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Climate change impacts on nesting and internesting leatherback sea turtles using 3D animated computational fluid dynamics and finite volume heat transfer

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ABSTRACT

Shifting suitable range limits under global warming will threaten many species. Modeling and mapping these potential range shifts is important for conservation. As global warming will introduce new sets of abiotic conditions, predictive empirical niche models may not perform well and the best method to model a specie's projected range shifts may be to model their fundamental niche with a biophysical mechanistic niche model. However, this class of model requires many physiological parameters that are difficult to measure for species not easily kept in captivity. It is also difficult to estimate these parameters for marine species given the interactions among their in-water motion, metabolism, and heat transfer. To surmount these difficulties, we use our previously verified novel technique combining 3D digital design, computational fluid dynamics, and finite volume heat transfer modeling to find animal core temperatures. We then use this method to build a fundamental niche map for internesting and nesting leatherback sea turtles (*Dermochelys coriacea*). With these niche maps we analyze three main nesting areas. We show that global warming poses a large overheating risk to leatherbacks in Southeast Asia, a slight risk to leatherbacks in the West Atlantic and a low risk to leatherbacks in the East Atlantic. We also show that the impact may be less on leatherbacks that shift their nesting location or who are smaller. Methods such these are important to produce efficiently and economically accurate maps of regions that will become inhospitable to species under global warming conditions.

1. Introduction

Global warming poses a large extinction risk for many species (Thomas et al., 2004). A species' inability to shift its current range to match the future suitable range accounts for much of the extinction risk (Parmesan and Yohe, 2003). Therefore, mangers and conservationists will likely need accurate range shift predictions to successfully address the global warming threat to their focal species. For leatherback sea turtles (*Dermochelys coriacea*) estimating new suitable ranges is quite complex. The first difficulty is that leatherbacks are gigantotherms, endothermic poikilotherms, whose large body size traps waste heat thus elevating their core temperature (Paladino et al., 1990). This effect means that leatherbacks are neither thermal conformers nor regulators and thus makes predicting their core body temperature difficult. The second difficulty is their complex life history. They have the largest range of any reptile (Saba, 2013) and are biphasic (nesting on land and living in the water). Thus, global warming will affect leatherbacks over a wide geographic range as well as in two distinct environments. Hence, there is not only a need to determine the leatherback's marine distribution (National Marine Fisheries Service and U.S. Fish and Wildlife Service, 1992) but also potential future nesting locations (Fuentes et al., 2012).

Despite the logistic difficulties of tracking leatherbacks given their pelagic life history, scientists have tracked this species for over three decades and are now producing studies with hundreds of tracks (Fossette et al., 2014). While these studies can provide information on the lower thermal limits of leatherbacks, they cannot analyze the potential future threat of increased water temperatures in the leatherback's equatorial ranges because water temperatures as high as those under climate change do not yet occur. In addition to higher temperatures, global warming may introduce new combinations of abiotic conditions, thus the best method to model leatherbacks' response to climate change may be to model their

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fundamental niche using a biophysical mechanistic niche model (Kearney and Porter, 2009; Porter et al., 2002). However, this class of model requires many physiological parameters that are difficult to measure for leatherbacks as they are not easily kept in captivity (Jones et al., 2011). Since leatherbacks are marine species, it is also difficult to estimate these parameters given the interaction between their in-water motion, metabolism, and heat transfer (Boisclair and Tang, 1993).

In our earlier work we avoided these difficulties by simply making reasonable assumptions about missing physiological parameters and simplifying assumptions about the leatherbacks physiology in general (Dudley and Porter, 2014). In this current work, we attempt to address and overcome these difficulties by using an animated, 3D computational fluid dynamics (CFD) simulation and a numerical internal heat transfer model. Our previous work showed how CFD simulations can match the forces on and heat transfer from complex animal shapes in wind tunnel experiments (Dudley et al., 2013). In later work we then demonstrated that, using only stroke frequency, ambient water temperature and an allometric relation for resting metabolic rate (RMR), this method is able to accurately predict leatherback core temperatures in a laboratory environment (Dudley et al., 2014). Thus, by combining the data from our CDF model (power, heat transfer coefficients, infrared (IR) absorption and radiation, and internal temperature profiles) with global climate models (GCMs) we can predict regions within the leatherback's current marine and terrestrial range that may become inaccessible under global warming conditions. We examine potential shifts in nesting and internesting time and, range, as well as body geometry and size. To our knowledge, this is the first projection of the fundamental niche of an organism using this high level of detail, which can only come from CFD and numerical heat transfer models (Dudley et al., 2013).

