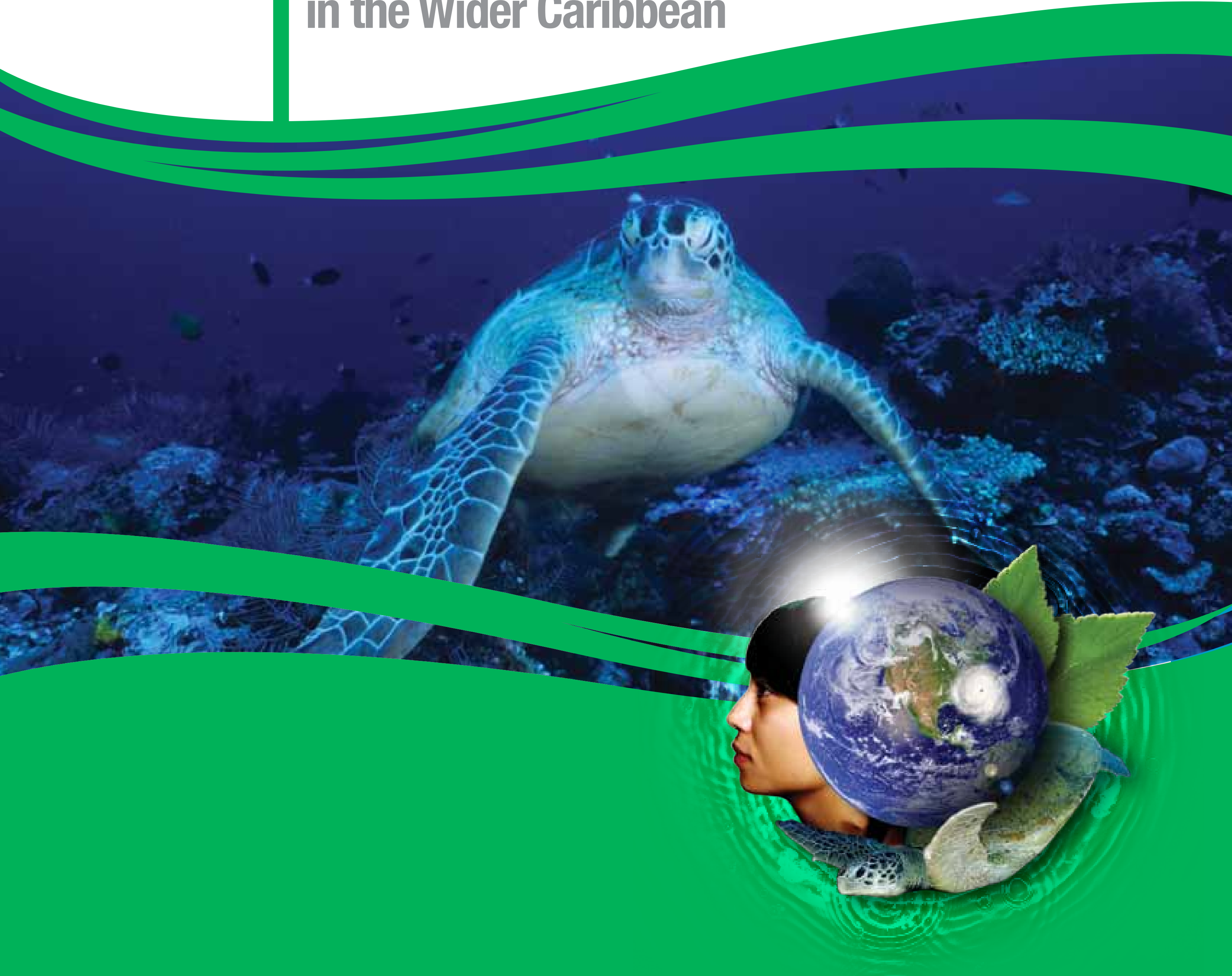
Regional Climate Projections

Climate Change and Marine Turtles in the Wider Caribbean



Marianne Fish, Alfonso Lombana & Carlos Drews

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Table of Contents

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Summary

Changing conditions in sea turtle nesting areas as a result of climate change are potentially serious for sea turtle populations already under pressure from over-exploitation, fisheries bycatch and habitat modification. Successful reproduction is key for population survival and is strongly influenced by the nesting environment. Understanding how nesting habitats may be affected by climate change, specifically changes in temperature and precipitation, is an important early step in assessing the vulnerability of regional sea turtle populations.

Climate changes will not be uniform across the globe as they are influenced by local physical processes. WWF has used regional projections for changes in temperature and precipitation to investigate projected changes in nesting conditions in the Wider Caribbean. The main aims of this project are:

- to create a comprehensive, interactive, online map that can be used by conservation groups and coastal managers to examine the local changes in climate that sea turtles will face throughout their range in the Wider Caribbean
- to assess the relative vulnerability of different nesting areas in the region to climate change

Regional climate change projections for the Caribbean have been developed by the PRECIS-Caribe project and temperature and precipitation projections for thirty-eight countries within the region were analysed. The Wider Caribbean region is facing much warmer and drier conditions in the coming decades. In general, small islands show less dramatic projected changes in both temperature and precipitation than mainland countries and as such may provide refugia from hotter, drier conditions in other parts of the region. The variation in local changes seen here, particularly for precipitation, highlights the importance of examining future projections on a finer scale than global climate models can provide.

Introduction

Changes in climate predicted as a result of increasing concentrations of greenhouse gases in the atmosphere include higher air and ocean temperatures, a rise in sea-level, increased frequency and intensity of extreme weather events and altered precipitation patterns [1]. These changes will have knock-on effects, bringing about a multitude of physical changes to ecosystems. Species in many areas are already exhibiting responses to a changing climate, and shifts in the phenology and distribution of plants and animals have been observed in terrestrial, freshwater and marine habitats [2].

The life history and biology of sea turtles are finely tuned to their environmental conditions. Changing conditions in nesting and foraging areas that could limit growth and reproductive potential are potentially serious for populations that are already under pressure worldwide due to high mortality from fisheries, over-exploitation and habitat modification [3]. Successful reproduction is key for population survival and consequently understanding how nesting habitats may be affected by climate change is an important early step in assessing the vulnerability of regional sea turtle populations. Nesting conditions are likely to be different in the future given projected shifts in temperature, precipitation, sea level and extreme weather events.

