A HABITAT SUITABILITY MODEL FOR PREDICTING CORAL COMMUNITY AND REEF DISTRIBUTIONS IN THE GALAPAGOS ISLANDS

By: Terence P. Dawson[1], Felicity Jarvie[2] & Femke Reitsma[2]

[1]School of Geography, University of Southampton, UK. <t.p.dawson@soton.ac.uk>
[2]School of Geosciences, University of Edinburgh, UK

SUMMARY

The coral communities and coral reefs of the Galapagos Marine Reserve support tens of thousands of species, including many rare and endemic species. Reef-building corals are sensitive to elevated temperatures, which have been linked to coral bleaching (loss of symbiotic zooxanthellae) and therefore their distribution around the islands has been strongly affected by extreme climatic events over the last 30 years. Following the 1982–3 El Niño-Southern Oscillation event, coral cover was reduced by 95 %, with further mortality in the 1997–8 event. Although there has been significant recovery of the communities in recent years, there is concern that by 2100 the global climate system and sea surface temperatures will warm by between 1.4° and 5.8°C, which could result in 100% mortality of Galapagos corals. This paper reports a temperature and depth bioclimatic envelope (or niche) model of potential coral distribution, developed using an historical analysis of monthly sea surface temperatures, derived from the NOAA AVHRR over the period 1985–2001, and a near-shore bathymetry data set derived from Shuttle Radar Topography Mission digital topographic data integrated with ship-based depth sounding surveys and digitised hydrographic maps. The model was validated against known coral community and coral reef localities. Application of the model can support the identification of potential new areas where conditions for coral growth are favourable and enable predictions of the effects of future climate change.

RESUMEN

Un modelo de hábitat apropiado, para predecir la distribución de comunidades y arrecifes de coral en las islas Galápagos. Las comunidades y arrecifes de corales en la Reserva Marina de Galápagos mantienen decenas de miles de especies, incluidas muchas especies raras y endémicas. Los corales formadores de arrecifes son sensibles a temperaturas elevadas, las cuales han sido ligadas al blanqueamiento de corales (pérdida de algas simbióticas zooxanteladas) y por lo tanto su distribución alrededor de las islas ha sido fuertemente afectada por eventos climáticos extremos durante los últimos 30 años. Después del evento de El Niño-Oscilación Sur de 1982–3, la cobertura de corales fue reducida en un 95 %, con una mortalidad adicional en el evento de 1997–8. Aunque ha habido una significante recuperación de las comunidades en los años recientes, hay la preocupación que para el 2100 el sistema climático global y la temperatura superficial del mar se calentarán entre 1.4° y 5.8°C, lo cual podría resultar en la mortalidad del 100 % de los corales de Galápagos. Este artículo reporta un modelo "sobre" o "nicho" bio-climático de temperatura y batimetría, de la distribución potencial de corales, desarrollado usando un análisis de datos históricos de la temperatura superficial mensual del mar, derivados de la NOAA AVHRR sobre el período de 1985–2001, y un juego de datos de batimetría costera derivado de datos topográficos digitales de la Misión del Transbordador espacial de Radar Topográfica integrados con estudios de sondas de profundidad a bordo de barcos y mapas hidrográficos digitalizados. El modelo fue validado contra las localidades de comunidades y arrecifes de coral conocidas. La aplicación del modelo puede sostener la identificación de nuevas áreas potenciales donde las condiciones para el crecimiento de corales son favorables, y permitir predicciones de los futuros efectos del cambio climático.

