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CHAPTER 4

Galápagos Marine Vertebrates: Responses to Environmental Variability and Potential Impacts of Climate Change

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1. INTRODUCTION

1.1. Vertebrate Diversity

The Galápagos marine vertebrates constitute a diverse group of species that includes marine iguanas, sea turtles, seabirds, sea lions, dolphins, and whales. (Teleost fishes and sharks are not considered in this report). Several of these species rely on coastal ecosystems, and even spend substantial portions of their time ashore, whereas others have an entirely aquatic existence and normally are found far from land. As major consumers of secondary and tertiary productivity, most marine vertebrates are widely regarded as the ocean's top predators, with the exception of marine iguanas and green turtles which feed almost exclusively on vegetation. Perhaps the most distinctive feature that the marine vertebrates of the Galápagos have in common is that they are among the most charismatic fauna of the archipelago.

Globally, climate change is expected to have deleterious impacts on marine vertebrates, primarily through food shortages and physiological impairment (secondary and tertiary impacts are also expected but less understood). However, quantifying, or even describing at a basic level, how climate change will affect the Galápagos marine vertebrates is a tall order. This stems from 1) our limited and fragmented knowledge of the ecology of the species, 2) a lack of adequate local-scale, spatio-temporally resolved climate change scenarios, and 3) the fact that climate change is expected to be a unidirectional, progressive process with no past analog on which to base predictions. The purpose of the present report is to provide an overview of known or observed responses to environmental variability, which could inform future responses to changes in environmental conditions driven by climatic change.

1.2. Biogeographic Affinities

The archipelago is divided into three biogeographic zones—the western, central-southern, and northern regions—which are determined by their location and degree of exposure to prevailing currents and water masses. Not surprisingly, the marine vertebrates of the Galápagos display distinct distribution patterns within these regions. Given that the predicted impacts of climate change include the alteration of oceanic currents (notably the Equatorial Undercurrent that fuels an elevated marine productivity in the Galápagos), consideration of present biogeographic affinities will be useful in predicting the impact of these changes on the Galápagos fauna. The green sea turtle (*Chelonia mydas agassizi*) is predominantly found in the western region (where most nesting occurs between December and May), as well as in the central-southern region. Marine iguanas (*Amblirhynchus cristatus*) occur throughout the archipelago, but their highest densities are found in the western region. The Galápagos sea lion (*Zalophus wollebaeki*) also occurs throughout the archipelago, but the largest colonies are found in the central-southern region. In contrast, the major breeding colonies of the Galápagos fur seal (*Arctocephalus galapagoensis*) are found in the western and northern regions.

More than a dozen species of seabirds make their home on different islands of the Galápagos, which they use for breeding and as a base for launching their ocean-going foraging trips. While the magnificent frigatebird (*Fregata magnificens*), the blue-footed booby (*Sula nebouxii*), and the brown pelican (*Pelecanus occidentalis urinator*) are ubiquitous throughout the archipelago, most seabirds have more region-specific distributions. The western region is host to 100% of the flightless cormorant (*Nannopterum harrisi*) and 90% of the Galápagos penguin (*Spheniscus mendiculus*) populations. In the central-southern region, Española Island hosts the largest concentration of Nazca boobies (*Sula granti*) and waved albatrosses (*Phoebastria irrorata*), while Santa Cruz Island is home to the lava gull (*Larus fuliginosus*). The Galápagos petrel (*Pterodroma phaeophygia*) nests primarily on San Cristóbal, Santa Cruz, Santiago, and Floreana Islands, while the swallow-tailed gull (*Creagrus furcatus*) nests on Plazas and Española Islands. The northern region is home to the red-footed booby (*Sula sula*), the great frigatebird (*Fregata minor*), the swallow-tailed gull, and two species of storm petrel (*Oceanodroma tethys* and *Oceanites gracilis*). The sooty tern (*Onychoprion fuscatus*) also nests on the northern islands of Darwin and Wolf.

A diverse cetacean community inhabits Galápagos waters, including several resident species and long-distance migrants such as the humpback whale (*Megaptera novaeangliae*) and the blue whale (*Balaenoptera musculus*). Among the residents, the short-beaked common dolphin (*Delphinus delphis*), the striped dolphin (*Stenella coeruleoalba*), the Risso's dolphin (*Grampus griseus*), the short-finned pilot whale (*Globicephala macrorhynchus*), the sperm whale (*Physeter macrocephalus*), the killer whale (*Orcinus orca*), and the Bryde's whale (*Balaenoptera edeni*) are predominantly found in the upwelling-modified waters of the western and the central-southern regions. In contrast, the pantropical spotted dolphin (*Stenella attenuata*) and the spinner dolphin (*Stenella longirostris*) are the predominant species in the warm and stratified waters of the northern region. The bottlenose dolphin (*Tursiops truncatus*) is common in nearshore waters of all three regions.

