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SUPPLEMENTARY INFORMATION

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Projected response of an endangered marine turtle population to climate change

Supplementary Methods

Earth System Model 2.1

The Geophysical Fluid Dynamics Laboratory's Earth System Model (ESM 2.1) is a comprehensive ice-land-ocean-atmosphere coupled general circulation model that includes terrestrial and marine biogeochemistry[5]. The marine biogeochemistry model is comprised of macro- and micro-nutrients (N, P, Si, and Fe) as well as three phytoplankton functional groups with variable stoichiometry. We extracted sea surface temperature (SST) and large phytoplankton productivity from the eastern equatorial Pacific (2.5°N to 2.5°S, 85°W to 125°W) from 1975 to 1999 (IPCC 20C3M historical experiment)[6] and from 2000 to 2100 (IPCC-SRES A2 experiment)[26]. Considering SST variability as a proxy for ENSO variability[31], we detrended and converted SST to anomaly form by subtracting a 10-year moving average from each decadal period. Large phytoplankton productivity was extracted from ESM 2.1 from the same region as SST and converted to anomaly form but we did not detrend this data. Therefore, we were able to assess the projected relationship between SST variability and large phytoplankton productivity (Fig. 1a) and determined that SST variability could be used climate models assessed in the IPCC-AR4 as a proxy leatherback foraging conditions in the eastern equatorial Pacific.

Climate Models Assessed in the IPCC-AR4

We examined 14 climate models assessed in the IPCC-AR4 from the Coupled Model Intercomparison Project (CMIP3)[6] and selected only those models that resolved the contemporary (1976-1999) relationships between SST variability in the eastern equatorial Pacific (2.5°N to 2.5°S, 85°W to 125°W) and surface air temperature/precipitation in northwestern Costa Rica (10°N to 11°N, 85°W to 86°W) from the IPCC 20C3M historical simulations. The observed contemporary relationships were established by comparing Hadley Centre SST anomalies[32] in the eastern equatorial Pacific to land station measurements of precipitation and air temperature from the Daniel Oduber Quiros International Airport in Liberia, Costa Rica from 1976 to 1999 (Fig. S1). The Liberia airport is in close proximity to the nesting beaches of Parque Nacional Marino Las Baulas such that the air temperature and precipitation data recorded at the airport were used to predict hatchling sex ratios and nest success of leatherbacks at Playa Grande, Costa Rica[1,2]. This evaluation resulted in the use of seven climate models (Table 1).

We bias-corrected SST and air temperature/precipitation data from the seven models based on observed data during the contemporary period (1976-1999). For SST, we compared modeled data to Hadley Centre data[32] (mean and standard deviation) from 1976-1999 in the eastern equatorial Pacific. We then calculated average monthly means along with the residuals for each dataset and determined each model's bias-correction factors for each month of the year and for the residuals of the entire time-series. The bias-correction factors were then multiplied to each model's monthly data (1976-2100; IPCC 20C3M and SRES A2) so that the bias-corrected modeled SST from 1976-1999 has the same mean and standard deviation as the observed SST from the Hadley Centre for

the same time period. This same method was applied to each model's air temperature/precipitation data in northwestern Costa Rica and the bias-correction factors were based on observed data from the Liberia airport from 1976-1999.

Bias-correcting the climate model data was an essential step because the leatherback population dynamics model (CLIMPOP see below) combines ocean[3] and nesting beach components[1,2] that were parameterized based on observed contemporary climate data. The sensitivities of the ocean and beach components of CLIMPOP to climate were high enough such that biases in both the mean and variability of modeled climate data (when compared to the observed contemporary data) caused substantial deviations among the population trajectories during the historical experiments. For example, climate models that were too cool in terms of air temperature produce too many male hatchlings and higher than observed nest success when compared to observed data in the contemporary period. Bias-correcting the climate model data enabled us to reduce population trajectory deviations by reproducing the contemporary nesting beach and ocean climate in the initial conditions, and yet still retain the differential responses of each model's climate to changes in radiative forcing over the next century.