INTRODUCTION

Coral reefs form one of the richest and most diverse marine ecosystems in the world. Although corals do not form reefs in Galapagos except at the northern islands of Darwin and Wolf, coral communities exist throughout the archipelago, resulting in increased diversity compared to areas without corals. Hermatypic or reef-building corals containing photosynthetic dinoflagellates (zooxanthellae) are only located in warm tropical and subtropical regions of the world in a limited physical, chemical and biological range. For example, coral reefs cannot develop below 18°C whilst coral bleaching, the expulsion of the coral's symbiotic zooxanthellae pigments under stress, is associated with extended periods of elevated sea temperatures above 30–35°C. The symbiotic association between corals and dinoflagellates is mutualistic, with zooxanthellae providing oxygen and food (e.g. glucose, amino acids), whilst the coral host provides carbon dioxide, nutrients and living space. Zooxanthellate corals are limited to clear, well-lit shallow water because of their phototrophic symbionts. This study uses our knowledge of these constraints to develop a habitat suitability model based on bathymetry and sea surface temperature (SST) data, which can be used to predict the coral's spatial distribution around the Galapagos Islands. The Galapagos Marine Reserve, created in 1998, covers *c.* 133,000 km^2, and the whole archipelago has been designated as a World Heritage Site by UNESCO. However, the vulnerability of the Galapagos Islands and their coral communities, in particular to El Niño-Southern Oscillation (ENSO) events, is well documented. During the past three decades coral research in Galapagos has demonstrated that widespread coral bleaching and subsequent mortality resulted from increases in sea temperature during the events of 1982–3 and 1997–8 (Fitt *et al.* 2001, Glynn 2001, Reaser *et al.* 2000). This has heightened concern regarding the effects of global warming on the marine environment (Glynn 1993, Hoegh-Guldberg 1999, Obura 2005, Stone *et al.* 1999). Indeed, West & Salm (2003) suggested that "climate change may now be the single greatest threat to [coral] reefs worldwide". This paper presents a method for predicting coral distributions in the Galapagos Islands using depth and SST, which can facilitate research on the impacts of climate change on coral communities and reef habitats and be useful for predicting the distribution of hermatypic coral across the study area. Based upon the concept that species distributions can be described by a range of environmental conditions (biological and physical), this approach has been widely applied in terrestrial and more recently marine ecosystems (Pearson & Dawson 2003, Guinotte *et al*. 2006).

METHODS

The potential coral habitat model was developed by integrating a wide range of satellite and survey data, including SST data from an analysis of AVHRR imagery and bathymetric data from ship surveys (Fig. 1). Eco-physiological parameters were used to set acceptable limits for each variable.

The bathymetric component of the model included extensive data from a range of remotely sensed sources, specifically:

1. Data from ship surveys and digitised hydrographic maps *c.* 1994 provided by W. Chadwick (http://www.pmel.noaa.gov/vents/staff/chadwick/galapagos.html, accessed 16 May 2008), including high resolution mapping data and all known measurements for this area (Fig. 2).
2. A 3 arc-second resolution digital elevation model of the islands derived from the Shuttle Radar Topography Mission (SRTM) (Global Land Cover Facility, http://glcfapp.umiacs.umd.edu:8080/esdi/index.jsp, 16 May 2008). These data allowed the terrestrial topography of the islands to be included in determining the slope gradient transition from land to water at a high spatial resolution.
3. The coastlines of the islands, provided by the Charles Darwin Research Station (CDRS) to force a clear delineation between the marine and terrestrial environments, through the assignment of a weighted value.

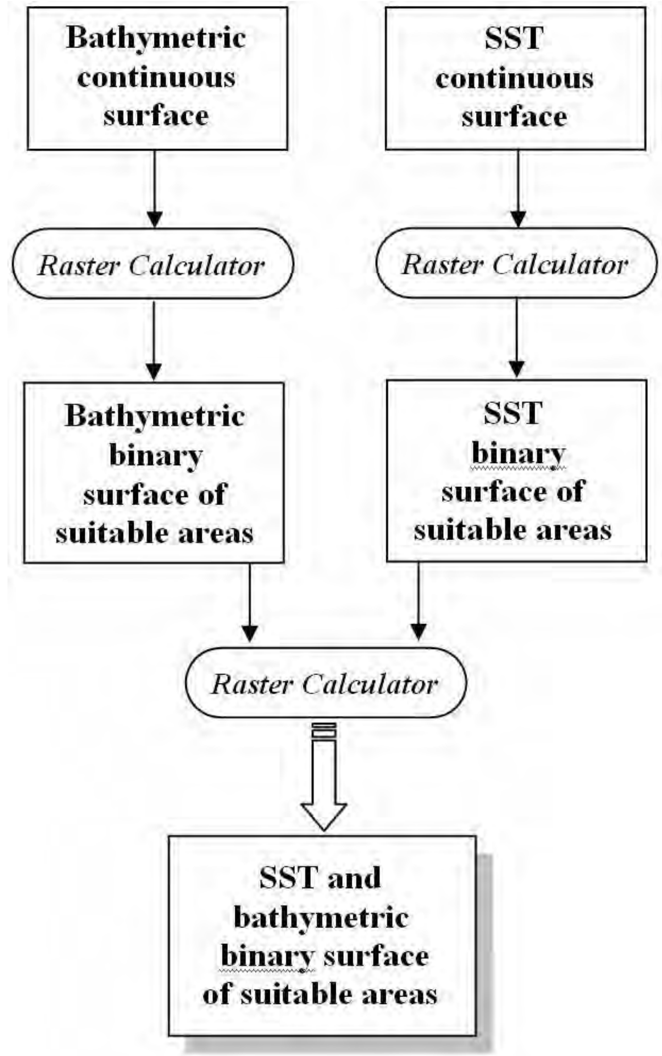

Figure 1. Steps in producing the habitat suitability map.