From timing of arrival at nesting sites to construction of nests and emergence of hatchlings, temperature and moisture play a critical role in the nesting process. For most populations of sea turtles, nesting occurs in a distinct season, usually in the warmest months [4]. Sea surface temperature plays a role in determining the onset of nesting and has also been shown to have a significant effect on remigration intervals [5]. Once eggs have been laid, the environmental conditions in the nest, namely temperature and moisture, are critical for successful incubation and play a crucial role in how embryos develop. On the beach, sand and corresponding nest temperatures influence incubation period, hatchling growth, sex ratios and ultimately hatching success [6]. Successful egg incubation occurs within a limited temperature range of approximately 25 ˚C to 35 ˚C, although the exact range differs between species [7]. The time for the eggs to incubate varies with temperature, with warmer nests incubating faster [8]. Incubation temperature also influences the phenotype of hatchlings, with higher temperatures producing smaller hatchlings [9, 10]. These hatchlings may be more at risk from predation outside the nest from gape-limited predators that cannot prey on larger hatchlings but smaller hatchlings can also swim faster and have faster growth rates [11, 12]. Temperature also determines the sex of hatchlings: higher temperatures during the middle third of the incubation period produce more females, lower temperatures more males. At a 'pivotal temperature' of between 28 and 31 °C for most species, a 50:50 ratio is produced and around this there is a transitional range that results in a mixture of sexes [13].

Alongside temperature, precipitation also plays a role in reproductive success. In some areas, nesting seasons correspond to the season of maximum rainfall [14-18], while in others, peak nesting occurs in the dry season [19] or straddles both rainy and dry periods [20]. Precipitation can have a range of effects on sea turtle nests by increasing the moisture content of the sand. Rain may help to consolidate the substrate, facilitating nest excavation [21, 22]. The amount of moisture in the sand in turn affects oxygen transport, gas exchange, salinity and calcium mobilization [7, 23-25]. A number of studies have found relationships between moisture and hatching success. McGehee [26] determined that hatching success was greatest at 25% moisture and significantly less at lower (0) and higher (50, 75, 100%) levels. Similar findings are reported by Ozdemir and Turkozan [27], Ozdemir *et al* [28] and Yalcin-Ozdilek *et al* [29]. Moisture also influences thermal conditions in the sand with protracted rainfall having a marked cooling effect on nests [30, 31], to the extent that it may influence sex ratios [31, 32]. Incubation time has been shown to be longer at higher moisture levels [26].

Given the numerous ways in which temperature and moisture can affect sea turtle reproduction, there is concern that the rapid changes in these variables expected in the coming century could have a considerable impact on sea turtle populations. Determining how conditions will change in the Wider Caribbean region's coastal areas is therefore an important early step in assessing the overall outlook for the region's sea turtle populations. The manifestations of climate change will not be uniform across the globe as they are strongly influenced by local physical processes. Similarly, they are unlikely to be homogeneous within the region of analysis. While the means to accurately project nesting temperatures on an individual beach basis do not exist, regional climate models allow us to examine projections at a level that is more meaningful for management purposes than broader scale global projections. It is important to understand how conditions might change in the future and plan conservation programs accordingly. The goal of this project is to facilitate this process for conservation groups and coastal managers in the Wider Caribbean.

Objectives

The main objective of this project is to provide a tool for conservationists and managers to investigate the conditions that sea turtle nesting populations are likely to face in the coming decades. This analysis focuses on future scenarios of temperature and precipitation in the Wider Caribbean. We present an initial exploration of those projections for the region in relation to sea turtle nesting sites. Specifically, the project has:

- Created an interactive, online map that can be used by conservation groups and coastal managers to examine the local changes in climate that turtles may face in the Caribbean

- Examined temperature and precipitation projections for the Wider Caribbean region for the next century and related these changes to current nesting areas. We also discuss the implications of altered nesting conditions for the vulnerability of regional sea turtle populations to climate change.

Regional climate changes

Climate projections

Our climate is the result of complex interactions between incoming solar energy and the atmosphere, oceans (hydrosphere), land (lithosphere), ice (cryosphere) and life (biosphere) [33]. Modeling how the climate is likely to change in the future is possible using atmosphere-ocean coupled general circulation models (AOGCMs), which take into account these physical and chemical relationships and interactions. Global Circulation Models (GCMs) integrate as many physical processes as possible to project changes in climate variables with increasing greenhouse gas emissions.

While GCMs are adequate for grids of greater than a hundred kilometers, they do not supply the detail needed for country-level assessments. In the Caribbean, a region of some 7,000 islands, islets and cays, many countries are not represented at all in global models and higher resolution data are needed. There exist a number of ways to improve on GCMs, including using higher resolution atmospheric GCMs, statistical techniques linking GCMs with higher resolution climate information and regional climate modeling. Regional Climate Models (RCMs) are full-scale, physically-based climate models that incorporate the processes and interactions of global models but add a finer spatial scale. Aside from the greater detail they provide, some additional advantages of using the regional model are: more realistic projections for areas where the terrain is not flat, better prediction of changes in extreme weather and, perhaps most importantly for the Caribbean, representation of small islands [34].

PRECIS (Providing Regional Climates for Impact Studies) is a PC-based regional climate model developed by the Hadley Centre, UK, which can be applied to any area of the globe to generate detailed climate change projections. The PRECIS-CARIBE project is a multi-institutional effort to provide climate projections for the Wider Caribbean region using PRECIS models. The Instituto de Meteorología de la República de Cuba (INSMET) provides public access to the results of this project and data on precipitation, surface temperature and humidity, amongst other variables, can be accessed online and downloaded from the project's website (http://precis.insmet.cu/Precis-Caribe.htm). These data provide the basis for our analysis (see methods in Appendix A).

Scenarios

Climate projections depend on future changes in greenhouse gas emissions, the variation in which is represented by different climate scenarios. It is difficult to predict exactly how society will react to the threat of climate change and to what extent will be willing, or able, to reduce emissions. As we look further into the future, our ability to accurately predict greenhouse gas emissions diminishes. To take this uncertainty into account, climate projections are based on a number of different future scenarios, i.e. possible future situations with varying levels of population growth, socio-economic development and technological progress [35]. Figure 1 summarises the different climate scenarios, as detailed in the IPCC Special Report on Emissions Scenarios (SRES) [36]. Currently, PRECIS-CARIBE has run models for the A2 and B1 scenarios. For more information on the PRECIS-CARIBE project see Taylor et al [37].

The data available from the PRECIS-CARIBE website were generated from simulations developed for two "time periods", 1961-90 and 2071-2100 (using the SRES A2 scenario). The results are presented as the difference between the baseline control period (1961-1990) and the period simulated (2071-2100). Projections for the period between 2010 and 2070 and for the B1 emissions scenario are also available, having been estimated using scaling factors from global climate models. For the purposes of this study, PRECIS-CARIBE datasets were used to examine regional patterns in temperature and precipitation projections for two months (January and July, roughly corresponding to the dry and wet seasons) in three years (2020, 2050 and 2099 [38]). The data were downloaded and used to develop GIS (Geographical Information System) layers for each variable, which were overlaid on a regional coastline map. Detailed methods on how the data were extracted and analyzed are in Appendix A.