2. RESPONSES TO ENVIRONMENTAL VARIABILITY

In spite of being located on the equator, the Eastern Tropical Pacific undergoes marked seasonal changes driven by the annual north-south migration of the Intertropical Convergence Zone (ITCZ) and its associated trade winds. In addition, every four to seven years this region is affected by more dramatic changes caused by the El Niño-Southern Oscillation (ENSO) and its two phases: El Niño, with associated anomalously warm conditions, and La Niña, with cooler-than-normal conditions. As long-lived organisms, marine vertebrates are adapted to cope with these variations, although some species are more successful than others. Some species' responses to ENSO variability are illustrated below, as their responses to ENSO events are the best information available for understanding how species might respond to climate-induced changes. We know much less about how other environmental factors related to climate change will affect Galápagos marine vertebrates, but we provide brief discussions about their presumed impact where relevant.

2.1. El Niño

Green sea turtles and marine iguanas

Turtles and marine iguanas are primarily affected by the reduction in the amount of algae of the genuses *Ulva*, *Spermothamnium*, and *Centroceras*, which are their main food, and their food's replacement by inedible species or less palatable genuses such as *Giffordia* and *Enteromorpha*. Consumption of undigestible brown algae is one of the leading causes of mortality. During the last strong El Niño of 1997-98 the population of marine iguanas suffered 90% mortality. El Niño also affects reproduction and recruitment. Lower numbers of females arrive at the nesting beaches during these events, as nutritional stress may limit in their ability to perform long migrations. In addition, extreme high air and ground temperatures during incubation may cause feminization or death of embryos during development. Nest flooding and beach erosion caused by elevated sea level during El Niño also can have an impact in subsequent-year cohorts.

Sea lions

Severe reductions of up to 50% of the total population have occurred during strong El Niño events. During these events, up to 90% of the pups and 67% of the alpha males have died. Widespread movements, probably in search of food, have been recorded between islands and even to the South American mainland. Feeding habits are also significantly altered. Lantern fishes (*Myctophidae*) and serranids replace the South American pilchard (*Sardinops sagax*) as the main prey items, implying a switch to nocturnal and coastal foraging. The population can take up 10 years to recover after strong events. In 2005 the population was estimated at 18,000 to 20,000 individuals and appeared to be increasing. An expansion in the distribution range is expected in future warming events.

Fur seals

Less data on the effects of El Niño are available for fur seals, but the data are expected to be similar to those recorded for the sea lions, perhaps with less dramatic mortality. Like the sea lions, fur seals appear to range widely during El Niño events, as evidenced by move-

ments to mainland South and Central America and even into the Gulf of California. The population also appears to be increasing from the strong events in the 1980s and 1990s, with numbers estimated at 8,000 to 10,000 individuals in 2005. Similar to sea lions, an expansion in the distribution range is expected in future warming events.

Penguins, cormorants, and other seabirds

Mortalities of up to 77% in penguins and 50% in cormorants were recorded during the strong El Niño events of 1982-83 and 1997-98. Breeding success is known to be lower in both species during weak El Niño events. Boobies, frigatebirds, and albatrosses show low reproductive rates and increased migrations outside the Galápagos Marine Reserve, while most young pelicans starve during El Niño events. One seabird species appears to benefit from El Niño: the wide availability of carrion results in an enhanced reproductive output in the lava gull. However, an increased abundance of migratory gulls arriving in the Galápagos during El Niño events may lead to competition with the endemic lava gull. Seabirds of the Galápagos also are negatively affected by the increased abundance of introduced, land-based predators (e.g. rats and cats) and disease vectors during El Niño events.

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Cetaceans

As highly migratory species, cetaceans are able to redistribute quickly in response to events such as El Niño. The reduction or collapse of the Equatorial Undercurrent coupled with decreased winds during El Niño results in the shrinking of the upwelling habitat in the western region. This in turn may lead to increased competition for food among the dolphin species that are dependent on this habitat. Warm-water species not normally found close to the islands might be more common during these episodes. Species such as sperm, Bryde's, and blue whales, which depend on the productive Galápagos ecosystems, may experience decreased foraging success during an El Niño year and decreased reproductive success in subsequent years.