After integrating all the data, interpolation using ordinary kriging was deployed to generate a regular gridded bathymetric data set where pseudo-depths were estimated in locations where measurements had not been recorded. However, the accuracy of the resultant bathymetric map depends strongly upon the density of ship survey data, and the distribution of ship track data was very uneven and sparse across much of the archipelago (see W. Chadwick website for further information).

The interpolated bathymetric data were then bounded to depths suitable for coral formation. Nybakken (2001) determined that coral reefs worldwide are limited to

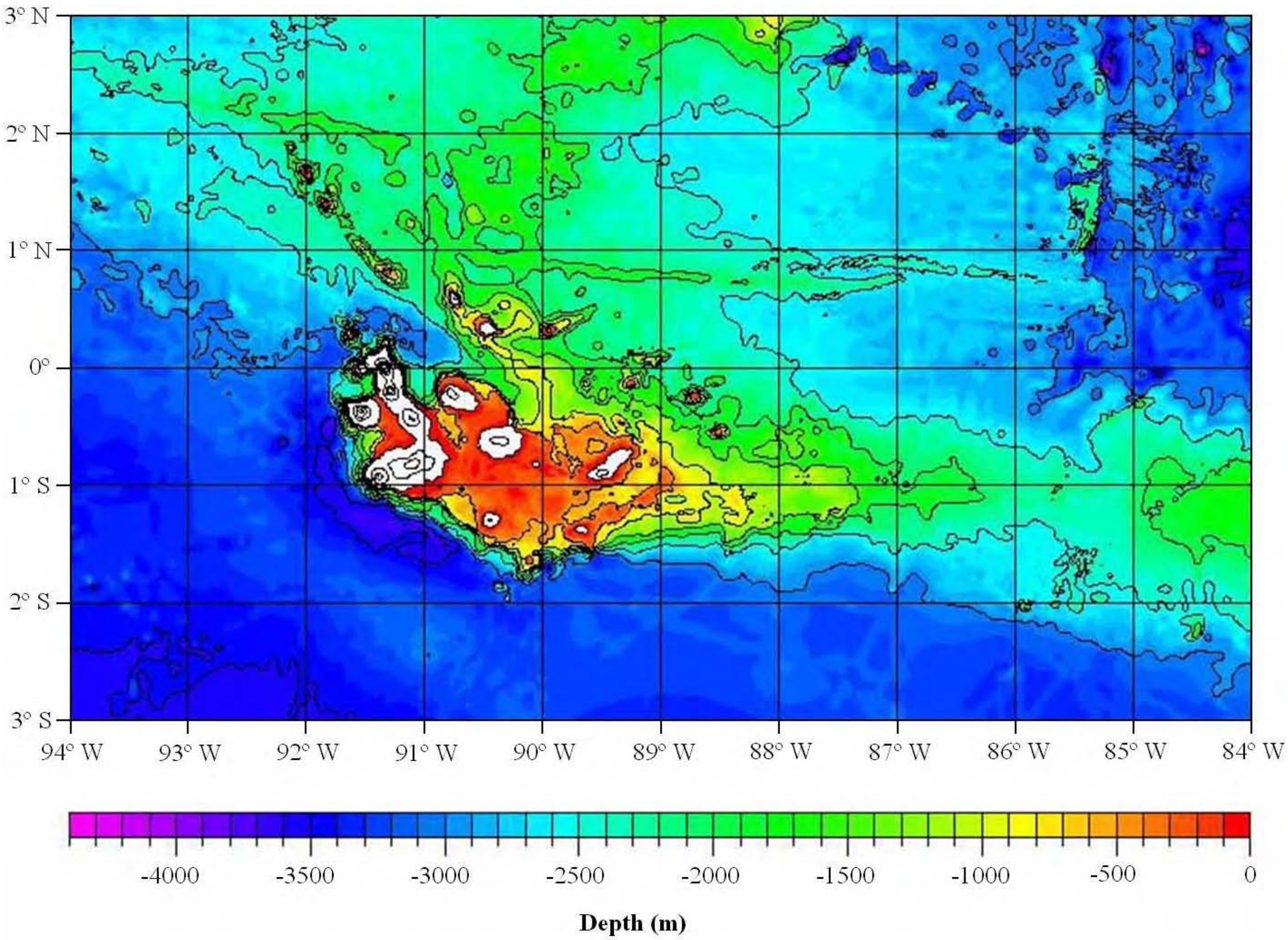

Figure 2. Interpolated ship-survey bathymetry data.