Climate-Forced Population Dynamics Model

Design and Assumptions

Nearly two decades of observed climate and leatherback life history data from Playa Grande, Costa Rica provided a modeling framework in which we could project the population's response to climate change over the next century. We designed a climate-

forced leatherback nesting population dynamics model (CLIMPOP) that estimates mature female recruitment and remigration as a function of the local climate in northwestern Costa Rica and ENSO variability in the eastern equatorial Pacific. Female and male hatchling recruitment rates (sex ratios and nest success) from the nesting beach are a function of the local temperature and precipitation in northwestern Costa Rica[1,2] while mature female foraging reproductive frequency is a function of ENSO variability[3]. Estimating each year's number of nesting females allows for the estimation of the entire population demography in the ocean based on male and female hatchling recruitment rates combined with juvenile and adult survival rates.

In order to reconcile the population's sensitivity to climate change in their terrestrial and oceanic habitat, we assumed population stability when CLIMPOP is forced with a contemporary climate and thus eliminated the impacts from incidental fisheries mortality and egg poaching. Although egg poaching is no longer active at Playa Grande, it is likely that the observed precipitous decline in nesting females is partially due to historically high rates of illegal poaching from 1975 to 1991[12]. Incidental fisheries mortality of leatherbacks has also been suggested to be responsible for the precipitous decline in the eastern Pacific[13] and may still be a factor based on current low annual survival estimates at Playa Grande (~0.78)[33]. The annual survival rate of western Atlantic leatherbacks nesting in St. Croix is estimated to be ~0.90 and this population has been successfully recovering due to beach protection and egg relocation[34]. Therefore, we used a higher annual survival rate (0.90) for mature adults than observed at Playa Grande (0.78) because we were interested in assessing the effects of climate change on an otherwise stable population. Current adult annual survival rates of ~0.78 are considered

unsustainable for leatherbacks[35] and may thus outweigh any impacts of climate change. Therefore, using an unsustainable annual survival rate would mask the effects of climate change and negate the goal of our modeling study.

We assumed an age of maturity of 15 years, based on a leatherback captive growth study (~16.1 years)[36], and that the annual survival of 0.90 is achieved after age 3. Juvenile leatherbacks have extremely fast growth rates relative to other sea turtles (4 to 11 times greater than green and loggerhead juveniles)[36]. Captive juvenile leatherbacks reach a length of 72 cm (straight carapace length) at age 2.23 years[36]. Field observations in the Pacific Ocean, through incidental fishery captures, suggest that juveniles as young as 3 years old are susceptible to the same incidental capture rates as mature adults[36], possibly due to similarities in their tropical and sub-tropical foraging/migration areas (i.e. Hawaii and Peru). Moreover, the estimated size of a 3 year old leatherback is ~80 cm (straight carapace length) based on the von Bertalanffy growth curve[36] and thus it is unlikely that 3 year old leatherbacks have substantially higher predation rates than adults (> 121 cm straight carapace length). Therefore, we assumed the annual survival of leatherbacks ≥ age 3 is the same as mature adults (≥15 years old) (0.90). Survival rates to age 3 were calibrated to produce a stable population forced by observed contemporary climate data (see below). It is important to note that we could have used higher/lower annual survival rates for turtles older than age 3 but doing so would only decrease/increase the survival rate of turtles to age 3 to achieve population stability when forced with the observed contemporary climate.

We assumed no effect of sea level rise on leatherback nests. Sea level rise projections over the next century have significant geographical variability and there is substantial

spread (5 to 95%) between climate model results assessed in the IPCC-AR4[25]. Moreover, there is a great deal of uncertainty on the response of global sea level to changes in the Greenland and Antarctic Ice Sheets[25]. Considering the rise of sea level exclusively from thermal expansion, which accounts for 70 to 75% of global sea level rise, the increase along the west coast of Central America is projected to be less than the global average[25]. Under IPCC-SRES A2, which is the largest forcing scenario of AR4, the models project between 0.23 and 0.51 m (5 to 95% range) of global sea level rise from all factors (thermal expansion, ice sheets, glaciers, etc.) by the last decade of the 21st century[25]. Sea level rise on the west coast of Central America over the next century is projected to be less than the global average. The primary nesting area at Playa Grande lies on a berm 1 to 2 m above the mean high tide line[27]. Moreover, protected areas extending 125 m inland from the highest tide line should facilitate gradual beach adjustment to rising sea level.