2.2. La Niña

For most marine vertebrates, the La Niña phenomenon represents a favorable period of resource abundance, particularly in the western upwelling area. The cold waters bring nutrients and increased prey resources. For marine

iguanas and sea turtles, the bloom of green algae provides sufficient food for adults and young individuals. The main limiting factor for these poikilothermic (cold-blooded) organisms during La Niña events is thermoregulation. For sea lions, fur seals, penguins, and cormorants, this is a perfect time to breed and increase in numbers.

2.3. Transient events

There is scant information regarding transient events such as upwelling Kelvin waves at the end of an El Niño, but it is presumed that sudden drastic reductions in water temperature on the order of 5–10°C over a few days, as occurs during the passage of upwelling Kelvin waves at the end of an El Niño event, may induce thermal shock and undermine the health of poikilothermic marine vertebrates.

2.4. Acidification

At present, we do not know the direct impacts of acidification. However, acidification seems to affect plankton abundance and distribution. Acidification also could affect the abundance of mollusks, crustaceans, and bony fishes, which constitute important prey for marine vertebrates.

2.5. Thermocline

The general prediction under climate change scenarios is that the thermocline will deepen and become more stratified. A deepened thermocline would reduce access to food resources for vertebrate predators, which are shallow divers. For instance, adult marine iguanas have been recorded feeding on algae up to depths of 12 m, while 90% of dives by Galápagos penguins and cormorants are conducted in water less than 6 m and 15 m deep, respectively. Galápagos fur seals get their prey at 10 to 35 m, while sea lions dive to an average depth of 115 m. Presently, the Galápagos thermocline is situated at between 10 and 20 m depth. If the thermocline were to deepen, the shallow divers are expected to be physiologically affected, and may possibly starve. Changes in foraging behavior also are expected, such as predators shifting to different prey.

2.6. Surges and extreme tides

Storm surges and extreme tides are infrequent under present conditions, as they are tied to earthquakes and volcanic eruptions. Surges and extreme tides also occur during El Niño because sea level is higher during these events. The effects of surges and extreme tides on the coastal areas will depend on the magnitude of the surge, the area affected, and the time of year. These three factors will have to coincide to generate a major impact at specific areas important for marine vertebrates (e.g. nesting areas of sea turtles, penguins, cormorants, and marine iguanas); and pupping locations for sea lions and fur seals. There are records of nest losses in penguins and cormorants by flooding during extreme tides and surges.

2.7. Sea temperature

The marked seasonal variation in sea temperature probably acts as an important factor in the synchronization and initiation of breeding seasons to match the availability of food resources. The prediction under climate change scenarios is for increased sea temperature, which may affect the breeding seasonality, in addition to reducing prey abundance and availability.

2.8. Air temperature

The effects of air temperature are unknown for most marine vertebrates. However, the lower temperatures of shady areas such as lava tubes and large boulders appear to be important for nesting penguins and resting fur seals. The normal variation of air temperatures seems at present fairly well tolerated by Galápagos marine vertebrates. However, extreme high air temperatures could result in increased stress and energy demands on species that need to thermoregulate while on land, such as marine iguanas, sea lions, fur seals, and seabirds. Dehydration could be another problem during high temperatures in tropical environments. Disease vectors, such as insects, also may increase in abundance due to rising temperatures on land and in the water, raising the risk of disease transmission. Disease outbreaks that resulted in a high morbidity (but low mortality) of sea lions were recorded in 2001 and 2006, mostly affecting the pups. The eye-disease (conjunctivitis and parasitosis) outbreak of 2001 has subsided, but these diseases persist today at a lower prevalence. High air temperatures also can generate a favorable environment for the breeding of introduced mosquitoes, such as the vector of avian malaria (*Culex quinquefasciatus*), and affect the endangered Galápagos penguin.

2.9. Upwelling

The upwelling areas in the western part of the archipelago provide reliable feeding conditions for marine vertebrates such as cormorants, penguins, sea lions, fur seals, and cetaceans. However, as this upwelling diminishes in intensity in a future warmer climate, these habitats will deteriorate and the marine vertebrate species that inhabit them will become vulnerable.

2.10. Sea level rise

At present, there is no clear evidence of an increase in sea level in the Galápagos. If this happens in the future, coastal flooding could impact breeding colonies for beach nesting species, erosion of nesting, pupping, and resting areas caused by coastal erosional processes. Sea level rise also could lead to a relocation of the breeding colonies or an increase in competition for breeding habitat in sea lions, fur seals, and seabirds.