≤ 80 m depth. However, Glynn (2003) discovered that many of the hermatypic coral communities around the Galapagos Islands were found in < 20 m, which may reflect the high water turbidity (and low light penetration) in the Galapagos Islands compared to other regions of the world, due to high zooplankton concentrations during the period from June to October, when the nutrient-rich Humboldt Current runs up the west coast of South America from Antarctica. The bathymetry constraints were therefore conservatively set at 1–50 m depth.

The SST component of the model was based on AVHRR data at 4 km resolution for the area 88–93°W and 3°N to 3°S, acquired through the NASA Physical Oceanography Distributed Active Archive Center (PO.DAAC) utilising the Ocean ESIP Tool (http://poet.jpl.nasa.gov/ accessed 23 July 2006). Monthly averages for 1985–2001 were used to calculate the absolute minimum, maximum and average SST over this period. It was necessary to take into consideration the influence of ENSO events on our analysis; the SST anomalies during the well-documented 1997–8 event were therefore considered separately. The AVHRR data provided a record of SSTs throughout the study area. Because of missing data due to pixel removal as a result of coastal–terrestrial contamination, an inverse distance weighting of the SSTs was undertaken to fill missing values. A mosaic of three Landsat ETM+ images for March 2001 was also used to compare the coastal effect on SSTs at high resolution (60 m) with the AVHRR coastal pixels. Digital number (DN) values from the Landsat ETM+ thermal band were converted to radiances in degrees C using the following equations (see Trisakti *et al.* 2004, Lu 2005):

$$L_{\lambda} = \frac{(Lmax_{\lambda} - Lmin_{\lambda})}{(DNmax - DNmin)} . (DN - DNmin) + Lmin_{\lambda} \quad (1)$$

$$T_{Landsat} = \frac{K2}{\ln((K1/L_{\lambda}) + 1)} - 273 \quad (2)$$

Where:

L_{λ} = Spectral radiance ($W.sr^{-1}.m^{-2}$)

DN = Digital Number

$Lmin_{\lambda}$ = Spectral radiance that correlates to DNmin ($W.sr^{-1}.m^{-2}$)

$Lmax_{\lambda}$ = Spectral radiance that correlates to DNmax ($W.sr^{-1}.m^{-2}$)
DNmin = Minimum value of DN (1 or 0)
DNmax = Maximum value of DN = 255
$T_{Landsat}$ = Effective temperature (Celsius)
K1 = 666.09 ($W.sr^{-1}.m^{-2}$), constant
K2 = 1282.71 ($W.sr^{-1}.m^{-2}$), constant

Six 4-km transect profiles, chosen at random to reflect different coastal depth gradients and temperature variation across the region, were delimited on the ETM+ images perpendicular to the coast of the islands to evaluate within-pixel variability and the coastal effect of SSTs on the AVHRR data.

To determine the most suitable SST range around the Galapagos Islands, known coral sites were overlaid on a map of average SST. The suitable range was found to be 23–25°C. However, as individual daily SSTs exceed the monthly mean values during the period from March to June, and in consideration of the optimum figures suggested by Kaiser *et al*. (2005), a range of 18–28°C was chosen as acceptable for coral reef habitats. Values beyond this range were classified as unsuitable, where stress and bleaching may be evident.

The location of known coral communities and coral reefs around the islands was acquired from a number of sources including 1-km polygons from the United Nations Environment Programme World Conservation Monitoring Centre (UNEP-WCMC) and point data provided by the CDRS. Other sources included extrapolation from maps, literature and field surveys from around the Galapagos Islands (Glynn 2003). The mortality of corals caused by the 1982–3 and 1997–8 ENSO events has undoubtedly changed their current status compared to earlier observations. Consequently, the integration of these records in the model was limited to the addition of depth and localities of known coral communities to the bathymetry database and testing of the baseline habitat suitability map.

RESULTS

The interpolated AVHRR SST imagery for the Galapagos Islands shows considerable differences in SSTs between the 1997–8 ENSO event and the whole period excluding the 1997–8 period (Fig. 3). Many of the thermal patterns are evident in both images, including the cool ocean upwelling in the southwest and the latitudinal temperature gradient. However, the pattern of warm water regions on the southern coasts of several islands (Marchena, Santiago, Santa Cruz, San Cristóbal, Fernandina, Isabela, Floreana and Española) during the 1997–8 ENSO event was not evident in the non-ENSO years.

Excluding during El Niño events, areas in the southwest were found to experience temperatures as low as 16°C due to upwelling, thus making them uninhabitable for hermatypic corals. The maximum SST divided the study area, with the northern section exceeding the temperature tolerance for reef growth and the south remaining suitable. The duration of extreme fluctuations in temperature will also affect coral survival, with prolonged periods causing stress, possible bleaching and mortality.