The CLIMPOP model also assumes that a change in the population's sex ratio over the next century will not affect breeding rates unless the mature adult population becomes a 100% single-gender proportion. Using 57 years (1950-2007) of local precipitation data, the proportion of female hatchlings produced at Playa Grande is estimated to be 88% but that over 25% males can be produced during pluvial years associated with La Niña events[1]. Many other sea turtle populations have been reported to be female-biased[9] yet the consequences of a reduction in males due to climate change is very difficult to assess[37]. A recent empirical study[18] reported that male sea turtles return to nesting beaches (for breeding) almost three times more often than females and thus a reduction (but not elimination) of males due to climate change might be less acute than previously

suggested. Therefore, we assumed that breeding rates do not change as long as the proportion of males produced does not become zero over a decadal period.

Finally, we assumed no evolutionary adaptation to climate change over the next century. The evolutionary response of long-lived organisms to rapid climate change is questionable and may depend on the level of plastic effects acting synergistically with evolution[22]. Moreover, a large effective population size is required to maintain substantial genetic variation and evolutionary potential[22]. Genetic analysis of eastern Pacific sea turtle populations, including leatherbacks, revealed that these populations are ephemeral and may have been extirpated during glacial intervals[38]. These data suggest that eastern Pacific sea turtle populations cannot adapt fast enough to keep up with the slow rate of tropical-glacial regime shifts. Therefore, the long-lived nature of eastern Pacific leatherbacks, small population size, and their ephemeral population regimes (boom-bust) throughout the paleo-record suggest that this population may not be able to adapt to rapid climate change over the next century and CLIMPOP does not include an evolutionary adaptation term.

Climate Forcing and CLIMPOP Evaluation

The ocean and beach components of CLIMPOP have each been evaluated against observed leatherback remigrant and nest data in previous studies at Playa Grande, Costa Rica[1-3]. For the ocean component[3], the 15-year estimate of the number of remigrant nesting females compared to the observed is statistically robust and significant ($r^2 = 0.89$, $P < 0.001$). For the nesting beach component, estimates of hatching success[2], emergence

rate[2], and hatchling sex ratio[1] are also significantly similar to the observed values over nearly a decade (r^2 = 0.81, 0.65, 0.69 respectively, $P < 0.001$).

The CLIMPOP model is first forced with the observed contemporary climate data from the Liberia airport (air temperature/precipitation) and the Hadley Centre (SST) in the eastern equatorial Pacific from 1976-1999. We looped the contemporary climate data to produce ~300 years of climate prior to the IPCC-SRES A2 scenario. The first 15 years of nesting female numbers (N_y) are initialized with 1000 individuals for each year y and then afterwards the number of nesting females (N_y) becomes a function of the beach and ocean climate. The nesting population is then stabilized over the looped contemporary climate period (~300 years) by resolving the survival rate for hatchlings to reach age 3 (s = 0.0195). Combining this survival rate with the annual survival of leatherbacks older than 3 years (S = 0.90) results in a survival to maturity (age 15) of 0.0055 (6 of every 1000 hatchlings that enter the ocean survives to age 15). Our estimate of survival to maturity is similar to estimates from prior leatherback population modeling studies[12,35]. From 2000 to 2100, CLIMPOP is forced with the bias-corrected climate model data under the A2 scenario from each of the seven selected models.

Our estimate of the mean annual proportion of new nesting females (ages 15 to 22) during the contemporary looped climate is 35% (±6). Comparing our estimate to the observed annual proportion of untagged nesting females at Playa Grande from 2000-2009 [40% (±10)], our estimated proportion is lower in terms of bias and variability. However, some of these untagged females may not in fact be "first-time" nesters due to tag loss, a previous nesting at a different beach where tagging doesn't take place, or a lack of

observer beach coverage at Playa Grande when the turtle first nested. Therefore, the observed proportion is likely smaller and thus closer to our estimate.