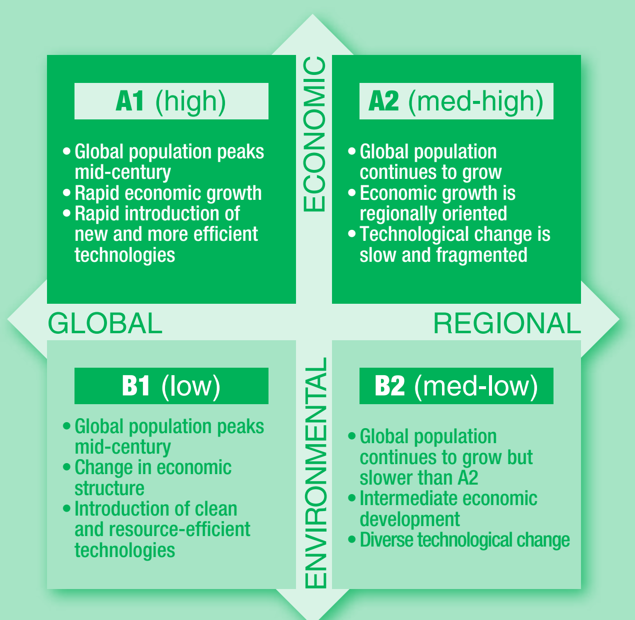
Limitations and uncertainties

Climate modelling is an evolving science and therefore any interpretation of results from current climate models should fully acknowledge the inherent limitations. It is critical to understand the uncertainties associated with these models and not take the values produced as absolutes.

Figure 1

Emissions Scenarios

There are forty different scenarios divided into four scenario families depending on the emissions they generate: A1 (High emissions), A2 (Medium to High), B2 (Low to Medium), B1 (Low). Each family represents different demographic, social, economic, technological, and environmental developments (Fig. 1).



Uncertainty arises from various sources:

- Uncertainty about future emissions and concentrations of greenhouse gases. It is possible to account for uncertainty surrounding future emissions by considering projections for both high and low emissions scenarios. However, understanding of some processes in the carbon cycle is imperfect, which creates uncertainty when converting emissions into concentrations. Models also do not take into account feedbacks between the climate, carbon cycle and atmospheric chemistry.

- Uncertainty about the response of the climate. Knowledge of the climate system is incomplete and some feedbacks and processes may not be adequately represented. One way to address this uncertainty is to use different GCM projections in the regional models and present the results as a range of possible values. The current PRECIS-CARIBE projections were developed using the Hadley Centre GCM. However, future work by the project will incorporate alternative GCM projections.

- Natural variability. Anthropogenic climate change is occurring concurrently with natural climatic variability. Climate varies on timescales from annual to decadal as a result of natural interactions between atmosphere, ocean and land and this natural variability could serve to add to or subtract from changes resulting from human activity [38]. This natural climatic variability can be addressed by running ensembles of future climate projections, where each model in the ensemble is identical except that it is started from a different starting point. These runs will provide a range of possible projections that should span the actual evolution of the climate system [37].

- Uncertainty surrounding the regionalization technique. As mentioned previously there are a number of ways to obtain higher resolution results from coarser resolution GCMs. Ideally, any projections should be compared to those produced by different techniques.

It seems wise to approach the interpretation of outputs from climate modelling by covering a range of scenarios. Lower limits may be indicative of the minimum to which society should be prepared to cope with. Upper limits are worst-case scenarios, the consequences of which should be part of risk assessments and response design with a precautionary perspective. General trends are probably a good indication of likely developments of regional climate.

Climate projections for the Caribbean

The Caribbean region

The Wider Caribbean region consists of 29 mainland countries and islands (13 sovereign states, 14 dependent territories and two overseas departments) that lie around and within the Caribbean Sea and the Gulf of Mexico. The region is bordered by the mainland countries of South America (Colombia, Venezuela and the Guianas) to the south and Central America (Panama, Costa Rica, Nicaragua, Guatemala, Belize and Honduras) to the west. The islands of the West Indies form an arc that borders the sea to the east, and to the north lie the southern USA, the Bahamas and the Turks and Caicos Islands (Fig. 2).

The region can be divided into several geographically distinct areas: North America (USA and Mexico), the Bahamian Islands (The Bahamas and Turks and Caicos Islands), the Greater Antilles (Cuba, Jamaica, Haiti, the Dominican Republic and Puerto Rico), the Lesser Antilles (Leeward Islands and the Windward Islands, the southern Caribbean (including mainland countries of South America and the Leeward Antilles), Central America and the Cayman Islands. Figure 2 shows the countries included in this analysis. Suriname and French Guiana are part of the region, but our analysis here is limited to the coverage from the PRECIS CARIBE data, which does not currently extend to these countries.

Regional projections

All temperature and precipitation projections are presented as the difference between a baseline control period (1961-1990) and the year of interest. Table 1 shows the overall trends for the entire region (not just coastlines) for three years: 2020, 2050 and 2099. In general the Caribbean region is likely to be warmer and drier, but with a great deal of regional variation. All observed patterns are more pronounced under the A2 (high emissions) scenario than for the B1. Average warming is similar in January and July in 2020 and 2050 but by 2099, July shows a greater increase in temperature than January for both scenarios. There is a mean decrease in precipitation for both months in 2020 and 2050, and for July 2099. January 2099 shows a slight increase in rainfall. Climate projections by country are shown in Appendix B.

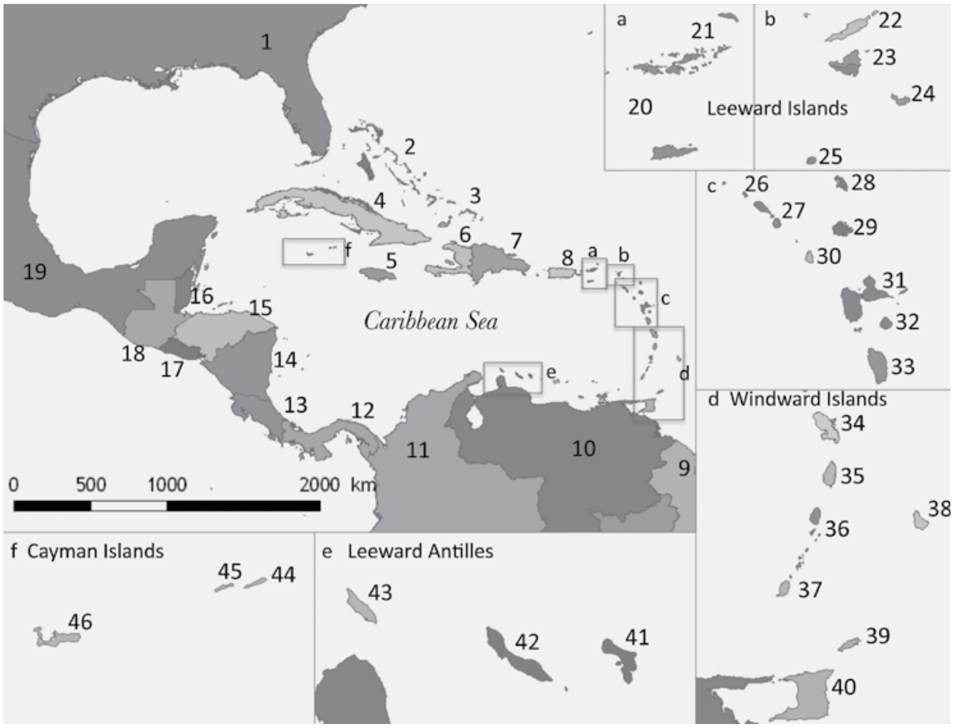


Figure 2. Countries and islands of the Wider Caribbean.