Investigation of the coastal effect on SSTs showed variation in SST across the 4-km transects, with most profiles experiencing the greatest deviation very close to

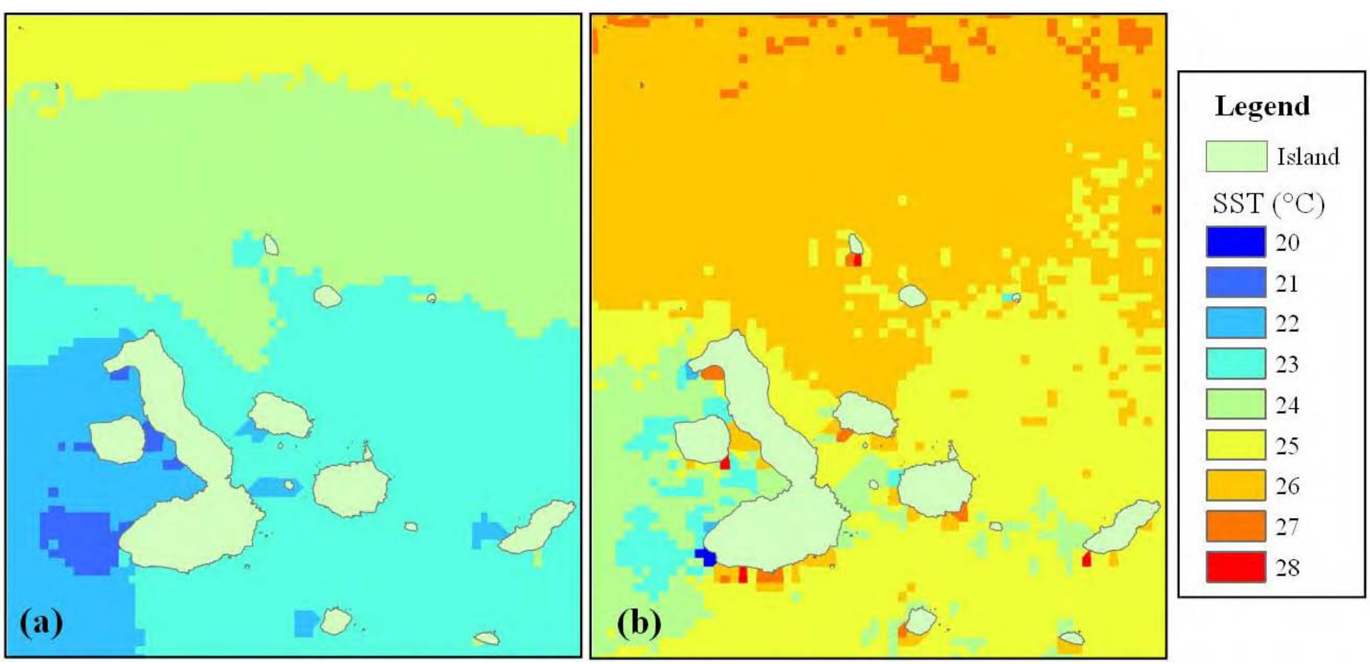

Figure 3. Mean SSTs (a) excluding El Niño records (1985–2001) and (b) during El Niño events (1997–1998).

