SEA TURTLE CLIMATE CHANGE BIOLOGISTS SHOULD DO MORE MEASURING AND LESS MODELING

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ABSTRACT

Anthropogenic climate change poses many threats to threatened and endangered species, including sea turtles. These threats include the erosion of nesting beach habitat, altered sex ratios of hatchlings, and latitudinal shifts in preferred nesting conditions as temperatures warm globally. Researchers and conservation practitioners often model the potential consequences of climate change to help guide management practices, but greater focus should be placed on measuring the responses of species to climate change through long-term field studies. Here, we review studies undertaken to assess, simulate, or project the impacts of climate change on sea turtles. We placed 53 recently published (2003–2015) studies into one of three categories (Historical Assessment Only, Current Conditions and Projections, Historical Assessment and Projections). The first and most common category (58% of surveyed publications) includes short-term studies of current environmental needs and models of future climate changes to determine if those conditions will be met in the future. The second category (32%) includes studies of historical responses of sea turtles to climate change derived from long-term (>10 year) datasets, without projections into the future. The least common approach (9%) included studies that used both long-term datasets on species' responses to observed climate change and quantitative models of future climate scenarios. We synthesize the relevant literature on this topic and argue for new studies that integrate long-term historical datasets for species responses to climate change, rather than models extrapolated from current conditions.

Key words: *Caretta caretta*, *Chelonia mydas*, conservation, global warming, management, marine turtle, sea-level rise.

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INTRODUCTION

Threatened and endangered species face many threats, including anthropogenic climate change (McKinney and Lockwood, 1999; Hughes, 2000). Independent researchers and management agencies working on these species often focus their research and conservation efforts on assessing and projecting threats that climate change may pose to those species (Myers et al., 2000; Brooks, 2006). This is particularly true for sea turtles (Hawkes et al., 2007, 2009). However, the typical approach to integrating climate change threats with conservation efforts is a two-step process: assess the perceived needs and requirements of a given species and then use a model of future climate to determine the changes to those needs or requirements (Elith and Leathwick, 2009; Pike, 2013a, 2013b). There are at least two issues with this approach: first, species' needs and requirements are complicated and may be inadequately assessed by researchers (Elith and Leathwick, 2009), and second, models of future climate change may be uncertain (Murphy et al., 2004). Increasingly, climate projections are viewed by the public as unrealistic, uncertain, and overly dire (Carvalho, 2007; Feldman et al., 2015). Here, we argue for a change of practice in the case of sea turtles to assess species responses (e.g., shifts in phenology, sex ratios, or geographic distributions) to historical climate change, and to extrapolate those responses into future scenarios while also considering the current context. Historical climate change might include inferred shifts during previous glacial cycles (Reece et al., 2005) or responses over decades as measured by long-term field studies. This change in practice is fundamentally different because assessing how species have responded to climate change in the past is not burdened with determining what species are responding to or why, but rather, what that response is – this eliminates the problem of adequately characterizing species' environmental needs (Arendt et al., 2013; Reece et al., 2013b). The second problem, that models of future climate may be inaccurate, may be addressed in the following way. Extrapolations of historical responses of species to future climate change should include straight-line extrapolations assuming that the future rate of climate change is unchanged from the historical rate of climate change. These extrapolations are unlikely (IPCC 2007). Most of the public does not believe model results that deviate from warming trends of the last 100 years (Feldman et al., 2015). Using these extrapolations as a baseline, we should then include more realistic (although less accepted politically) projections that account for the accelerated rate of climate change supported by the overwhelming majority of climate scientists.

Here, we review 12 years of recent literature on climate change and sea turtles, and categorize approaches of most published research on sea turtles and threats posed to them by climate change. Researchers have thoroughly identified threats that climate change poses to sea turtles, such as altered sex ratios, geographic and phenological shifts in nesting, storm-related egg mortality, and erosion of nesting beaches (reviewed in Hays, 2008; Hawkes et al., 2009; Witt et al., 2010; Bolten et al., 2011; Hamann et al., 2013; Hawkes et al., 2014). However, too much effort is being focused on how sea turtles might respond to an uncertain future using data from the present (<10 years), when we should be addressing this question with data on how they have responded to a known past (>10 years).