1	USA	13	Costa Rica	25	Saba	37	Grenada
2	The Bahamas	14	Nicaragua	26	St Eustatius	38	Barbados
3	Turks and Caicos	15	Honduras	27	St Kitts and Nevis	39	Tobago
4	Cuba	16	Belize	28	Barbuda	40	Trinidad
5	Jamaica	17	El Salvador	29	Antigua	41	Bonaire
6	Haiti	18	Guatemala	30	Montserrat	42	Curacao
7	Dominican Republic	19	Mexico	31	Guadeloupe	43	Aruba
8	Puerto Rico	20	US Virgin Islands (USVI)	32	Marie-Galante	44	Cayman Brac
9	Guyana	21	British Virgin Islands (BVI)	33	Dominica	45	Little Cayman
10	Venezuela	22	Anguilla	34	Martinique	46	Grand Cayman
11	Colombia	23	St Maarten/St Martin	35	St Lucia		
12	Panama	24	St Barthélemy	36	St Vincent and the Grenadines		

Table 1 Mean (± SD) difference in temperature and precipitation between 1961-1990 and 2020, 2050 and 2099 in the Wider Caribbean for two months and two emissions scenarios. N= 38 states and island groups.

		TEMPERATURE		PRECIPITATION	
		A2	*B1*	*A2*	*B1*
2020	January	0.69 (0.15)	0.62 (0.13)	-0.41 (0.48)	-0.37 (0.43)
	July	0.69 (0.24)	0.62 (0.22)	-0.73 (0.71)	-0.66 (0.64)
2050	January	1.46 (0.31)	1.10 (0.23)	-0.87 (1.02)	-0.65 (0.77)
	July	1.46 (0.51)	1.10 (0.39)	-1.56 (1.51)	-0.18 (1.14)
2099	January	3.32 (0.54)	2.02 (0.33)	0.32 (1.18)	0.19 (0.72)
	July	3.47 (1.23)	2.11 (0.75)	-2.55 (1.48)	-1.55 (0.90)

Source: calculated from PRECIS-CARIBE outputs (http://precis.insmet.cu/eng/Precis-Caribe.htm)

1) Temperature

General regional patterns

Figures 3a and 3b show the regional patterns in change in temperature, under a B1 and A2 emissions scenarios respectively. Temperature increases are projected to be greater over land than over the sea and therefore mainland countries show a greater change in temperature than islands (Fig. 3a). Temperature changes within the region will be highly variable, particularly over land areas; warming is more pronounced over land areas in July than January for all years. From 2050, a relatively cooler patch appears in the southwestern Caribbean, near the coast of Nicaragua and Costa Rica. Surface temperatures over open water are projected to increase more in the north than in the southern Caribbean.

By area

Given the differences in geography between parts of the Caribbean, we compared the projected changes in temperature for each of these areas (Fig. 4). The small islands of the Lesser Antilles and Cayman Islands show less of an increase in temperature than the Greater Antilles and mainland countries (Fig. 4) and this difference is more prominent in July than in January.

2) Precipitation

General regional patterns

There is a mean overall decrease in precipitation under both scenarios, with the exception of a mean increase in January 2099 (Table 1) driven by much wetter conditions in the northern part of the region and Colombia (Fig. 5). The projected decrease in precipitation is greater for July than January overall but in January there is a large patch of decreased precipitation in the western Caribbean (Fig. 5), south of the Greater Antilles (encompassing the Cayman Islands). In 2020, there is a small patch of higher precipitation on the coast of Costa Rica. This anomalous patch off the Caribbean coast of southern Central America expands in subsequent years to include the coasts of Costa Rica, Panama and Nicaragua. In July, the north is generally drier than the south, with a large patch of higher precipitation in the south-western Caribbean, and the eastern tropical Pacific, between Panama and Colombia (Fig. 5).

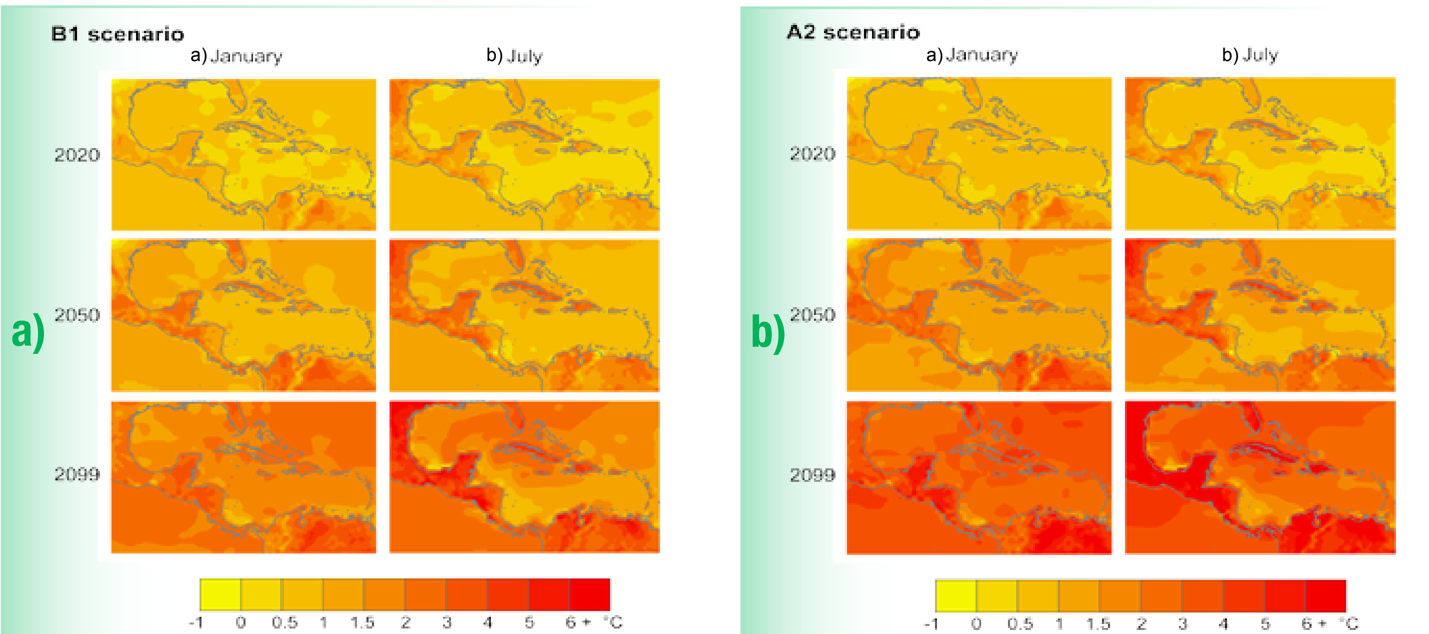


Figure 3: Projected changes in temperature for the Wider Caribbean region, for two months in 2020, 2050 and 2099 and for two different emissions scenarios a) B1 and b) A2.

