temporal response to climate change in loggerhead sea turtles (Caretta caretta) by conducting multi-level regression analysis on first nesting dates from ninety beaches in the Southeast United States over a 30-year period. Loggerhead sea turtles arrived 0.2 days earlier every year over this period, 1.4 days earlier for every point increase in the NAO index, and 3.6 days later for every degree increase in latitude. These results suggest that loggerheads are capable of a behavioral response to climate variability and appear to be responding to long-term trends.

Introduction

On July 28th, 1978, loggerhead sea turtles (Caretta caretta) were listed as threatened throughout its’ range under the Endangered Species Act of 1973, and have received federal protection since that time(Service 2008). This protection has done little to change the trajectory of the population. From 1989 to 2008, the Peninsular Florida
recovery unit saw a 20% decrease in nesting females (Service 2008). This area is home to
up 90% percent of the US nesting effort (Bolten and Witherington 2003). The 2008
recovery plan for Northwest Atlantic loggerhead sea turtles listed bottom trawl, pelagic
longline, demersal longline, and demersal large mesh gillnet fisheries; legal and illegal
harvest; vessel strikes; beach armoring; beach erosion; marine debris ingestion; oil
pollution; light pollution; and predation by native and exotic species as the highest
priority threats (Service 2008). Climate change is not listed, yet it has the potential to
decimate loggerhead populations.

Sea turtles would be predicted to be uniquely sensitive to rapid global warming
due to two features of their life history, temperature dependent sex determination (TSD)
and high nesting site fidelity (Mrosovsky, Hopkins-Murphy et al. 1984; Davenport 1997).
In 2007, the newest report of the Intergovernmental Panel on Climate Change (IPPC)
stated that warming of the global climate system is now occurring at an unprecedented
rate. Scientists have observed significant temperature changes in both the air and ocean,
and predict that there is more warming yet to come (IPCC, 2007). Rising sea levels that
will accompany increased global temperatures threaten to inundate sea turtle nesting
habitat. All sea turtles show temperature dependent sex determination (TSD), where the
temperature of incubation determines the hatchlings gender with high temperatures
yielding females and low temperatures yielding males. Local temperature shifts in turtle-
nesting regions may affect the gender balance of one or several sea turtle species. While
sea turtles can only overcome sea level rise by nesting elsewhere, loggerheads could
potentially reduce substantial skews in sex ratio by nesting further north of earlier in the
season.
An almost certain consequence of increasing global temperature is sea-level rise. The IPCC found that the global sea-level had risen by 10-20 cm in the past century and predicts that it will rise by up to a meter by 2100 (IPCC, 2007). This rise could impact low-lying habitat where sand depth is a limiting factor (Baker, Littnan et al. 2006). It is expected that migrating beaches along undeveloped shores will provide nesting habitat as the sea level rises (Service 2008). Along developed coastlines and especially in areas with erosion control structures, we can expect permanent loss of dry nesting habitat as sea level rises (National Research Council (U.S.). Committee on Sea Turtle Conservation. 1990; Service 2008). Loss of habitat might be accelerated by oceanographic and environmental changes such as changes in currents or increased frequency of storms, both of which will increase beach loss via erosion (Baker, Littnan et al. 2006; Service 2008). It is unknown how sea turtles will respond to disappearing habitat, particularly loggerheads which have high nesting site fidelity.

While there is no strong evidence that sea turtles specifically home to their natal beaches to lay eggs, there is genetic evidence linking breeding loggerheads to their region of birth (Bowen, Avise et al. 1993; Bowen, Kamezaki et al. 1994; Bowen, Abreugrobois et al. 1995; BOWEN, BASS et al. 2005). Once loggerhead has selected a nest, it will tend to re-nest in a relatively close proximity (0-5 km) during successive nesting attempts within the same and subsequent breeding seasons, although a small percentage of turtles will utilize more distant sites in the general area (Bjorndal, Meylan et al. 1983; Limpus 1985; Avens, Braun-McNeill et al. 2003; Bolten and Witherington 2003). Loggerheads’ high nesting site fidelity might influence sex ratios.

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The temperature of incubation during the middle third of the incubation period determines the sex of the hatchlings with high temperatures yielding females and low temperatures yielding males. Pivotal temperature (PV) is the threshold for the production of one sex to another (i.e. a sex ratio of 1:1) and is around 28 to 30°C for all species for which there are data (Lutz, Musick et al. 1996; Davenport 1997). The transitional range temperature, the range of temperatures where both males and females tends to be small, approximately 1 degree for most sea turtles (Davenport 1997). This small transitional range results in nests that are predominantly one sex.

The combination of climate change, TSD, and a high degree of nesting site fidelity creates an obvious concern for skewing sex ratios. In a rookery in Florida, it was estimated that over 90% of individuals produced on a beach over a three year period were female (Mrosovsky and Provancha 1992). Mathematical models have predicted that turtle species with narrow transitional range of temperatures will be unable to evolve to rapid climate change (Hulin, Delmas et al. 2009). Sea turtles have been around for over 100 million years. We know that in the last 400 thousand years they have survived multiple, rapid, climate changes (Vimeux, Cuffey et al. 2002). Although it is improbable that sea turtles will evolve to overcome climate change, there are data that would suggest a behavioral response is possible.