MATERIAL AND METHODS

We used three search engines to find recent literature published on sea turtles and climate change: JSTOR (www.jstor.org), Academic Search Complete (www.ebscohost.com/academic/academic-search-complete), and Google Scholar (scholar.google.com). Our search terms included all possible combinations of "marine turtle," "sea turtle," "climate change," "sea-level rise," and "global warming." We acquired additional resources through reading several review papers and from citations within publications found through these searches. We completed all searches between February and June 2015. The two authors read each paper independently and assigned them into one of three different categories. These categories include: 1) studies that assessed current conditions (or historical conditions over 5–10 years) and projected species needs into a future climate scenario (e.g., Marcovaldi et al., 2014), 2) studies that assessed historical responses of sea turtles to climate change (>10 or more years, e.g., Cavallo et al., 2015), and 3) studies that fit the criteria for category 2, but also extrapolated or modeled responses in a future climate scenario (e.g., Arendt et al., 2013). We compared resulting classifications between the two authors and found 100% agreement. Reviews and syntheses that did not add novel information were not counted, but are integrated into our discussion. Lastly, we found several papers on potentially important components of climate change and sea turtle research; these will be summarized in the discussion. The full list of papers and their classifications is in Table 1.

RESULTS

We found and classified 53 articles with publication dates between 2003 and 2015 relevant to the impacts of climate change on sea turtles. Publications (summarized in Table 2 with details in Table 1) either focused on current conditions and projected those into a future scenario (58% of the papers), focused only on long-term observed responses to climate change (32%), or used historical responses to project future responses (9%, Table 2). The studies we reviewed included 17 (31%) focused solely on *Caretta caretta* (Loggerhead Sea Turtles), six (11%) on *Eretmochelys imbricata* (Hawksbill Sea Turtle), two (4%) focused jointly on *C. caretta* and *Chelonia mydas* (Green Sea Turtle), 12 (23%) focused primarily or exclusively on *C. mydas*, seven (13%) on *Dermochelys coriacea* (Leatherback Sea Turtle), and two (4%) on all species of sea turtles. The remaining studies included one of *Lepidochelys kempii* (Kemp's Ridley Sea Turtle), and six other studies of various combinations of species. Most publications focused on Atlantic distributions of species (43%), followed by studies in the Mediterranean (13%), and the Indo-Pacific (primarily studies in Australia) (25%); 19% were global or mostly global in extent. Overall, relatively few studies make a crucial connection between long-term, historical datasets of species' responses to climate change and projections of responses to future climate scenarios.

DISCUSSION

Our review detailed how recently published studies approach the issue of climate change and sea turtles and found that the majority of research takes two approaches on the topic. The first and most common approach undertaken to date (58% of surveyed publications) is to conduct a short-term study or create a model of the current environmental needs of a one or more sea turtle species and then assess directly from empirical thermal data or a future climate scenario model whether the current environmental needs of a given species are met in future models. In other words, is what sea turtles need now also included in future scenarios? For example, Fuentes et al. (2010b) used published values for sand temperatures (not incubating nest temperatures) and combined those data with data from published studies on the impact of sand temperature on hatchling sex ratios. The authors then combined those data with a model of future sand temperatures in Australia and demonstrated the potential for feminization of hatchlings under extreme climate scenarios. This study is both alarming and insightful, but involves virtually no direct measurements of the impacts of climate change on sea turtles. A second approach (32% of surveyed publications) is to report observed responses of species to climate change from a long-term dataset (defined here as ≥10 years of data). Such studies make anecdotal inferences relevant to future climate scenarios. For example, Weishampel et al. (2010) used nest survey data to demonstrate that *C. caretta* and *C. mydas* in the Western Atlantic started to nest earlier in the season as a function of warming sea-surface temperatures, but with divergent outcomes on the nesting season phenology: a shortening of the *C. caretta* season and prolonging the *C. mydas* season. This altered phenology "*could* have a bearing on the future population dynamics of the two species" (Weishampel et al., 2010). In other words, this group of studies assessed historical responses to climate change, but at best made qualitative claims about future implications. Far fewer studies (9%; Fig. 2) use data on historical responses to climate change to inform models of

Table 1. List of studies reviewed, (CC = *Caretta caretta*, CM = *Chelonia mydas*, EI = *Eretmochelys imbricata*, DC = *Demochelys coriacea*, ND = *Natator depressus*, LK = *Lepidochelys kempii*, LO = *Lepidochelys olivacea*), and the three categories into which publications were placed.