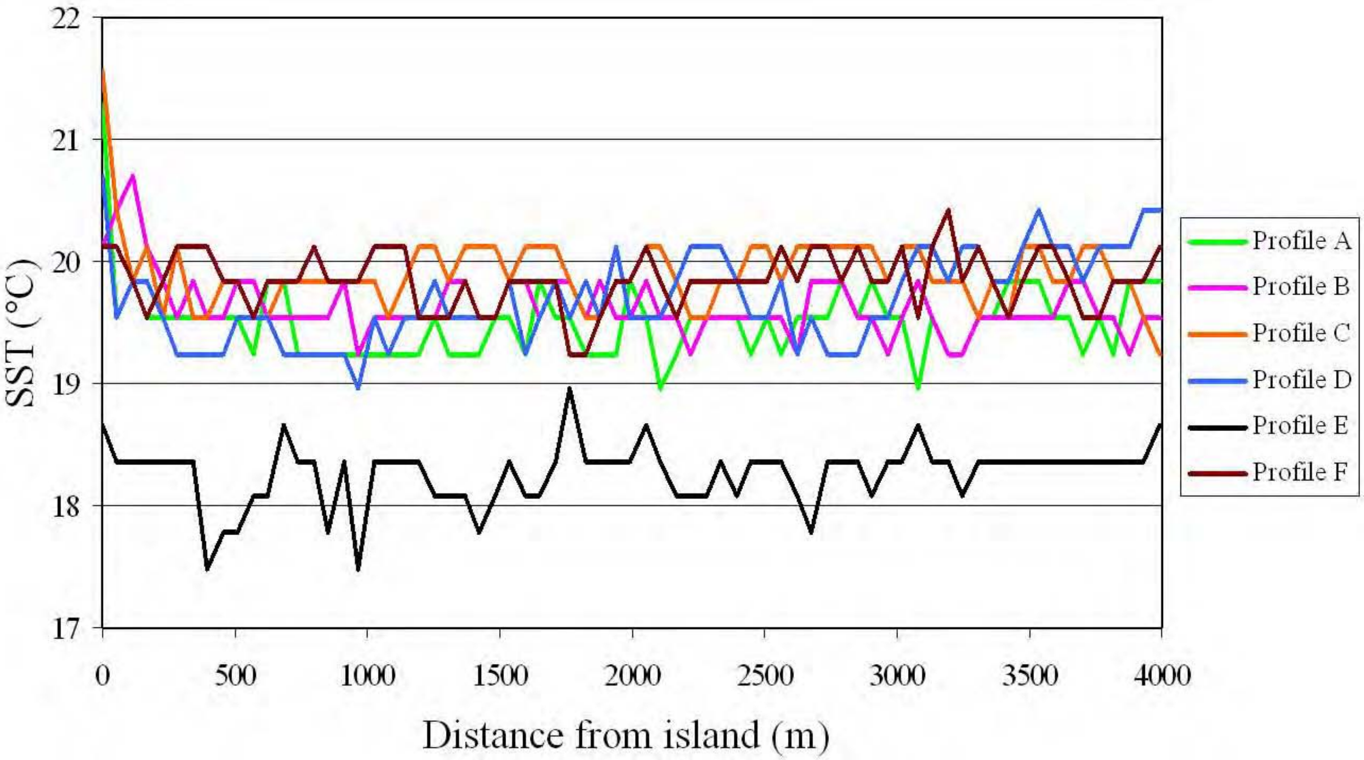

Figure 4. Variation in SST over six 4-km transects perpendicular from the coastline around the Galapagos Islands.

the coast (Fig. 4). Profile E recorded generally lower temperatures, as it was located in a cool upwelling region. However, all SSTs were within ± 1°C variability across the 4 km profile of the AVHRR pixel, so we remain confident that the AVHRR SST data are adequate for delineating coral temperature suitability.

With mean monthly SSTs within 18–28°C, the baseline historical habitat map was subsequently constrained by the bathymetry (Fig. 5), and compared against known coral distributions. Results were good, with all the known coral sites captured within the predicted suitable habitat areas. However, the model over-predicted for many potentially suitable areas where corals have not been recorded.

DISCUSSION

A coral reef habitat suitability model based upon a bioclimatic envelope approach is applied in the Galapagos Islands, illustrating that extensive potentially suitable coral habitat exists around all of the islands, with a greater abundance in the central area where a shallow plane links the islands. The non-existence of coral reefs in many of the over-predicted areas of potential suitability can be attributed to the absence of a hard benthic substrate, which is essential for corals to establish. Most of these areas have sandy or soft sediment substrates, although it is conceivable that new reefs might be found in such areas where surveys have not yet been carried out. Recent El Niño events have caused extensive bleaching and subsequent mortality throughout the archipelago and field research remains necessary to determine the current extent and scope of recovery for these critical habitats.

SSTs of up to 31°C in both the 1982–3 and 1997–8 ENSO events (Glynn *et al*. 2001) resulted in extensive bleaching and coral mortality across the archipelago, particularly in the shallow plane linking the central islands. Significant coral reefs in the south and west sectors of the archipelago were at Devil's Crown and Champion Island (off Floreana), east of Puerto Villamil (southern Isabela), Punta Baquerizo (western point of Santiago) and in tidal pools near Punta Espinosa (east Fernandina). These were lost due to coral mortality and subsequent bio-erosion by urchins following the 1982–3 ENSO event with only a few isolated coral communities remaining.

Glynn *et al*. (2001) estimated that over 95% of coral populations were killed in the 1982–3 event. However, recent surveys in Darwin Island reported significant recovery, with actively accreting reef structures (Glynn *et al*. 2009). This suggests that corals are resilient to episodic extreme temperatures given enough time for recovery and where the original reef structures remain intact and there remains a source of coral propagules.