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2.11. Precipitation

The amount of precipitation varies by season: Most rain falls in the hot rainy season (late December to April) and less in the cool dry season (May to early December). This pattern changes during El Niño and La Niña events, when the rainy and dry seasons are extended, respectively. Climate models predict a more extreme climate, with warmer El Niño events and attenuated (less cool) La Niña events. Sustained levels of humidity and fresh water could trigger a higher prevalence of disease vectors, parasites, and associated diseases or increased predation by introduced mammals such as cats and rats, which are predicted to become more abundant as prey resources increase.

2.12. Winds and ocean currents

Changes in wind directions and strengths likely will result in changes in ocean currents, precipitation, and thermal regime, which probably will affect the duration of the seasons as well as the synchronization of the breeding season for most marine vertebrates.

2.13. Native and introduced predators

In general, during warm years predation from sharks on Galápagos marine vertebrates appears to increase, especially from unusual visitors of these waters such as bull and mako sharks (Vargas, pers. obs.), probably in response to a reduced food supply. Populations of land birds such as finches and Galápagos hawks generally benefit from an overabundance of food during El Niño events. An increased hawk population could result in higher predation rates on young marine iguanas, penguins, and cormorants. In fact, young marine iguanas constitute an important prey item of hawks on coastal Fernandina Island (HV pers. obs.). Populations of introduced predators such as cats and rats also increase during El Niño years, when they tend to target the eggs and young of iguanas, penguins, and cormorants. Therefore, increased predation rates from both native and introduced species are expected to occur in a future warmer climate.

2.14. Parasites and diseases

Several new disease strains and parasite species have been recorded in the past ten years in Galápagos penguins, cormorants, and sea lions. Their prevalence appears to be closely associated with changes in the local climate. This situation is expected to worsen in a warmer, wetter climate-change scenario.

3. CURRENT AND FUTURE CLIMATE IMPACTS AND ADAPTATION MEASURES

Current and future climate changes indicate an overall negative impact on Galápagos marine vertebrates, with La Niña and the persistence of upwelling being the only events that probably have a positive effect on selected vertebrate populations (table 1). However, it is doubtful that extreme cold events, were they to occur, would have a beneficial effect on poikilothermic organisms such as sea turtles and marine iguanas. Climate models suggest that the current climatic conditions will prevail over the next 15 years, but the intensity of El Niño events will increase in the next 50 years (see outputs of Chapter 1), with a significant long-term negative effect on Galápagos marine vertebrates.

Based on current scientific and technological knowledge, it seems feasible to implement adaptation measures to counteract some of the impacts of El Niño events, extreme surge, air and sea temperature, sea level rise, and precipitation. Novel technologies and new scientific knowledge are required to counteract the current and future impacts of other climate factors (table 1). Adaptation measures are more feasible for vertebrates that spend a considerable amount of time on land.

4. RESEARCH AGENDA FOR THE DESIGN OF ADAPTATION MEASURES

A research agenda should begin immediately to enable adaptation measures before the next El Niño event, which is likely to occur within the next four years. The following research should be conducted:

a. Determine thermal tolerances, energy budgets, and the duration of periods needed for population recovery after mass-mortality events.
b. Assess incubation temperatures of sea turtles to determine threshold temperatures to ensure the development of male individuals.
c. Determine the movements and dispersal of Galápagos marine vertebrates outside the Galápagos region during El Niño and other extreme climatic events to plan for conservation needs beyond the archipelago.
d. Describe patterns of intensity and wind direction in relation to ENSO events, which affect birds that depend on wind for their movements (e.g. albatrosses) or that can be exposed to nest failures by wind knocking down nests (e.g. mangrove finches). This study also will help predict the intensity and distribution of extreme surges.
e. Develop methodologies for the design of cavities and artificial substrates for nesting penguins and cormorants, and test their acceptance by the species.
f. Monitor and evaluate tested adaptation measures.
g. Design modeling studies and improve existing models on population trends of the species more vulnerable to climate change.
h. Assess the likelihood of competition between sardine fishermen and marine vertebrates that are natural predators of sardines. Design management actions to ban temporarily the capture of sardines as bait during El Niño, when food for marine vertebrates is limited, and propose alternative bait.

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Table 1. Present and future climate impacts on selected Galápagos marine vertebrates and the feasibility of implementation of adaptation measures.

