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# Evolution of the Galapagos in the Anthropocene

The Galapagos Islands inspired the theory of evolution by means of natural selection; now in the Anthropocene, the Galapagos represent an important natural laboratory to understand ecosystem resilience in the face of climate extremes and enable effective socio-ecological co-evolution under climate change.

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The combined effects of climate change and other human-induced stressors have severely degraded marine ecosystems worldwide and pose an unprecedented threat to humanity[1]. There is an urgent need to understand current and future rates of change while attempting to mitigate impact. We argue that the Galapagos Islands, once the inspiration for the ground-breaking theory of evolution by means of natural selection, now in the Anthropocene can serve as a natural laboratory to study co-evolutionary processes between humans and the species we interact with as climate change pushes

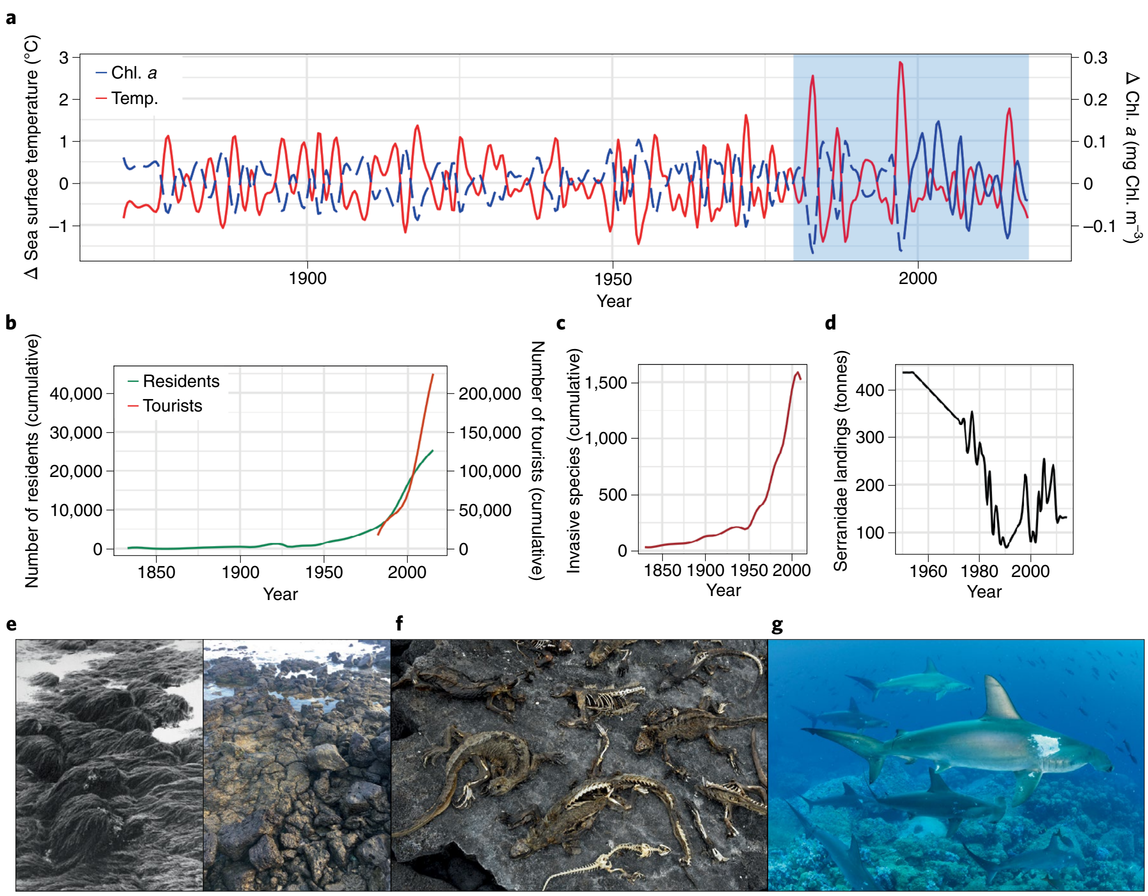


**Fig. 1 | Global change in the Galapagos.** **a**, Sea surface temperature[12] and chlorophyll time series 1870–2018 from the Galapagos region (89–92 ° W latitude; 1.5 °S –1 °N longitude). Chlorophyll concentration data (blue line) since September 1997 was obtained from GlobColour satellite estimates (http://www.globcolour.info/). Earlier estimates (dashed blue line) are based on a linear regression against Hadley Center Sea Ice and SST (HadISST) over the satellite period ($r = 0.65$; root mean square difference = 0.085). The shaded box highlights the higher amplitude of record-breaking ENSO events over the past 35 years. **b**, Increase in the number of residents (1830–2015) and tourists (1832–2015) visiting the Galapagos Islands. **c**, Number of invasive species introduced to the islands (1830–2000). This increase is closely related to the increase in human population[4]. **d**, Decline on the total fishing landings for the most important reef finfishes (Serranidae, groupers) for the period 1950–2015 (ref. [5]). **e–g**, El Niño impacts in the Galapagos islands include habitat loss and species extinction (**e**), such as the disappearance of intertidal beds of the brown algae *Bifurcaria galapagensis*[9]; mass mortality events (**f**), such as those recorded for marine iguanas[13]; or the outbreak of diseases in wild populations (**g**), such as seen for different fish families[14]. Photographs in **e** were taken by Gerard Wellington and Brae Price, copyright to the Charles Darwin Foundation; photographs in **f**,**g** were taken by Thomas Peschak/National Geographic.

ecosystems and dependent communities further away from historical baselines.