Category	CC	CM	EI	DC	ND	LK	LO	Atlantic	Indo-Pacific	Mediterranean	Publication
	x								x		Chaloupka et al., 2008
			x					x			Marcovaldi et al., 2014
			x					x			del Monte-Luna et al., 2012
	x	x	x	x		x	x	x			Dewald and Pike, 2014
	x	x		x				x			Edmiston et al., 2008
	x	x			x				x		Fuentes et al., 2011a
		x						x			Hays et al., 2003
	x									x	Mazaris et al., 2008
Historical Assessment Only	x									x	Mazaris et al., 2009
	x							x	x	x	Mazaris et al., 2013
		x						x			Pike, 2009
	x	x		x				x	x	x	Pike and Stiner, 2007
	x							x			Pike et al., 2006
				x					x		Santidrián Tomillo et al., 2014
	x	x						x			Van Houtan and Bass, 2007
	x							x			Weishampel et al., 2004
	x	x						x			Weishampel et al., 2010
		x							x		Baker et al., 2006
		x							x		Booth and Evans, 2011
				x				x			Caut et al., 2010
		x							x		Cavallo et al., 2015
Current Conditions and Projections	x	x	x	x	x	x	x	x	x	x	Donlan et al., 2010
			x					x			Fish et al., 2008
	x		x					x			Fish et al., 2005
		x							x		Fuentes and Cinner, 2010
		x							x		Fuentes and Porter, 2013

Table 1. Continued.

	x									x	Girondot and Kaska, 2015
	x							x			Hawkes et al., 2007
	x									x	Hays et al., 2010
	x	x	x	x				x	x	x	Hulin et al., 2009
	x									x	Katselidis et al., 2014
	x									x	Katselidis et al., 2012
				x				x			McMahon and Hays, 2006
				x				x			Patino-Martinez et al., 2012
				x				x			Patino-Martinez et al., 2014
	x	x	x	x	x	x	x	x	x	x	Pike, 2013a
						x		x			Pike, 2013b
								x	x	x	Pike, 2014
				x				x			Santidrián Tomillo et al., 2012
				x				x			Santidrián Tomillo et al., 2015
	x							x	x	x	Witt et al., 2010
Historical Assessment and Projections	x							x			Arendt et al., 2013
			x					x			Glen and Mrosovsky, 2004
	x									x	Özdemir et al., 2011
	x							x			Reece et al., 2013b
	x							x	x	x	Van Houtan and Halley, 2011
Total	28	22	11	14	3	5	4	33	23	17	

Table 2. Conceptual model of publication categories, including the percentage of the 53 publications reviewed that fell into each category. Problems with each of the three categories are given at the far right. Overall, we suggest that more research focus on the third, and currently least represented (9% of publications reviewed), category.

% of 53 Studies	Category	Historical Data	Current Data	Future	Problems
58%	Current conditions and projections	No historical data	Assess or model current environmental needs	Identify changes in those needs through quantitative modeling of future climate	No evidence for how species respond to changes
32%	Historical assessment only	Assess historical responses	No Current Data	Hand-wave about the future	Little actionable data for the future
9%	Historical assessments and projections	Assess historical responses	No Current Data	Extend historical responses to future climate through quantitative modeling	Requires access to long-term datasets

projected responses to future climate change. For example, Reece et al. (2013b) assessed evidence for latitudinal shifts in Florida *C. caretta* nesting aggregations and responses to coastal erosion due to sea-level rise over a 20-yr period and used those data to parameterize a model of responses to future climate change and sea-level rise. A key difference between this study and the example of Fuentes et al. (2010b) given above is that data were available on historical shifts in nesting aggregations for the Reece et al. (2013b) study, but no long-term dataset existed for historical changes in sex ratios for the Fuentes et al. (2010b) study, illustrating the need for long-term field studies.

Common Themes

Implications of climate change on sea turtles and suggested directions for future research have been captured in several reviews (Hays, 2008; Hawkes et al., 2009; Witt et al., 2010; Bolten et al., 2011; Hamann et al., 2013; Hawkes et al., 2014). After reading these reviews and the studies listed in Table 1, we identified six themes of climate change research on sea turtles that warrant further consideration. Some of these themes have been identified in the climate change literature (without reference to sea turtles) and some have been identified by sea turtle biologists, but all six of these themes are underrepresented in the literature on sea turtle climate change biology. These include: 1) interspecific variation in responses to climate change, 2) ignored uncertainty and complexity in climate projections, 3) the difference between "pulse" and "press" climate change, 4) threats that intersect with climate change, 5) a lack of long-term field studies with publically available data, and 6) a focus on measuring (not modeling) responses to climate change.