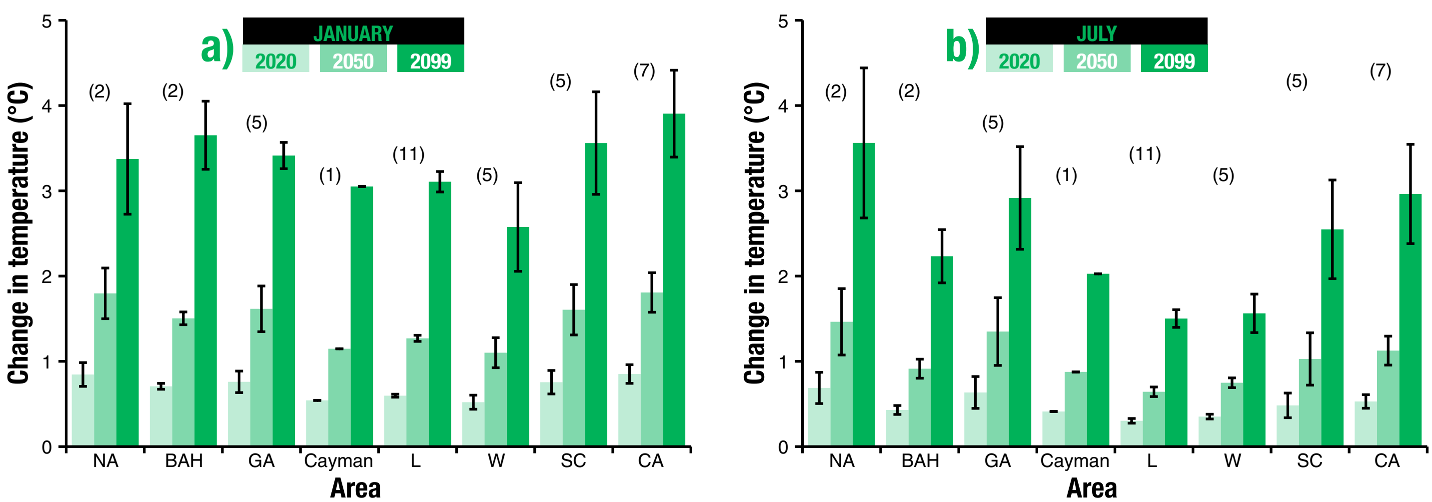


Figure 4. Mean (± SD) projected change in temperature from the 1961 – 1990 baseline average for a) January and b) July 2020, 2050 and 2099. Areas represented are North America (NA), Bahamian Islands (BAH), the Greater Antilles (GA), the Cayman Islands, the Leeward Islands (L), the Windward Islands (W), the southern Caribbean (SC) and Central America (CA). Number of countries in each area (N) are shown in parentheses.

The projections for 2099 show a large amount of regional variability. In January 2099 the overall pattern of drying shifts (Table 1), with 14 countries exhibiting wetter conditions (see Appendix B). In January there is an increase in precipitation over the sea that switches to a decrease by July. The patch in the south-western Caribbean fluctuates dramatically between the seasons, with projected changes in precipitation of around -10 mm day^{-1} in January up to +20 mm day^{-1} in July.

By area

In January, the Cayman Islands show the most pronounced decrease in precipitation for all scenarios except January 2099 when an increase is projected (Fig 6). The islands of the Greater and Lesser Antilles show lower average changes. The large variation in projections for Central America is driven by the highly variable patch near Costa Rica (Fig. 5). By 2099, more northerly areas (Bahamas, Greater Antilles, Leeward Island and the Cayman Islands) show a flip in the overall trend of drier conditions in January (Fig. 6). In July there is a general pattern of decreasing precipitation over time, with the exception of Central America (Fig. 6), which again shows a lot of variation driven by the patch of increased precipitation off the coast of Nicaragua, Costa Rica and Panama. Changes in precipitation by country are presented in Appendix B.

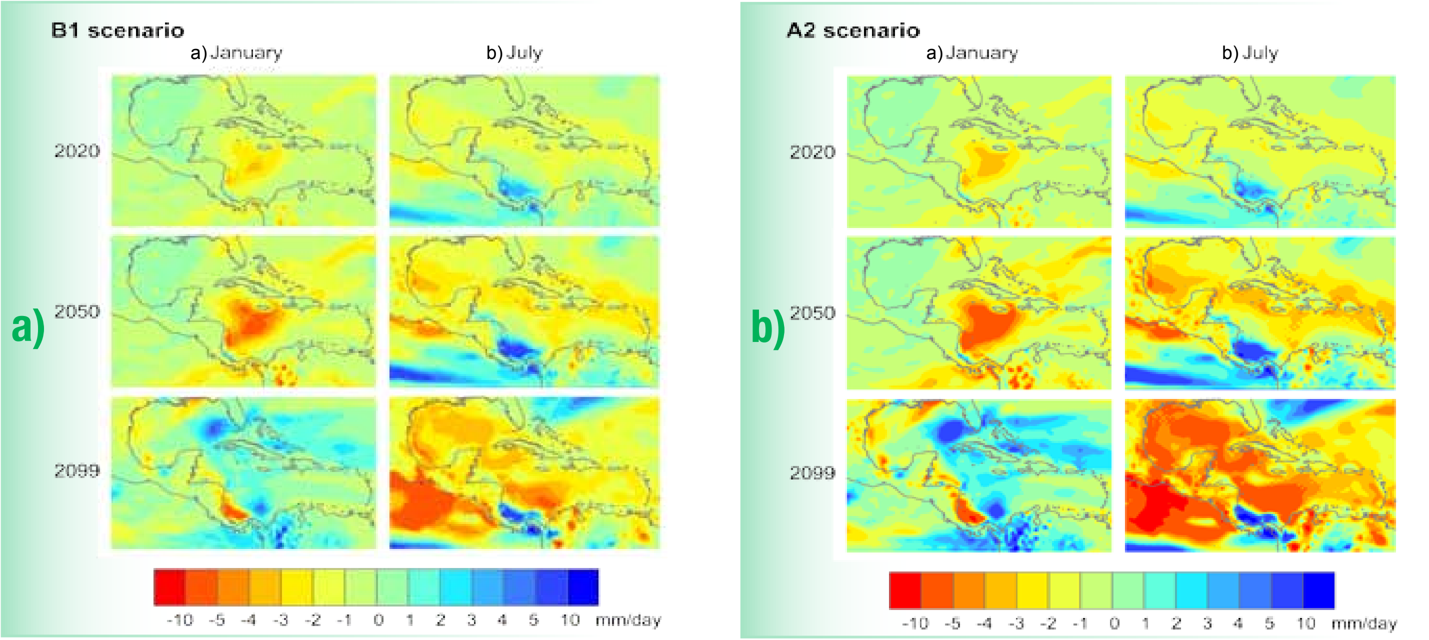


Figure 5: Projected changes in precipitation for the Wider Caribbean region, for two months in 2020, 2050 and 2099 and for two different emissions scenarios a) B1 and b) A2.