Kaiser *et al.* (2005) suggested that the latitudinal range of coral reefs corresponds with a temperature range of 18–36°C, with optimum reef development occurring at 26–28°. The average temperatures during the 1997–8 El Niño event verged on the upper 28° tolerance limit. Coral reefs tend to live at the upper limit of their temperature

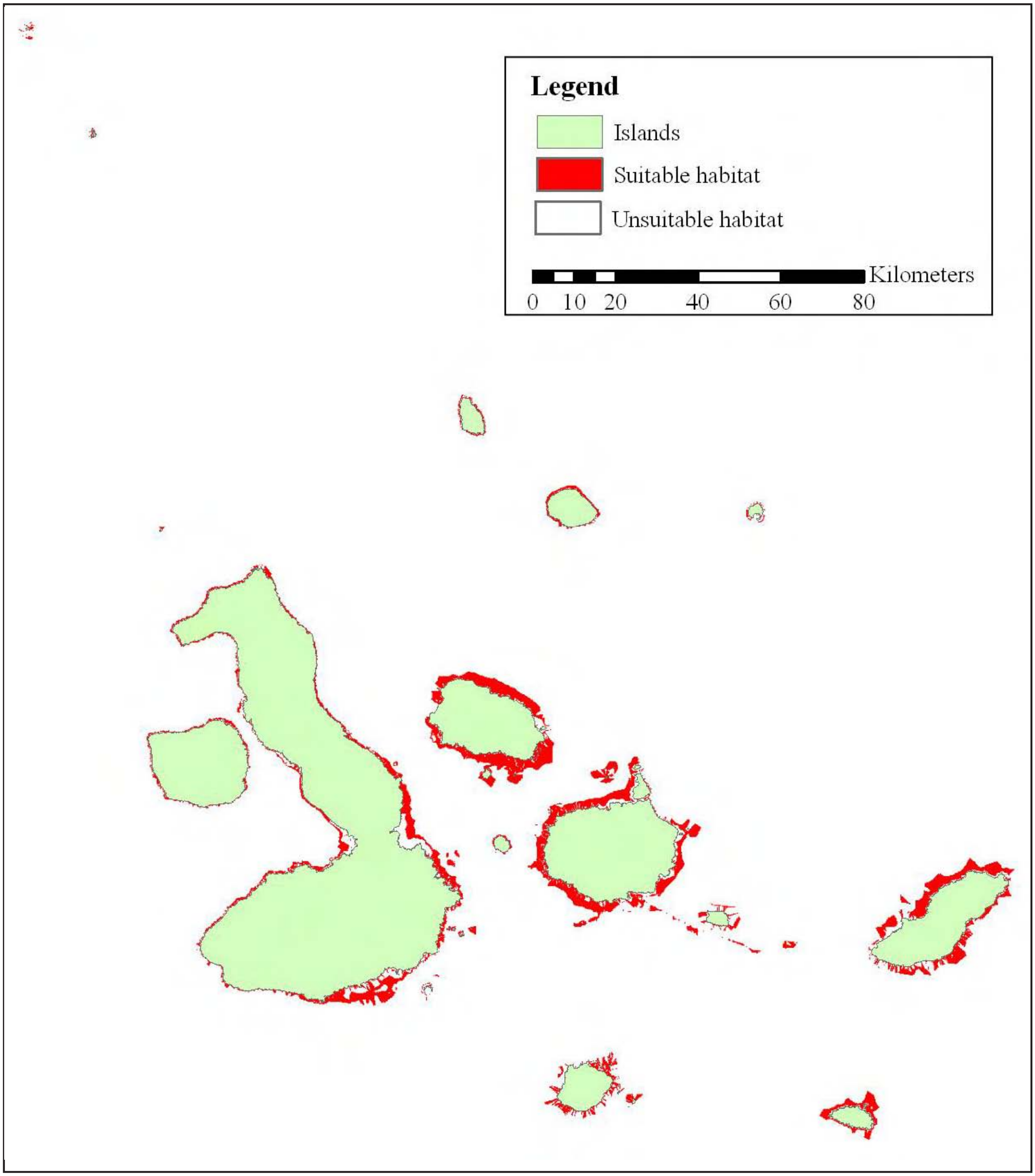

Figure 5. Potential habitat suitability map for hermatypic corals around the Galapagos Islands, based on bathymetry and SST variability (1985–2001).

tolerance and bleaching may result from slight increases (1–2°C) over a sustained period of time (Hoegh-Guldberg 1999). Other studies have identified the significance of temperature anomalies rather than absolute temperatures in determining the temperature tolerance of corals (Goreau *et al*. 1993, Goreau & Hayes 1994). For example, the absolute temperatures in Panama were higher than those in Galapagos during the 1982–3 ENSO event, yet mortality was lower in Panama since the anomaly was less (Glynn *et al*. 2001).