Supplementary References

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Figure S1. Observed contemporary relationships (1976-1999) between SST variability in the eastern equatorial Pacific, air temperature, and precipitation in northwestern Costa Rica. All correlation values are statistically significant ($P < 0.05$). These data were used to bias-correct the climate model data and to force the nesting population dynamics model prior to the year 2000. The Liberia Airport is located in northwestern Costa Rica at 10.594^{o}N, 85.544^{o}W.

Figure S2. Climate-forced nesting population projections of annual numbers of nesting female leatherbacks at Playa Grande, Costa Rica during SRES A2 when considering two different scenarios of the impacts of an increase or decrease in the amplitude of ENSO variability. Three climate models projected an increase in the amplitude of ENSO variability and four models projected a decrease (Table 1). The looped observed contemporary climate (1976-1999) forces the population model prior to the year 2000 when the A2 scenario begins. The nesting population is initialized with 1000 nesting females. Both time-series are a 10-year moving average.

Figure S3. Climate-forced population (CLIMPOP) demographic projections during SRES A2 for (**a**) female and (**b**) male adult turtles in the ocean and (**c**) female and (**d**) male hatchlings entering the ocean. (**e**) Projections of hatchling sex ratio in terms of the proportion female hatchlings entering the ocean. All time-series in **a** to **e** are a 10-year moving average.

Figure S1.