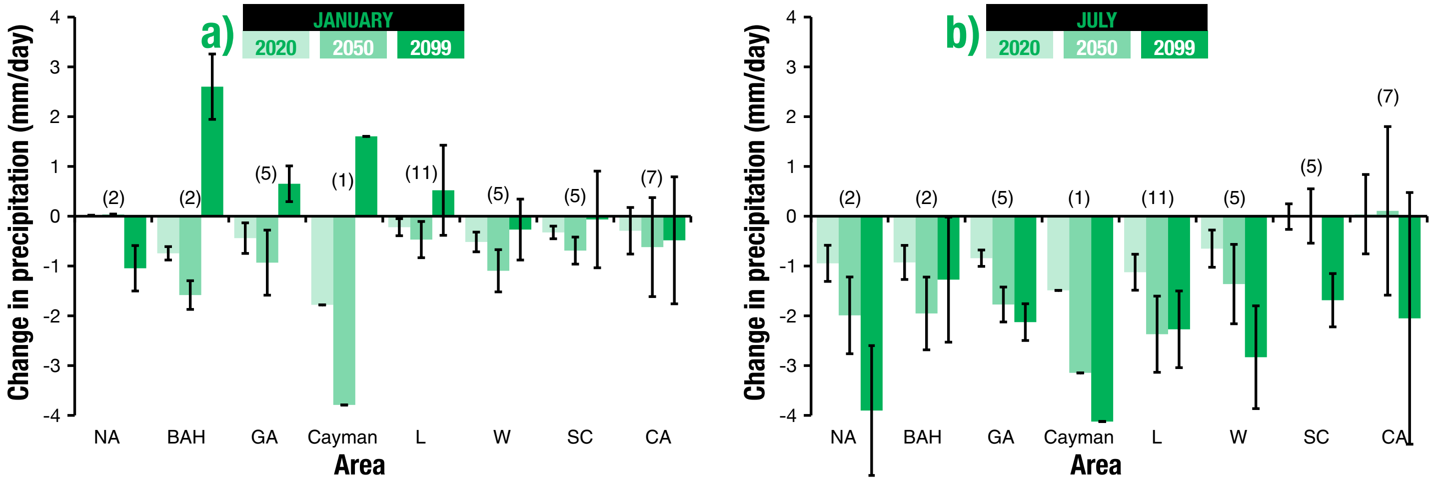


Figure 6. Mean (± SD) projected change in precipitation from the 1961 – 1990 baseline average for a) January and b) July 2020, 2050 and 2099. Areas represented are North America (NA), Bahamian Islands (BAH), the Greater Antilles (GA), the Cayman Islands, the Leeward Islands (L), the Windward Islands (W), the southern Caribbean (SC) and Central America (CA). Number of countries in each area (N) are shown in parentheses

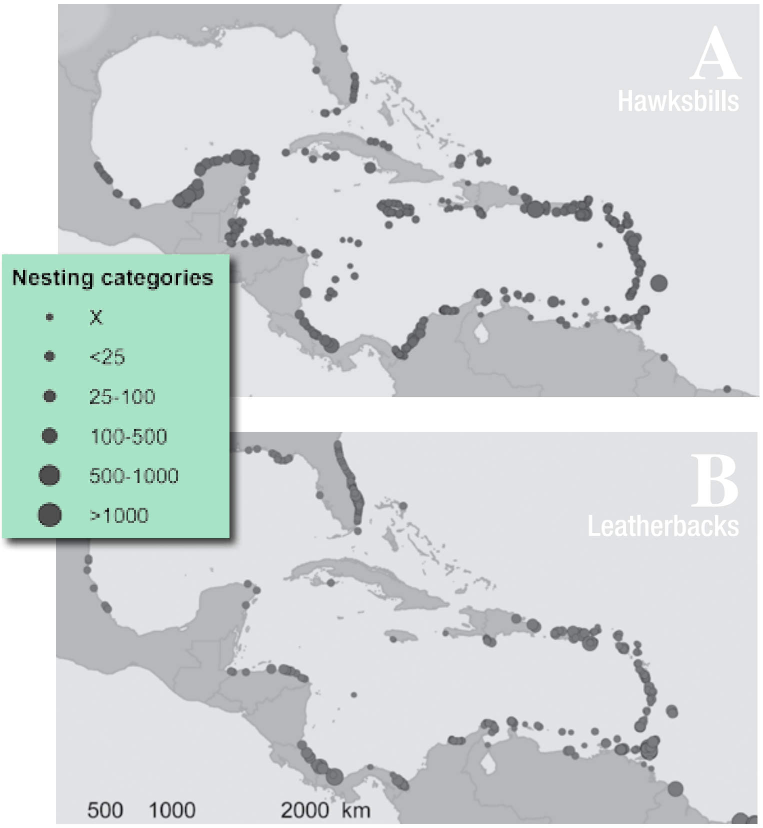


Figure 7. Distribution of hawksbill (a) and leatherback (b) nests in the Caribbean region (adapted from [39]). Nesting beaches are divided into categories based on the numbers of crawls per year: X = traces of nesting, <25, 25-100, 100-500, 500-1000, >1000.

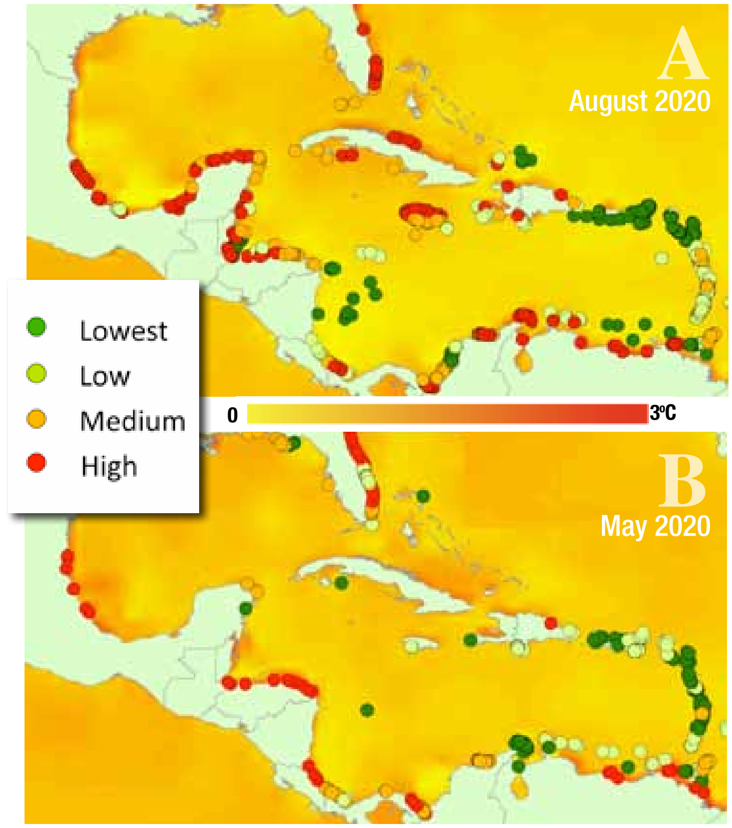


Figure 8. Projected changes in peak nesting month temperature for a) hawksbills (August) and b) leatherbacks (May) 2020 and ranking of nesting sites in the Caribbean region by projected temperature change (based on current nesting season).

