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**Size Differences in Hind Limbs and Carapaces  
of Hatchling Green Turtles (*Chelonia mydas*)  
from Hawaii and Florida, USA**

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For decades biologists have commented on morphological differences in green turtles (*Chelonia mydas*) from the Atlantic and Pacific Ocean basins. A number of investigators have enlisted morphological differences in arguments to separate *C. mydas* (a polymorphic species) into several subspecies or races (e.g., *C. m. agassizii*, *C. m. carrinera*, *C. m. japonica*). Deraniyagala (1939) felt that differences noted between Atlantic and Indo-Pacific forms were ontogenetic variations. Carr (1952, 1964, 1972) described two morphs of *C. mydas* in the Pacific. One morph was characterized by a deep body as well as dark pigmentation on the scales and plastron; the other had yellowish pigmentation and a flatter profile. He made brief mention that Pacific green turtles differed in form from Caribbean turtles. Caldwell (1962) listed a number of carapace, plastron, and scapular features that distinguished the different Pacific and Atlantic morphs. He felt that these differences were sufficient to justify their designation as subspecies. Kamezaki and Matsui (1995), using skull morphology, described 5 distinct geographic groups from the Atlantic, Pacific, and Indian Ocean basins. Pritchard and Trebbau (1984) noted that some populations of *C. mydas* had pigmen-

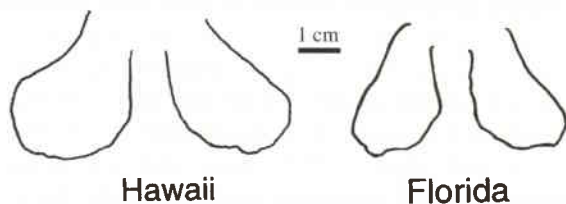
tation along the ventral surface of the marginal scutes, while others lacked this pigmentation. Ontogenetic changes in the plastral pigmentation of young green turtles from Hawaii have been documented (Balazs, 1986). No similar changes have been described in Western Atlantic green turtles, however, we have noted that plastron color changes from white in hatchlings to pale yellow in juveniles and adults from Florida (unpubl. data). An anecdotal observation suggested that the hind limbs of Hawaiian green turtles in the Pacific are proportionately larger than those of Atlantic turtles (A. Carr and L. Ogren, *pers. comm.* to GHB).

These observations prompted us to compare and contrast hind limb size and body size in hatchling green turtles from a Central Pacific population (Hawaii) and an Atlantic Ocean population (Florida). Our study shows that hind limb size and body size differ significantly and consistently between these two populations. This population-specific morphological variation can be attributed to differences in embryonic development. We interpret the presence of this polymorphic characteristic to be a consequence of geographic isolation and speculate as to the adaptive significance of these two morphs.

**Methods.**— We collected and measured 200 hatchlings (10 hatchlings from 10 nests of 10 different females at each of the two sites). Data were collected during 1989–91 in Hawaii and during 1991–92 in Florida. Hawaiian hatchlings originated from French Frigate Shoals (23°08'N, 166°02'W; see Balazs, 1976, 1980) and Floridian hatchlings originated from Boca Raton (26°19'N, 80°04'W). We measured hatchlings within one day of emergence. Data collection was restricted to hatchlings to insure that we measured population-specific differences in limb morphology and did not include any feet whose fleshy margin or terminal bony components may have been truncated by posthatching injury.

We measured, using vernier calipers, the midsagittal straight-line carapace length of each hatchling (SCL: to the nearest 0.1 mm) from the anterior-most point of the nuchal (cervical) scute to the posterior-most point of the last marginal scute. A flexible fiberglass tape measure was used for curved lengths (CCL: to the nearest 0.5 mm). CCL was measured on all Hawaii hatchlings ( $n = 100$ ) and a subset of the Florida hatchlings ( $n = 30$ ; due to the tape measure being unavailable during all collection times). Body size was compared between the two populations by t-test for unequal variances (SAS et al., 1981). Each measure (SCL and CCL) was tested separately.