Phenology is the timing of seasonal activities by animals and plants. It is also the simplest process by which to track changes in the ecology of species in response to climate change (Walther, Post et al. 2002). There is a growing body of literature on phenological shifts in response to climate change. Common changes in the timing of
spring activities include earlier breeding or first singing of song birds (Crick, Dudley et al. 1997), earlier arrival of migrant birds (Inouye, Barr et al. 2000), earlier emergence of hibernating species (Inouye, Barr et al. 2000), and earlier choruses and spawning in amphibians, and earlier shooting and flowering plants (Gibbs and Breisch 2001; Walther, Post et al. 2002). In general, spring activities have occurred progressively earlier since the 1960s (Walther, Post et al. 2002). Thus far, this large body of literature has precluded sea turtles.

There is evidence of a potential phenological shift in loggerhead sea turtle nesting. Almost all sea turtles are found in tropical environments, with the exception of the loggerhead which is found in warm temperate and subtropical waters (Lutz, Musick et al. 1996; Bolten and Witherington 2003). Because they live outside of the tropics the loggerheads must respond to temporally limited season, and the timing of this response may be more restricted at the northern or southern extent of their range (Bolten and Witherington 2003). Several other studies have correlated earlier arrival date of loggerheads with warmer sea surface temperatures (John, Dean et al. 2004; Pike, Antworth et al. 2006; Hawkes, Broderick et al. 2007), as well as earlier last nesting date of the season (Pike, Antworth et al. 2006). On the Atlantic Coast of Florida the median annual nesting date of loggerheads shifted approximately 10 days earlier from 1989 to 2003 (John, Dean et al. 2004). It would seem likely that if any sea turtle were to shift their nesting dates in response climate change, it would be loggerheads. In fact, green turtles, nesting on the same beach in Florida don’t respond to warmer sea surface temperatures in the same way that loggerheads do (Pike 2009). This study is the first to comprehensively investigate the potential shift in first nesting dates by loggerheads in the
Southeast Atlantic United States.

**Data**

The Southeast United States is home to 3 different nesting turtles: loggerheads (*Caretta caretta*), green turtles (*Chelonia mydas*), and leatherbacks (*Dermochelys coriacea*). This area hosts one of the largest nesting aggregates in the world (Bolten and Witherington 2003), but the nesting effort is not uniform across the region. Perhaps up to 90% of the nesting effort is on the Atlantic coast of Florida and the majority of the nests are by loggerheads (Bolten and Witherington 2003). Nesting monitoring programs have been going on since the early 80’s with nesting programs in Florida, Georgia, South Carolina, and North Carolina, making it an ideal area to investigate phenological shifts in loggerhead nesting.

I obtained nesting data from Florida, Georgia, South Carolina, and North Carolina State nesting programs. Coordinators from State Fish and Wildlife service’s helped select monitoring data very likely to include first nesting dates based on early survey starts (March 1st for southern beaches in Florida) and high effort (up to 7 days a week). The coordinators also provided the latitude and longitude of the center of each nesting beach. In all, 90 beaches were included in this analysis and can be seen in figure 1.
Before investigating any annual trends, I first determined whether or not loggerheads respond to large-scale climatic phenomena. The North Atlantic Oscillation (NAO) is a seesaw in air pressure systems and it is the most dominant form of recurrent climate variability over the North Atlantic (Hurrell, 1995). The NAO dictates climate variability from the eastern seaboard of the United States to Siberia and from the Arctic to the subtropical Atlantic, especially during boreal winter, so variations in the NAO are

**Meta-analysis**

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important to society and for the environment (Hurrell 2003). Swings in the NAO from one phase to the other produce large changes in mean wind speed and direction over the Atlantic, the heat and moisture transport between the Atlantic and neighboring continents, and the intensity and number of storms, their paths, and their weather.

The NAO influences surface air temperature and sea surface temperatures across wide regions of the North America, the Arctic, Eurasia and the Mediterranean are significantly correlated with NAO variability (Hurrell 2003). Positive NAO index values, as see in figure 2, show a stronger than normal subtropical high and a deeper than normal Icelandic low (http://www.ldeo.columbia.edu). This results in more, stronger winter storms moving on a northerly track. Northeastern Canada and Greenland experience cold dry winters and the eastern United States experiences mild wet winters. A negative NAO index value, seen in figure 3, shows a weak subtropical high and weak Icelandic low (http://www.ldeo.columbia.edu) and winter storms move along an east west pathway. The US coast experiences more cold air outbreaks and snowy weather conditions.