Six species of sea turtle nest in the Caribbean and nesting beaches are spread throughout the region. Here we focus on the nesting sites of critically endangered hawksbill (*Eretmochelys imbricata*) and leatherback (*Dermochelys coriacea*) turtles (Fig. 7).

Nesting is seasonal and varies by country with some regional patterns. Peak nesting months for hawksbills in the Caribbean fall between July and October and between April and June for leatherbacks (Source: WIDECAST Sea Turtle Recovery Action Plans http://www.widecast.org/Resources/STRAPs.html). Nesting locations and season were used to examine the relative vulnerability of nesting beaches to changes in temperature for 2020, as this year is within the feasible lifetime of current conservation projects. Nesting data were obtained from the Wider Caribbean Sea Turtle Network's (WIDECAST) spatial database of sea turtle nesting habitat for the Wider Caribbean Region, available online from OBIS-SEAMAP [40] (NB. some regional beaches may not be represented because they fall outside the limits of the PRECIS model). The range of temperatures at nesting sites for each species was obtained for 2020 and beaches were ranked by projected change in temperature from 1 (lowest change) to 4 (highest), based on the quartile ranges of expected temperature increments (Fig. 8). For both hawksbills and leatherbacks, the islands of the Lesser Antilles and other small islands within the region, show a smaller increase in temperature in peak nesting season than mainland areas and may therefore exhibit the least change in nesting conditions in the future.

Under the A2 scenario, the mean increase in temperature for coastal areas by May 2020 (leatherback peak nesting month) is 0.67 °C (± 0.17 SD) and for August 2020 (hawksbill peak nesting month) is 0.66 °C (± 0.23 SD). These are not markedly different from the projected increases when only nesting sites for each species are considered (leatherback nesting sites: 0.69 °C ± 0.25; hawksbill nesting sites: 0.65 °C ± 0.32).

An increase in temperature is projected for all months, although the extent of the increase varies by month. Figure 9 shows the average temperature by month for 1994-2006 and the projected increase in temperature for each month for 2020. There was no significant correlation between current temperature and projected increase ($R=0.48$, $p=0.14$) but the hottest month (April) also shows the greatest increase.

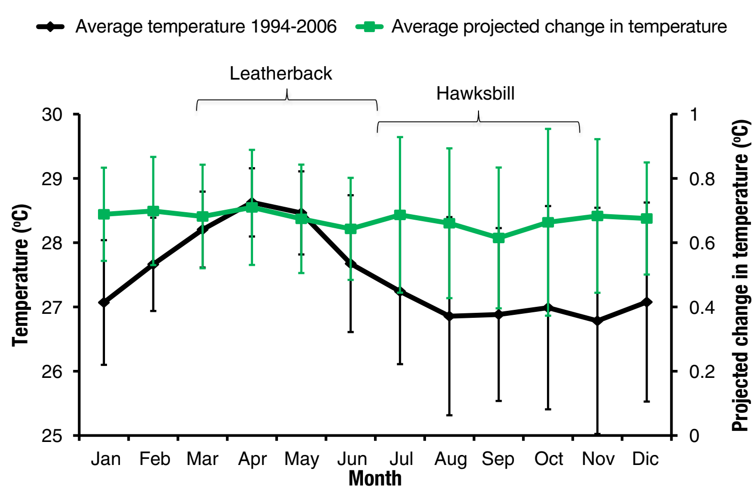


Figure 9. Mean (± SD) temperature (1994-2006) for each month and projected change in temperature for each month of 2020 as compared to the 1961-1990 baseline average, under an A2 scenario. Current peak nesting months for leatherbacks and hawksbills in the Caribbean are shown.

What do future climate projections mean for sea turtle populations?

The Caribbean region is facing much warmer and drier conditions in the coming decades. The variation in local changes seen here, particularly for precipitation, highlights the importance of examining future projections on a finer scale than global climate models can provide. In general, small islands show less dramatic projected changes in both temperature and precipitation than mainland countries and as such may provide refugia from hotter, drier conditions in other parts of the region.

1) How will changes in surface air temperature affect nesting conditions?

The temperatures represented here are changes in surface air temperature but the actual sand temperatures experienced by turtles will depend on more localized factors. Large thermal differences are seen both between and within beaches, depending on the physical characteristics of the beach substrate, including sand grain size, sand colour and moisture content [41, 42]. Lighter colour beaches are generally cooler and darker beaches warmer [41] and on any particular beach, sand temperatures generally increase landward of the high water mark, attributable to the lower moisture content of the sand. In addition to the nature of the substrate, overcast skies, rain, heavy seas, the position of the water table, vegetation and human developments near the beach can all affect beach temperature [24, 43-45].

Temperature also varies with depth and nest temperatures on the same beach can vary depending on their depth [10 46, 47]. The relationship between air temperature and temperature at nest depth is determined by the exchange of thermal energy at the surface and by the transmission of heat within the sand [48]. In general, a decrease in temperature is seen with increasing depth. Daily fluctuations in temperature are reflected below the sand surface but the amplitude of these decreases exponentially with increasing depth. These variations in temperature with depth result in shallower nests reaching higher daily temperatures for longer periods of time than deeper nests [49, 50] and deeper nests may avoid excessive temperature fluctuations. Even within a nest, eggs are exposed to different temperatures, with two parts of the nest varying by as much as 1 °C [12]. In short, sand and nest temperatures are likely to increase as air temperatures rise [48, 51], with a stronger relationship between temperatures at shallower depths [52], but this relationship is likely to be location-dependent.

Regional climate models suggest that cooling is very unlikely to happen in the foreseeable future anywhere in the Caribbean. Notwithstanding the variability and array of determinants of incubation temperature, if surface air temperature increases so will incubation temperature to some extent. However, given the variable relationship between surface temperatures and potential nesting temperatures, it is useful to examine relationships between air temperature and sand and/or nest temperatures at individual beaches. Establishing these relationships is necessary for determining how these regional temperature projections will translate into altered nesting conditions (see Baker-Gallegos J., M.R. Fish & C. Drews. 2009. *Temperature monitoring manual. Guidelines for Monitoring Sand and Incubation Temperatures on Sea Turtle Nesting Beaches*. WWF report, San José, pp. 16). If these relationships could be determined on a regional scale, it may allow us to highlight areas of concern and/or those locations that may serve as temperature refugia.