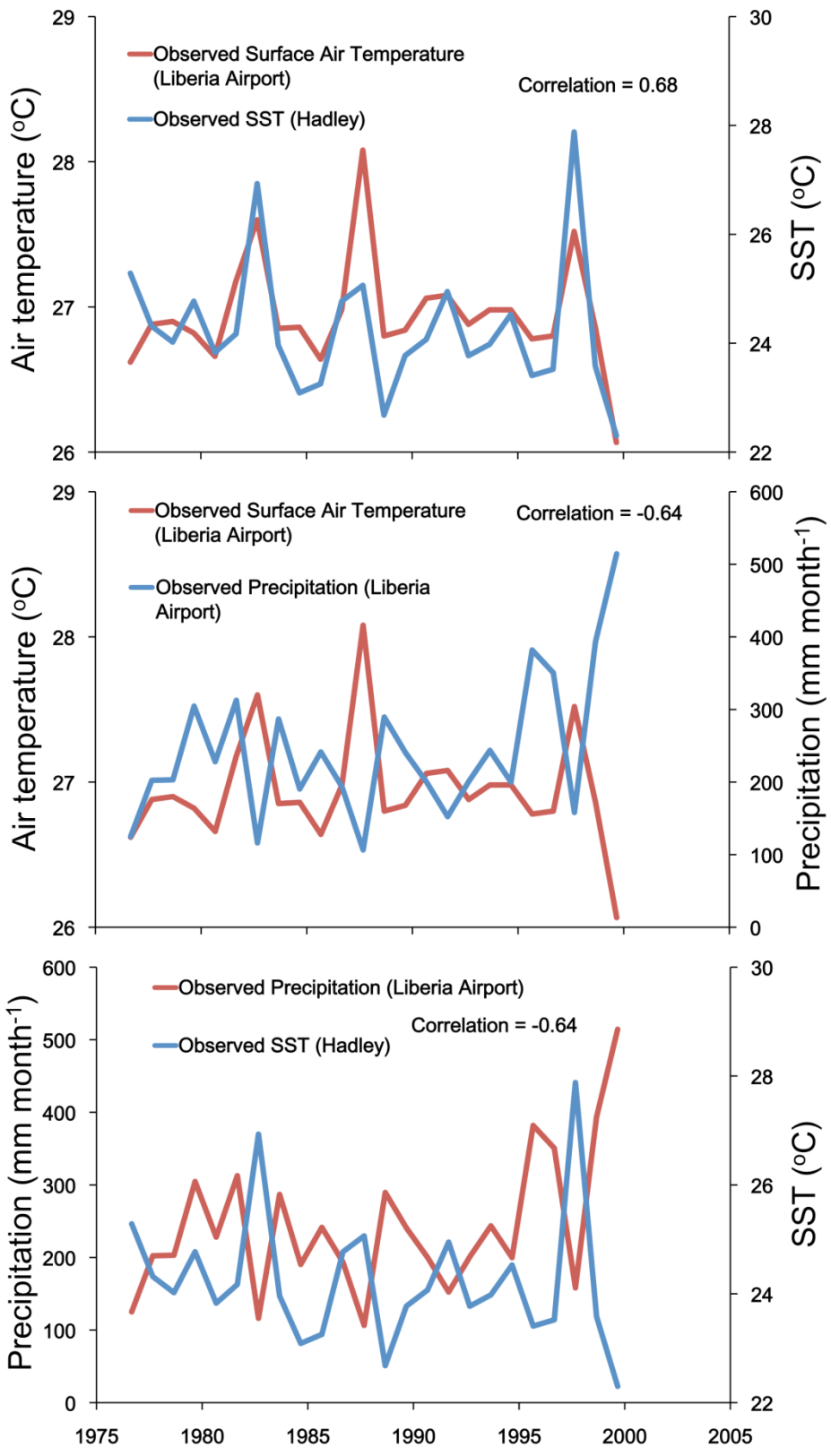

Figure S2.

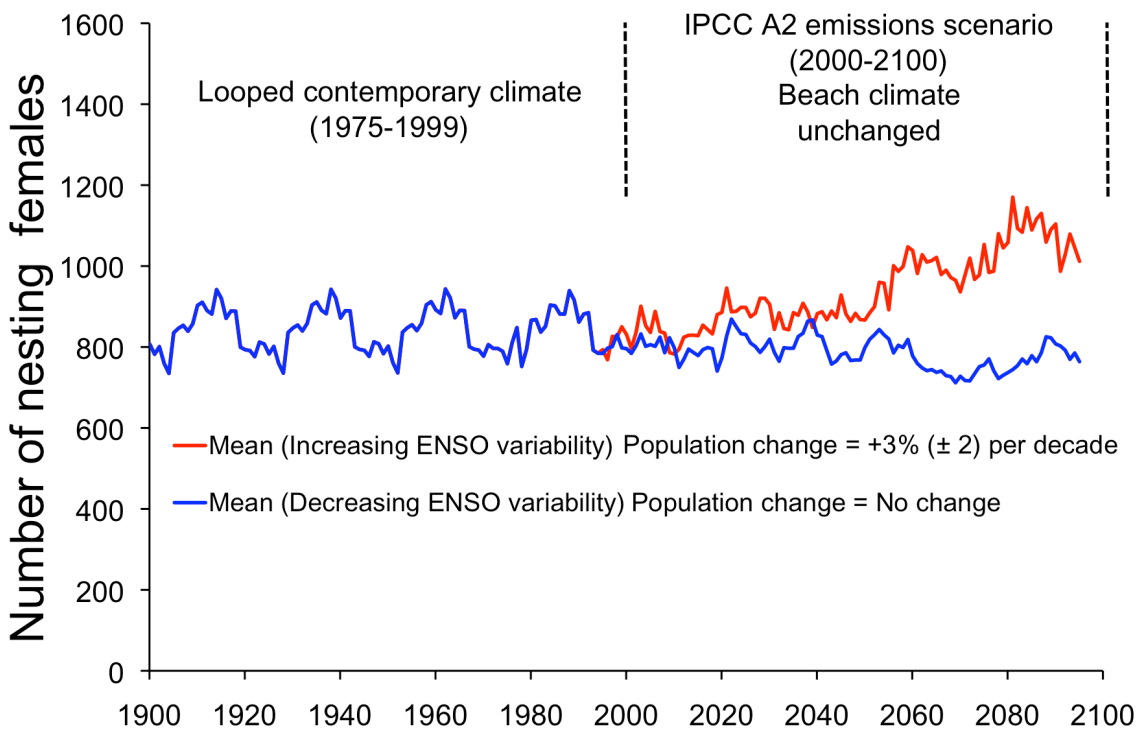

Figure S3.