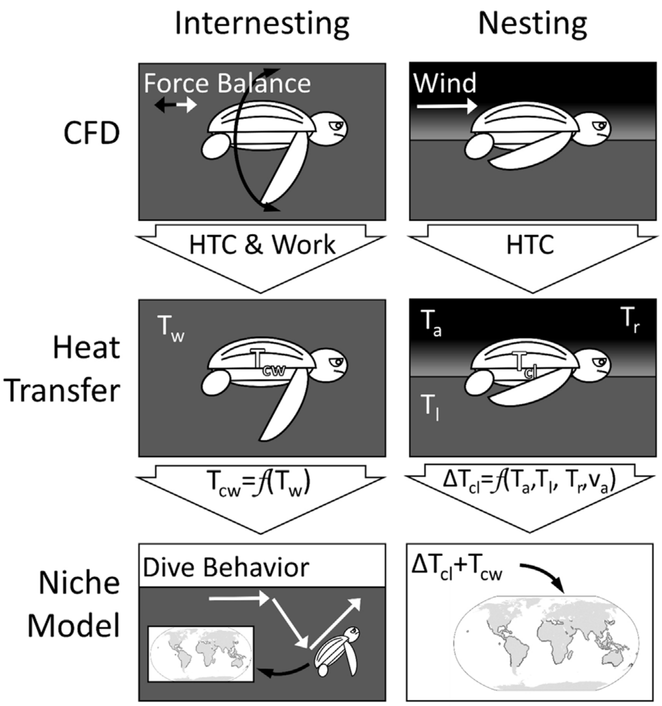

Fig. 1. A diagram of the modeling procedure. The procedure is divided into three steps (CFD, heat transfer, and niche model) each done on two different phases (internesting and nesting). The computational fluid dynamic (CFD) step produces heat transfer coefficients and work (in the internesting phase). The heat transfer step produces a function of environmental conditions (water temperature (T_w), air temperature (T_a), land temperature (T_l), radiant temperature (T_r), and air velocity (ν_a)) which predicts the turtle's core temperature, or change in core temperature during the nesting phase (in water (T_{cw}) and on land (ΔT_{cl})). The niche model phase uses the previously established relations to map the turtle's core temperature under climate change.

2. Methods

2.1. Outline

The modeling process has three steps and each of these steps is done for the leatherback while it is in the marine environment ("internesting phase") and while it is on land laying eggs ("nesting phase"). The first step ("CFD simulation step") uses CFD to calculate heat transfer coefficients from the leatherback, and, for the internesting phase, power required to maintain a set swimming speed. The second step ("heat transfer simulation step") takes the results of the first step and uses them in a heat transfer model to calculate the leatherback's core temperature given varying environmental conditions. The third step ("niche model step") takes the relations between environmental conditions and leatherback core temperature and combines those with climate models to produce maps of leatherback core temperatures under two climate change scenarios. Fig. 1 is a diagram of the modeling approach.

2.2. Internesting phase

2.2.1. CFD simulation step

We drew five different anatomically realistic adult leatherbacks in a non-uniform rational basis splines (NURBS) format using commercial 3D design software (MoI). NURBS are 2D irregular surfaces that can produce realistic 3D models of biological forms. The five different models are: one with the largest curved carapace length (CCL) to curved carapace width (CCW) ratio (1.5) and the longest CCL (171 cm) (called long narrow (LN)); one with the smallest ratio (1.2) and the longest CCL (called long wide (LW)); one with the largest ratio and the smallest CCL (128) (called short narrow (SN)); one with the smallest ratio and the smallest CCL (called short wide (SW)); and one which had an average ratio (1.4) and an average CCL (150 cm) (called average (Av)) (see Fig. A.1 and Table A.1 in Appendix S1 in Supporting Information). These leatherbacks would weigh approximately 477 kg, 633 kg, 201 kg, 266 kg, and 337 kg respectively. The ratios and lengths are based on data from three sources (James et al., 2007; "Jupiter Island sea turtle taging project (JISTTP)," 2012; Médicci et al., 2011). This size range more than covers the typical standard deviation observed in CCLs of sampled leatherbacks (typically less than 10 cm). The flipper length scaled with CCL and not with CCW (Walker, 2010). We placed one side of the model in a virtual half cylinder with buffer distances of approximately 4 m between the turtle's flipper tip and the cylinder's wall, which is adequate space to not affect the stroke mechanics. The plane dividing the cylinder in half also divides the turtle along the midsagittal plane. Using half the turtle and a symmetry boundary condition on the plane bisecting the turtle increases computational efficiency by only solving the fluid dynamics around one half of the turtle. This setup resulted in volumes ranging from 440 to 1450 m^3 depending on the size of the turtle. We meshed all the fluid domains with tetragons (a standard choice for an unstructured computational grid in CFD). All domains contained approximately 150,000 elements which is adequate to produce accurate results (Dudley et al., 2014).

We use a commercial CFD program, ANSYS Fluent (ANSYS, Inc., Cecil Township, Pennsylvania, USA), We wrote a supplemental program using Fluent's "DEFINE_GRID_MOTION" macro, which describes the leatherbacks' swimming motion (additional details Dudley et al., 2014). To mimic a turtle's flipper motion, we used ImageJ software (National Institutes of Health, Bethesda, Maryland, USA) to analyze frames from publicly available video of