Climate event	Period	Sea turtles	Marine iguanas	Sea lions and fur seals	Seabirds	Cetaceans	Adaptation measures
El Niño	Present	-	-	-	-	-	Feasible
	15 years	-	-	-	-	0	Feasible
	50 years	--	--	--	--	0	Feasible
La Niña	Present	+	+	+	+	+	Feasible
	15 years	+	+	++	++	++	Feasible
	50 years	0	0	0	0	0	Feasible
Acidification	Present	0	0	0	0	0	Not feasible
	15 years	0	0	0	0	0	?
	50 years	0	0	0	0	0	?
Thermocline	Present	0	0	0	0	0	Not feasible
	15 years	0	0	0	0	0	?
	50 years	0	0	0	0	0	?
Extreme storm surge	Present	-	-	-	-	0	Feasible
	15 years	-	-	-	-	0	Feasible
	50 years	--	--	--	--	0	Feasible
Sea surface temperature and ocean currents	Present	-	-	-	-	0	Not feasible
	15 years	--	-	-	-	0	?
	50 years	--	--	--	--	0	?
Air temperature	Present	-	-	-	-	0	Feasible
	15 years	-	-	-	-	0	Feasible
	50 years	--	--	--	--	0	Feasible
Upwelling	Present	+	+	+	+	+	Not feasible
	15 years	-	-	-	-	-	?
	50 years	--	--	--	--	--	?
Sea level rise	Present	0	0	0	0	0	Feasible
	15 years	0	0	0	0	0	Feasible
	50 years	-	-	-	-	0	Feasible
Rainfall	Present	-	-	-	-	0	Feasible
	15 years	0	0	0	0	0	Feasible
	50 years	0	0	0	0	0	Feasible
Wind	Present	0	0	0	0	0	Not feasible
	15 years	0	0	0	0	0	?
	50 years	0	0	0	0	0	?

Present Impacts
- = Reduction in local abundance, population size, or breeding success; unbalanced sex ratio.
+ = Increase in local abundance, population size, or breeding success; balanced sex ratio.
0 = Insufficient information to evaluate current impacts, or impacts not evident.

Future Impacts
-- = Significant reductions in biological parameters.
+ + = Significant positive effects on biological parameters.
0 = Insufficient information to evaluate future impacts.

Adaptation Measures
Feasible = With current knowledge and technology, it is possible to implement adaptation measures.
Not feasible = With current knowledge and technology, it appears unfeasible to implement adaptation measures.
? = With future scientific and technological knowledge, it may be feasible to implement adaptation measures.

i. Monitor the impact of tourist-boat lights on insects. Research the use of technological options that do not attract insects and prevent the transportation and introduction of insects among islands.

j. Produce vulnerability maps of nesting areas of marine iguanas, sea turtles, penguins, and cormorants to anticipate possible flooding during extreme surges.

k. Use flooding models under various scenarios of sea level rise to produce vulnerability maps that evaluate the potential loss of breeding-area quality.

l. Assess future scenarios of ocean-current shifts at the Galápagos regional scale, as these shifts could alter the ecosystems and habitat quality of marine vertebrates.

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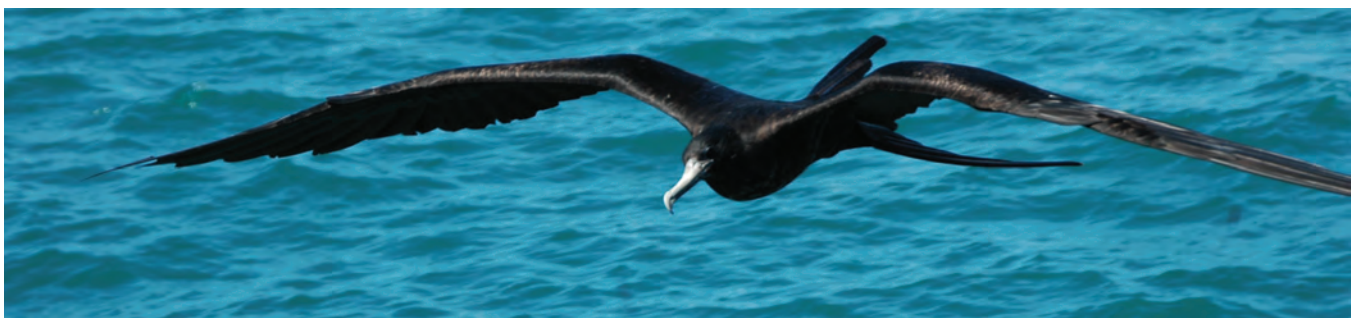

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