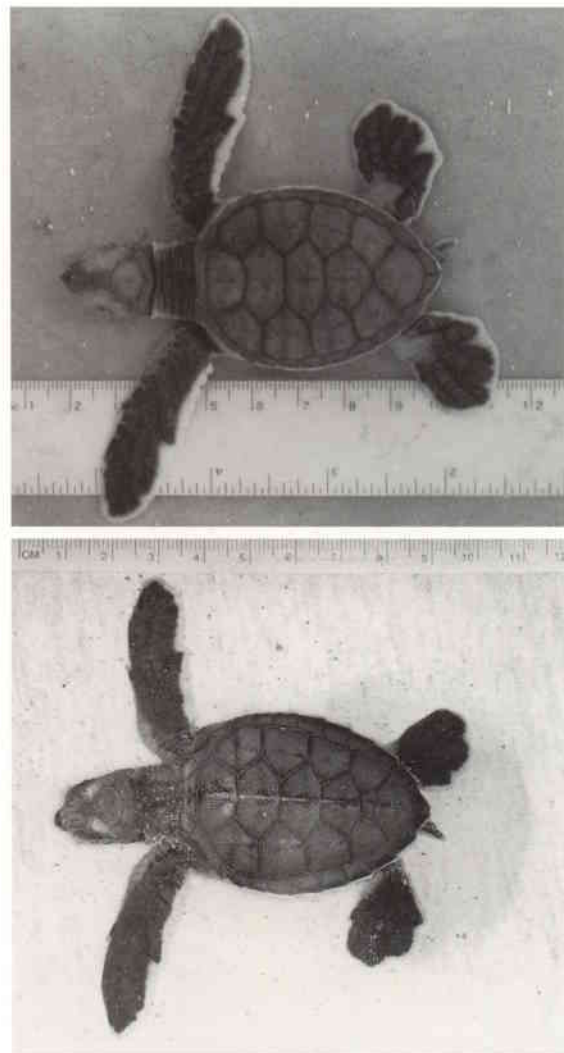
Using identical techniques, we held each hind limb flat with light finger pressure while we traced both hind limbs of



**Figure 1.** Sample tracings of the hind limbs of same-sized Hawaiian and Floridian hatchling green turtles. Bar = 1 cm.

live hatchlings from the anterior-most point on the knee, along the anterior and posterior crus and tarsus, and around the pes. The planar surface areas of these tracings (Fig. 1) were measured using a digital scanning program (Sigma-Scan Digitizer, Jandel Scientific). The precision of this method (assessed by measuring each hind limb tracing 3 times) was  $\pm 0.012 \text{ cm}^2$  (SE). The 3 tracing measurements were averaged, then the mean area of each hatchling's hind limbs was calculated, giving an average area for the pair. For each turtle, mean hind limb area ( $\text{cm}^2$ ) was tabulated, then converted to its square root ( $\sqrt{\phantom{x}}$ ) so that limb size and carapace size shared the same units. Hereafter the  $\sqrt{\phantom{x}}$  mean hind limb area is referred to as "limb size."

Data were analyzed using two protocols. First, each individual was treated as a single data point (ignoring that groups of 10 hatchlings were from the same clutch); this is referred to as the "individuals protocol." A second analysis was made to insure that our results were not biased due to pseudoreplication; this treated data for individual hatchlings from the same clutch as repeated measures and was desig-



**Figure 2.** Photographs of Hawaiian (top) and Floridian (bottom) *C. mydas* hatchlings just after emergence from the nest. The two animals share the same straightline carapace length. Note the proportionately larger hind limbs of the Hawaiian hatchling.

nated the "nests protocol." The data for each clutch were pooled, described as a grand mean and SE then analyzed by repeated-measures models.

Using the "individuals protocol," hind limb areas were compared by t-tests (Sokal and Rohlf, 1981). The natural logarithm (ln) of limb size was plotted as a function of (ln) body size (SCL). The data for the two populations were then characterized as linear models through simple linear regression. We then investigated how limb size covaried with body size. The slopes and y-intercepts of the regressions were compared by ANCOVA, followed by *post hoc* (Tukey-Kraemer) tests to determine if those metrics were homogeneous (SAS et al., 1981; Bookstein et al., 1985; Abacus Concepts, 1992).

For the "nests protocol," mean hind limb areas of 10 clutches for each site were compared using Mann-Whitney tests. The mean (ln) limb size of each clutch was plotted as a function of its mean (ln) SCL. These data were then characterized as linear models. As above, we investigated how limb size covaried with body size by applying ANCOVA for repeated-measures to the data. We then determined if the slopes and y-intercepts were homogeneous (SAS et al., 1981; Sokal and Rohlf, 1981; Zar, 1984).

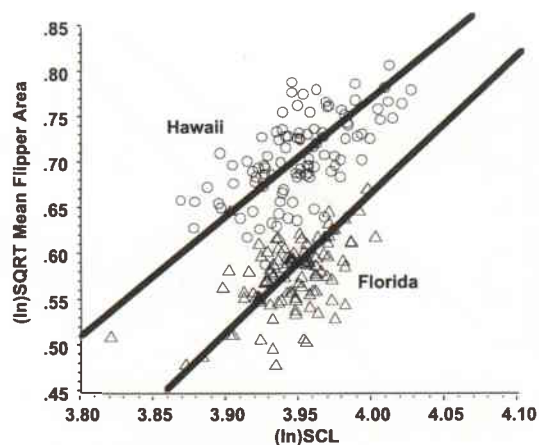
### Results

Body size SCL measurements did not differ significantly between Hawaiian ( $51.97 \pm 1.69$  mm,  $n = 100$ ) and Floridian ( $51.69 \pm 1.39$  mm,  $n = 100$ ) hatchlings ( $t = -1.29$ ,  $df = 198$ ). However, Hawaiian hatchlings had flatter carapaces ( $CCL = 54.63 \pm 1.91$  mm,  $n = 100$ ) than Floridian turtles ( $56.92 \pm 1.04$  mm,  $n = 30$ ). Because the CCL values differed ( $t = 45.49$ ,  $df = 99, 29$ ;  $p < 0.001$ ), we did not use this measure to investigate hind limb size as a function of body size. Turtles from Hawaii and Florida matched for similar SCL differed significantly in hind limb area (Figs. 2, 3).