Figure 2 Positive Phase  Figure 3 Negative Phase

(http://www.ldeo.columbia.edu/res/pi/NAO/)
Over the past decade there has been an increased interest in the ecological impacts of NAO variability. The NAO has been shown to affect a broad range of marine, terrestrial, and fresh water ecosystems across the northern hemisphere (Ottersen, Planque et al. 2001; Straile 2002). Multiple studies on bird migrations have found first arrival date to be negatively correlated with the NAO Index (Forchhammer, Post et al. 2002; HUBALEK and Zdenek 2003; HUBALEK and Zdenek 2004; Vähätalo, Rainio et al. 2004). The effects of the NAO have yet to be explored in the context of sea turtle nesting.

NAO index values were obtained from climate prediction center (CPC) at National Oceanic and Atmospheric Administration (NOAA) and averaged over the first 4 months of the year. When plotted with first nesting date against year (Figure 5), the NAO appears to mirror first nesting date. This negative correlation appears across our nesting range (Figure 6) and has a cross correlation showing a lag of zero. This analysis led me to include the NAO index into our model.

Methods
One of the obstacles to modeling nesting data is the short timeline of most beach monitoring programs. While several beaches have nesting data from 1980 through 2008, most beaches did not have early survey starts and the high survey effort till the mid 90’s. To achieve statistical power, one can pool nesting data from multiple beaches, but when pooling data, one has to assume homogeneity among beaches. This assumption is unrealistic, considering the myriad of factors that affect nesting habitat such as quality of sand, size, slope, erosion, and development (Kikukawa, Kamezaki et al. 1999). To overcome these obstacles we will use a multilevel regression.

A multilevel regression is tradeoff between the beach specific and pooling models. A multilevel model recognizes the differences among beaches by modeling the intercept and slope as beach-specific. The estimated First Nesting Date is a weighted average between the estimates from the beach specific values and the pooled values. Another advantage of a multilevel model is the ability to use group level predictors. Grouping observations based on certain characteristics of the subject or environmental and biological conditions is often necessary to understand the key relationship we are interested in finding (Qian 2009). This will allow for the inclusion of the NAO index and latitude.

Using the lme4 package in the statistical program R, a multilevel model was fit predicting first nesting date by the Year, NAO, and Latitude (Formula 1).

**Formula 1**  
**First Nesting Date ~ Year + NAO + Latitude + (1+ Year | Beach)**
The model is broken into 2 parts. The left side, which includes Year, NAO index, and Latitude, is referred to as "fixed effects", or population level effects. The right hand side in parentheses is referred to as the "random effects ", or local effects. The local effects create beach specific slopes and intercepts for first arrival date, predicted by year.

Results

The fixed effects of our multilevel regression are shown in table 1. The average first nesting date across the population is the 123rd day of the year (May 2nd). As a population, Northwest Atlantic Loggerheads are arriving 0.2 days earlier every year. Loggerheads arrive 1.4 days earlier for every point increase in the NAO index and a 3.6 day later for every degree increase in latitude. All three figures are significant based on their confidence intervals (±2*Std.Error).

Table 1

<table>
<thead>
<tr>
<th>Fixed effects:</th>
<th>Estimate</th>
<th>Std. Error</th>
<th>t value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>123.53000</td>
<td>2.12433</td>
<td>58.15</td>
</tr>
<tr>
<td>YEAR</td>
<td>-0.19187</td>
<td>0.06335</td>
<td>-3.03</td>
</tr>
<tr>
<td>NAO</td>
<td>-1.41982</td>
<td>0.22702</td>
<td>-6.25</td>
</tr>
<tr>
<td>Latitude</td>
<td>3.62965</td>
<td>0.27164</td>
<td>13.36</td>
</tr>
</tbody>
</table>

Figure 7 shows this trend with the influence of the NAO index, Latitude and Year. It holds the NAO constant at different values and regresses first nesting date by Year and Latitude.
Discussion

This is the first study to comprehensively investigate the potential shifts in loggerhead sea turtle nesting dates. From the results of this study it appears that the Northwest Atlantic loggerheads respond to interannual and long term climate variability by nesting earlier. This has been difficult to demonstrate in the past because of the size of most nesting data sets. The use of a multilevel regression allowed for the grouping of data over a large geographic range. Loggerheads are unique because they nest in the subtropics and have strong nesting site fidelity, and it cannot be assumed that other species to respond in a similar fashion. It is also unknown whether this shift will be adequate to prevent large sex skew ratios.

This model does indicate that loggerheads have the ability to respond to warmer temperatures. Sex skews of 90% female have been found on the beaches of Florida (Mrosovsky and Provancha 1992), but currently loggerhead hatchling sex ratio data has been limited to a few studies and more data is needed to complement this study. However these trends relieve some of the concern over potential sex skewing. It would seem that the largest threat to loggerhead sea turtles from climate change will be the loss of habitat due to sea level rise.

Figure 7 – The plots below show the interaction of year, latitude and NAO index to predict first arrival of nesting loggerheads. Each plot has the onset of nesting on the z-axis as predicted by latitude and year. Each of the 5 plots holds the NAO index a certain value from negative on the left to positive on the right. As the NAO index value increase, the entire plane shifts down.
Literature Cited