First, different species of sea turtles may respond independently to climate change and sometimes in unpredictable ways. For example, both *C. caretta* and *C. mydas* in the western Atlantic responded to warming temperatures by nesting earlier in the season. However, *C. caretta* also shortened the length of the overall nesting season, while sympatric *C. mydas* have extended their nesting season (Pike et al., 2006; Pike, 2009; Weishampel et al., 2010). Species also varied in their susceptibility to tropical cyclones (Pike and Stiner, 2007; Fuentes et al., 2011a; Dewald and Pike, 2014) and in their responses to beaches with modified slopes due to erosion from storms, sea-level rise, or storm surge (Brock et al., 2009). Species may also vary in their susceptibility to altered sex ratios as a consequence of the effect of warmer sand temperatures on incubating eggs (Hulin et al., 2009). Within species, vulnerability to climate change varies geographically, with greater impacts at the poleward range limit (Mazaris et al., 2013). Among species, historical phylogeographic studies have shown differential responses to climate change for more tropical versus more subtropical/temperate nesting species (Reece et al., 2005). Responses to climate change vary among and even within species, although we know of virtually no research on how to balance those differences in management strategies. Many rookeries overlap spatially across species, resulting in a need for further research on long-term and spatially explicit management strategies that facilitate climate change adaptation for multiple sea turtle species.

Second, impacts of global warming are complicated; projections on their impacts should be more nuanced and include estimates of uncertainty (Murphy et al., 2004). Impacts of a warming planet on sea turtles include, but are not limited to, altered ocean temperatures that may impact prey resources (Chaloupka et al., 2008), altered physiological constraints (McMahon and Hays, 2006), phenological changes in nesting (Weishampel et al., 2003, 2004, 2010), and altered sex ratios of hatchlings (Fuentes et al., 2010b; Hays et al., 2010; Özdemir et al., 2011; Katselidis et al., 2012; Marcovaldi et al., 2014; Santidrián Tomillo et al., 2014). Although we can speculate how sea turtles might respond to these changes and model their potential responses (e.g., Baker et al., 2006; Fuentes and Abbs, 2010; Fuentes et al., 2010c; Fuentes and Porter, 2013), too little research has focused on how sea turtle species have responded to warming temperatures historically despite the feasibility of collecting such data. Persistent problems include the issue of how or where sea-surface temperatures should be assessed (Mazaris et al., 2008). For example, should temperatures be assessed within 1 km of nesting beaches (Mazaris et al., 2008; del Monte-Luna et al., 2012), at adult foraging grounds months prior to nesting (Mazaris et al., 2009), in juvenile foraging grounds (Chaloupka et al., 2008), or nesting beaches decades prior to reproductive maturity (Arendt et al., 2013)? Do impacts of water temperature on hatchlings have long-term consequences (Booth and Evans, 2011)? Much of the research on warming temperatures focuses on altered sex ratios (Godley et al., 2001; Fuentes et al., 2010b; Özdemir et al., 2011; Katselidis et al., 2012; Santidrián Tomillo et al., 2014) as sand temperatures presumably increase with a warming climate, producing more females and fewer males. However, even this seemingly logical thermal endpoint has been challenged (Hawkes et al., 2007; Hays et al., 2010). Demonstrating that sex ratios could change (Marcovaldi et al., 2014) is very different from demonstrating they have changed. We have, or should have, long-term datasets that could answer that question (but see Hays et al., 2003 for an example of hindcast modeling). Temperatures of incubating nests depend on ambient air temperature and sea-surface temperature (it is unclear which is more important-Girondot and Kaska, 2015), albedo, and over-wash of surf, which cools nests during the day and warms them at night (Wood et al., 2000; Hulin et al., 2009). Because sea turtles lay multiple clutches that often vary in their distance from the surf (Wood et al., 2000), there is the potential for adaptive capacity to respond to warming air temperatures. What is clear from the current literature is that impacts of temperature on sex ratios are complex. The only way to clearly assess these impacts is through long-term monitoring, not frequent and complex modeling studies. Lastly, many species respond to warming temperatures by spatially shifting their distributions poleward (Bellard et al., 2012) or a temporal shift of the onset, shape, and duration of the nesting season (Parmesan and Yohe, 2003). Evidence for this pattern in the nesting distribution of sea turtles is mixed (Mazaris et al., 2013). Local conditions are important and limit the utility of global models for management (Pike, 2013a; Reece et al., 2013b).