**Individuals Protocol.** — Comparisons of hind limb size by "individuals protocol" showed that mean flipper area was  $4.15 \pm 0.42$  cm<sup>2</sup> for Hawaiian hatchlings and  $3.18 \pm 0.25$  cm<sup>2</sup> for Floridian hatchlings. The  $F_{max}$  test (Sokal and Rohlf, 1981) showed that the variances of the limb sizes ( $\sqrt{\text{mean hind limb area}}$ ) were homogeneous. We transformed the data to its natural logarithm to insure uniform variance for both low and high values.

Least squares regression analysis was applied to (ln) SCL vs. limb size. We found no significant interaction between body size and population. Different regression lines (Model II - reduced major axis) described the relationship between (ln) SCL vs. limb size (Fig. 3). In the Hawaiian population this was:  $y = 1.40 * (\ln)SCL - 4.82$ , ( $r = 0.62$ ,  $p < 0.001$ ); and in the Floridian population it was:  $y = 1.42 * (\ln)SCL - 5.01$ , ( $r = 0.50$ ,  $p < 0.001$ ).

The ANCOVA of factors influencing limb size showed that body size was a significant factor. In this analysis, the interaction factor was not significant. Therefore, the slopes of the lines describing each population's limb size were statistically indistinguishable. Because the interaction term



**Figure 3.** Linear regression of  $(\ln)\sqrt{\text{mean hind limb area}}$  as a function of  $(\ln)SCL$ . The slopes of the lines fitted to each population's data do not differ significantly, however, the y-intercepts do differ.

was not significant, it was removed from the model. The resulting ANCOVA (Table 1) showed that both population and body size factors affect  $(\ln)\sqrt{\text{mean limb size}}$ . A comparison of the least squares means by t-test showed that they differ, hence, the y-intercepts differ.

Comparisons of limb size ( $\sqrt{\text{mean hind limb area}}$ ) among individuals by t-test for unequal variances showed that the two populations differed ( $t = 1800.00$ ,  $df = 99, 99$ ,  $p < 0.0001$ ). Comparisons of least squares means matched for body size also showed that the Hawaiian turtles had significantly larger hind limbs than Floridian hatchlings (Figs. 2, 3).

**Nests Protocol.** — Least squares regression analysis was applied to (ln) mean SCL vs.  $(\ln)\sqrt{\text{clutch mean hind limb area}}$  (hereafter referred to as "clutch limb size"). We found no significant interaction between body size and nest number. As in the analysis of individuals, different regression lines (Model II - reduced major axis) described the relationships (Fig. 4). In the Floridian population this was:  $y = 1.84 * (\ln)SCL - 6.70$  ( $r = 0.67$ ,  $p < 0.03$ ); and in the Hawaiian population it was:  $y = 1.17 * (\ln)SCL - 3.90$ , ( $r = 0.91$ ,  $p < 0.001$ ).

The ANCOVA for repeated measures of factors influencing clutch limb size showed similar results to those

**Table 1.** ANCOVA of  $(\ln)\sqrt{\text{mean hind limb area}}$ . The factors tested were body size (described by (ln) SCL) and population (Hawaiian vs. Floridian), and the interaction of these two was removed. Least squares means were compared by t-test to determine if the intercepts were similar. Post-hoc (Tukey-Kraemer) tests contrasted the two assemblages.

|            | df  | SS     | MS     | F      | Significance |
|------------|-----|--------|--------|--------|--------------|
| Population | 1   | 0.8139 | 0.8139 | 674.76 | $p < 0.0001$ |
| (ln)SCL    | 1   | 0.1155 | 0.1155 | 95.80  | $p < 0.0001$ |
| Residual   | 197 | 0.2376 | 0.0012 |        |              |

#### Least Squares Means

|         | n   | Mean   | SE     | Diff.  | t-test       |
|---------|-----|--------|--------|--------|--------------|
| Florida | 100 | 0.5773 | 0.0035 | 0.2212 | 39.6116      |
| Hawaii  | 100 | 0.7090 | 0.0035 |        | $p < 0.0001$ |

#### Tukey-Kraemer Comparisons

|                    | Difference | Crit. Diff. | Significance |
|--------------------|------------|-------------|--------------|
| Hawaii vs. Florida | 0.1320     | 0.0128      | $p < 0.001$  |