The potential habitat suitability map (Fig. 5) does not account for substrate, which can determine coral presence, as they require a hard foundation for establishment. Maps of hard substrates in the coastal zone of the Galapagos Islands would significantly improve the potential habitat suitability model.

ACKNOWLEDGMENTS

This research was funded under theDEFRA Darwin Initiative project 14-048 *Galapagos Coral Conservation: Impact Miti-gation, Mapping and Monitoring*. We thank Stuart Banks (CDRS), Peter Glynn (University of Miami) and UNEP-WCMC for providing coral mapping, survey data and other materials.

LITERATURE CITED

Fitt, W.K., Brown, B.E., Warner, M.E. & Dunne, R.P. 2001. Coral bleaching: interpretation of thermal tolerance limits and thermal thresholds in tropical corals. *Coral Reefs* 20: 51–65.

Glynn, P.W. 1993. Coral reef bleaching: ecological perspectives. *Coral Reefs* 12: 1–17.

Glynn, P.W. 2003. Coral communities and coral reefs in Ecuador. Pp. 449–472 *in* Coatés, J. (ed.), *Latin American Coral Reefs*. Elsevier, Amsterdam.

Glynn, P.W., Maté, J.L., Baker, A.C. & Calderón, M.O. 2001. Coral bleaching and mortality in Panama and Ecuador during the 1997–1998 El Niño-Southern Oscillation Event: spatial/temporal patterns and comparisons with the 1982–1983 event. *Bulletin of Marine Science* 69: 79–109.

Glynn, P.W., Riegl, B., Romanski, A.M. & Baums, I.B. 2009. Rapid recovery of a coral reef at Darwin Island, Galapagos Islands. *Galapagos Research* 66: 6–13.

Goreau, T.J. & Hayes, R.L. 1994. Coral bleaching and ocean "hot spots". *Ambio* 23: 176–180.

Goreau, T.J., Hayes, R.L., Slarke, J.W., Basta, D.J. & Robertson, C.N. 1993. Elevated sea surface temperatures correlate with Caribbean coral reef bleaching. Pp. 225–255 *in* Geyer, R. (ed.) *A Global Warming Forum: Scientific, Economic, and Legal Overview*. CRC Press, Boca Raton.

Guinotte, J.M., Bartley, J.D., Iqbal, A., Fautin, D.G. & Buddemeier, R.W. 2006. Modeling habitat distribution from organism occurrences and environmental data: case study using anemonefishes and their sea anemone hosts. *Marine Ecology Progress* 31: 269–283.

Hoegh-Guldberg, O. 1999. Climate change: coral bleaching and the future of the world's coral reefs. *Marine Freshwater Research* 50: 839–866.

Kaiser, M.J., Attrill, M., Jennings, S., Thomas, D.N., Barnes, D., Brierley, A., Polunin, N., Raffaelli, D. & Williams, P. 2005. *Marine Ecology: Processes, Systems, and Impacts*. Oxford University Press, Oxford.

Lu, D. 2005. Urban classification using full spectral information of landsat ETM+ imagery in Marion Country, Indiana. *Photogrammetric Engineering and Remote Sensing* 71: 1275–1284.

Nybakken, J.W. 2001. *Marine Biology, an Ecological Approach* (5th ed.). Benjamin Cummings, San Francisco.

Obura, D.O. 2005. Resilience and climate change: lessons from coral reefs and bleaching in the Western Indian Ocean. *Estuarine, Coastal and Shelf Science* 63: 353–372.

Pearson, R.G. & Dawson, T.P. 2003. Predicting the impacts of climate change on the distribution of species: are bioclimate envelope models useful? *Global Ecology and Biogeography* 12: 361–371.

Reaser, J.K., Pomerance, R. & Thomas, P.O. 2000. Coral bleaching and climate change: scientific findings and policy recommendations. *Conservation Biology* 14: 1500–1511.

Stone, L., Huppert, A., Rajagopalan, B., Bhasin, H. & Loya, Y. 1999. Mass coral bleaching: a recent outcome of increased El Niño activity? *Ecology Letters* 2: 325–330.

Trisakti, B., Sulma, S. & Budhiman, S. 2004. Study of sea surface temperature (SST) using Landsat-7 ETM. Pp. 1–5 *in*: *Proceedings, Thirteenth Workshop of OMISAR — validation and application of satellite data for marine resources conservation*. Asia-Pasific Economic Cooperation, Bali.

West, J.M. & Salm, R.V. 2003. Resistance and resilience to coral bleaching: implications for coral reef conservation and management. *Conservation Biology* 17: 956–967.