Third, climate change includes both "press" and "pulse" impacts (Vose and Klepzig, 2013). The former includes constant pressures such as steadily increasing temperature and the later includes episodic events such as increased severity or frequency of storms. The overwhelming majority of research on sea turtles and climate change has focused on projections of press threats such as warming temperatures (Fuentes et al., 2011b), sea-level rise (Fish et al., 2005; Baker et al., 2006; Fish et al., 2008; Fuentes et al., 2010c; Patino-Martinez et al., 2014), or both (Reece et al., 2013b). However, pulse influences may be as or more important than press influences. The majority of research on those threats has focused on historical datasets without models of future impacts (Pike and Stiner, 2007; Van Houtan and Bass, 2007; Edmiston et al., 2008; Fuentes et al., 2011a; Dewald and Pike, 2014). Future research should focus on both responses of sea turtles to pulse or press influences in the past, and, crucially, use those responses in quantitative models of future impacts.

Fourth, synergistic, interactive, and cumulative impacts are critically important to assess (Urban et al., 2012). Sea turtles have faced rates of climate change and sea-level rise in the past that were orders of magnitude faster than any models of anthropogenic changes over the next 100 years or more (Pilkey and Young, 2009). They adapted to these changes in the past by shifting their spatial distributions (Reece et al., 2005). What makes anthropogenic climate change potentially detrimental during this and the next century is the fact that it is happening in the midst of widespread human modification of the globe. Thus, any assessment of the impacts of climate change should include land-use change and other synergistic impacts (Fish et al., 2008; Pike, 2013b; Reece et al., 2013a; Reece et al., 2013b). Long-term management strategies have not integrated these approaches.

Fifth, sea turtles are long-lived species with complicated life history patterns (Arendt et al., 2013). This is obviously not unknown to sea turtle researchers, but the more we uncover about sea turtle life history, it becomes increasingly clear that long-term datasets are necessary to make accurate inferences about their environmental needs, and how they will respond to future threats (e.g., Arendt et al., 2013). This and other studies point to the extreme value and importance of long-term monitoring projects, and the importance of making data from those projects readily available to the scientific community.

Sixth, and perhaps most important, most of the studies reviewed here do not use historical responses to climate change to predict future responses. Instead, they either assess historical responses and stop there, or make projections without assessing historical responses. Given the complicated life histories and the many unknown impacts and interaction effects, understanding historical responses to climate change is critical. An increased focus on this approach would require several changes to the status quo and would likely result in major advances in conservation efforts. What has to change is an increased focus on rigorous, detailed long-term studies, which are increasingly difficult to fund in the current economic and research environment. Some long-term monitoring projects include Florida's networked statewide Index Nesting Beach Survey (INBS: http://myfwc.com/research/wildlife/sea-turtles/nesting/beach-survey-totals, since 1989), monitoring at the Archie Carr National Wildlife Refuge (since 1981), and the Conservancy of Southwest Florida Science Department (since 1983). Studies outside Florida include the Sea Turtle Conservancy project in Tortuguero, Costa Rica (since the 1960s), tagging studies in Clack Reef, Australia (late 1980s), and nesting surveys on Heron Island, Australia (since 1974). Those long-term datasets need to be made available for publication and analysis. All too often, however, the data remain secreted away for decades while researchers find time to analyze and publish them. This comes at the cost of scientific advancement. The benefits of sharing long-term data include more accurate projections of how sea turtles will respond to climate change, and ultimately, improved conservation efforts. Researchers and managers would benefit from this approach by being able to make projections of species' responses to climate change in the future that are grounded in species responses to climate change in the past. There is also a benefit to the public. Much of the public refuses to accept the realities of climate change (Carvalho, 2007; Feldman et al., 2015), and even scientists are unsure of the impacts of climate change on sea turtles (Donlan et al., 2010). For example, the state of North Carolina, U.S., in 2012 banned projections of future sea-level rise that went beyond straight-line extrapolations from 1900 to 2000. In Florida, the governor forbid state employees in 2012 from using the terms "climate change" in official reports and documents. Having data on historical trends in responses to climate change allow for straight line projections (such as those still allowed in North Carolina), which are more acceptable to climate skeptics, and for more accurate projections based on increasing rates of climate change. We caution against pandering science to public opinion, but such an approach would at least bracket perceived uncertainty and may result in greater public acceptance of the impacts of climate change on sea turtles.

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