## *The Voyage of the Beagle* to globalism

When Charles Darwin visited the Galapagos in 1835, the archipelago's iconic flora and fauna had evolved in complete isolation for hundreds of thousands of years. The species' unique evolutionary pathways inspired Darwin's theory of evolution, revolutionizing our understanding of life on Earth. In 1835, the islands were populated by less than 1,000 settlers, tourism was not a global industry and atmospheric carbon dioxide ($CO_2$) concentrations were well below 300 ppm (ref. [2]). Since then, the world has entered the Anthropocene, an era marked by human domination of fundamental Earth system processes[3]. The Galapagos are no longer isolated, with over 25,000 inhabitants and 250,000 visitors per year, more than 1,500 recorded alien species[4] and erosion of coastal fisheries due to overfishing[5]. Planetary $CO_2$ levels now exceed 400 ppm (ref. [2]), and climate change is rapidly altering ecosystems[1] and intensifying climate extremes[6], including those associated with El Niño/Southern Oscillation (ENSO)[7].

## A living laboratory in peril

The Galapagos Islands experience dynamic oceanographic variations that profoundly shape its unique biological communities. The upwelling of the equatorial undercurrent creates a distinctive cold-water refuge in some areas of this otherwise tropical archipelago. ENSO climate cycles alternate between warm (El Niño) and cool (La Niña) states. Along with warmer ocean temperatures, El Niño events bring highly stratified surface waters that impede the delivery of nutrients to surface waters and impede ocean productivity. Cool La Niña events, in contrast, bring nutrient-rich, highly productive waters[8].

Repeated ENSO cycles have created a natural laboratory for understanding species adaptations to climate variability and extremes, and for probing adaptation limits. The consequences of intense El Niño events can be drastic: during the severe 1982–1983 El Niño, sea surface temperatures increased from an average of 18 °C to a maximum of 32 °C, and live coral cover was permanently reduced by 95–99%. Suppressed ocean productivity resulted in sharp population declines (40–80%) of endemic Galapagos penguins, flightless cormorants and fur seals, and several endemic species became extinct[9,10].

Three of the most severe El Niño events since pre-industrial times have occurred since 1980 (Fig. 1a), and projections under probable greenhouse gas emission scenarios suggest that intense ENSO events are likely to become more common[7,11]. This adaptive challenge is compounded by projected ocean warming, deoxygenation, acidification and the rising resident and tourist populations in the Galapagos. This population increase, driven largely by a booming tourism industry, has led to overfishing and the introduction of alien species (Fig. 1b–d). Together, these factors present an unprecedented challenge to the archipelago's natural systems (Fig. 1e–g) as well as to human society[6].

## A future role for the Galapagos

The insights provided by the exposure of the Galapagos to extreme environmental changes are becoming globally relevant as climate change pushes ecosystems further from the conditions under which they evolved. The recent spate of marine heatwaves, for example, have produced drastic disturbances similar to those regularly experienced during El Niño events in the Galapagos[15]. The Galapagos' laboratory can thus offer important insights into factors determining ecosystem resilience when faced with environmental extremes and adaptive limits. For example, dedicated research on the role of local cold-water refugia in building resilience in the face of an El Nino would provide important insights that could inform 'climate-smart' conservation planning. Such considerations are critical for the design of effective marine protected areas (MPAs) in the face of unprecedented change[16]. Similarly, the profound dependence of local communities on the Galapagos' ecosystem provides a powerful means to understand and improve socioeconomic resilience in the face of marine ecosystem extremes[17]. For example, elements of the ecosystem identified to promote resilience to El Niño events could be targeted for additional protection and incentivized economically[18]. Such insights drawn from the Galapagos' laboratory could then help to address the needs of vulnerable coastal communities elsewhere.

Just as the Galapagos captured the world's attention 180 years ago, it can once again inspire and inform the global community's response to increasing environmental extremes. Darwin's focus on naturally occurring evolutionary processes, however, must be expanded to consider conscious co-evolution of resilient human and natural ecosystems. In the end, failure to undertake this co-evolution process to address climate change globally would be to ignore the fundamental lesson of Darwin that change is inevitable, and only the most adaptable organisms will survive in the face of it. Indeed, Darwin's theory of natural selection also demonstrates that the survivors, if they adapt well, can emerge even stronger than before. ❐

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Published online: 27 April 2020
https://doi.org/10.1038/s41558-020-0761-9

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## Acknowledgements

We thank M. Schuiteman for reviewing early drafts of the manuscript. We also thank the staff of the Charles Darwin Research Station that made possible the International Workshop to develop a Climate Change Research Agenda to inform climate change adaptation and mitigation for the Galapagos Marine Reserve, and to the Galapagos National Park Directorate for institutional support. We also thank the Helmsley Charitable Trust and the Dr. Gerard 'Jerry' Wellington Memorial Fund created by A. Blackwell for the funding provided to the Charles Darwin Foundation. This publication is contribution no. 2329 of the Charles Darwin Foundation for the Galapagos Islands.

## Author contributions

All authors contributed to the workshop, synthesis of information and manuscript preparation.