2) How will changes in precipitation affect nesting conditions?

Changes in precipitation in either direction could influence the suitability of beaches for nesting. Precipitation, along with groundwater input and tidal processes, determine the amount of moisture in the sand [53]. Rainwater can percolate through the sand from the surface and high levels of precipitation, particularly over a short period of time may cause groundwater tables to rise, increasing the water content of the sand. As with temperature, sand characteristics can influence moisture conditions in the sand. Coarse-grained sands are much more permeable than finer sands and may dry out faster [53].

Sea turtle eggs are coupled with the nesting environment through transfer of water, oxygen, carbon dioxide and heat through the egg membrane [7] and all of these processes are influenced by the moisture content of the surrounding sand. The moisture content of the sand affects the cohesion, thermal conductivity and respiratory properties of the beach. In moist sand, grains are held together by surface tension giving the sand cohesion, which facilitates nest construction. The presence of water also affects the rate at which heat is transferred through the sand [54]. Thermal conduction is much higher in water films than in air-filled pores so sands with a higher water content exhibit greater thermal conductivity [54]. Water content also influences the gas permeability of sand. Completely dry sand consists of sand grains and air and when water is present it fills the gaps between sand grains, displacing the air and limiting the movement of gases.

3) What might the impacts on sea turtles be?

Although the relationship between surface air and nest temperatures is not necessarily straightforward, the projected shifts in precipitation and temperature have the potential to affect sea turtles in a number of ways. If we assume that turtles can and will adjust behaviorally and/or genetically to the pace of the changing climate (but see next section below), then warmer water temperatures may drive earlier or later nesting [55], a decrease in inter-nesting interval and shifts in timing of peak nesting. In addition, breeding in sea turtles is resource-dependent and if availability of prey items is influenced by temperature changes, then decision to breed and timing of remigration and clutch frequency could all be affected [6]. Along with temporal shifts, an increase in thermally suitable nesting habitat, could lead to expansion of current distribution.

An issue of concern is the influence of increased beach temperatures on sex ratios and subsequently on population fecundity [52, 55-57]. Most studies examining primary sex ratios, either directly or indirectly, have demonstrated a female bias. This ratio may be natural, or potentially at some sites the result of changes in temperature over the last few decades [48, 52]. Nevertheless, increased incubation temperatures may lead to more extreme sex-ratio biasing towards female hatchlings and in some cases to embryo mortality [55]. As a result, population fecundity may be impaired through two mechanisms. Firstly, if there are insufficient males to fertilize all females, populations will become sperm limited. Alternatively, even if all females can be fertilized by a few males, the dearth of males may lead to inbreeding, which may be associated with declines in fitness (inbreeding depression) [58]. The population-level impacts of temperature-mediated biases in sex ratios are therefore complex and may depend on the reproductive ecology such as mating system and mate encounter rates [59].

Altered precipitation patterns in either direction could cause problems for nesting sea turtles and their hatchlings. Drier conditions could potentially hinder nest construction if the sand lacks cohesion and collapses during excavation[7]. Also, low moisture may lead to reduced nest success as successful egg development is dependent on uptake of moisture from the surrounding substrate [26]. Conversely, increases in precipitation, particularly a rise in the frequency of extreme rainfall events could result in rain-induced suffocation of hatchlings either through direct water influx from the sand surface or from rising water tables that flood nests from underneath [43, 45], particularly in flat, poorly drained areas. Additionally, rainfall can cause sand hardening producing resistant surface crusts [60], raising the energetic cost of emerging from the nest [61, 62].

3) Can sea turtles adapt to climate change?

The severity of the risk to regional sea turtle populations from climate change will depend to a large extent on their ability to adapt to changing conditions. Sea turtles can respond in three ways to the selective pressure of changing environmental conditions: disperse to suitable habitats elsewhere, stay put and adjust by means of phenotypic plasticity or adapt over time by means of genetic changes through natural selection [63]. A combination of these responses is also possible.

Phenotypic plasticity, i.e. the ability of individuals to modify their behavior, morphology or physiology in response to change [64], is likely to be key in any adaptive response to climate change as it provides the potential for organisms to respond rapidly and effectively to changing conditions [65]. Many of the species responses to climate change already seen have been attributed to phenotypic plasticity [66].

Sea turtles may exhibit spatial shifts by using different areas on current nesting beaches, choosing different nesting beaches or expanding their range to include beaches at the (lower) thermal limits of their current distribution. Temporal shifts are also possible. Sea turtles may compensate for changing temperatures by nesting earlier or later or by extending the nesting season in both directions. If females can shift nesting location and/or timing to compensate for increasing temperatures the negative impacts on populations may be lessened. The response may vary between species depending on nest site fidelity (high in hawksbills, relatively low in leatherbacks) and behavioral flexibility. While additional thermally-suitable habitat could prompt dispersal to higher latitudes and new nesting or foraging areas, this assumes that habitats are suitable in other ways, that is, beaches provide suitable nesting substrate and conditions or, for foraging sites, that prey species are also able to shift with temperature.

An important next step in understanding how sea turtles will respond to climate change is to decipher the limits of phenotypic plasticity in sea turtle populations. For example, assessing the risk to sea turtle populations from rising temperatures might include attempts to determine how traits such as nest-site selection and pivotal temperature respond plastically to changing environmental conditions, and how this plasticity influences survival and reproductive success [67]. Plasticity in pivotal temperature is a major question in determining temperature impacts on sex ratios, although it appears that this is relatively conserved [6]. Given that sea turtles may shift to cooler areas to compensate for increasing temperatures at currently used beaches, studies are needed that identify where these areas might be so that trends in nesting can be observed.

While sea turtles have survived large climatic fluctuations during their evolutionary history, plasticity is unlikely to provide a long-term solution if a limit is reached beyond which loss of fitness cannot be mitigated [63]. A number of additional factors could limit sea turtles ability to adapt naturally; the fast rate of current climate change is concerning, as is the fact that there are multiple additional stressors on sea turtles and their habitats from human activities and that many populations are remnants of historic levels, including some already on the verge of extinction [68].

Conclusions and next steps: What can we do?

The vulnerability of sea turtle populations to climate change in specific areas depends not only on the turtles' response to climate change, but also ours. Here we have shown the projected regional increases in temperature and changes in precipitation for the Wider Caribbean region. While the exact conditions and timing of changes that we are facing is uncertain, we know that changes in temperature and precipitation will occur and are likely to affect future nesting conditions, which should be taken into consideration in planning management. Adaptation measures put into place now to mitigate any negative impacts of changing conditions, may help to reduce the future vulnerability of regional sea turtle populations.

Adaptation to climate change in this context is different from the biological adaptation of sea turtles discussed above and involves accepting that some changes in climate are inevitable and acting to mitigate the negative impacts of those changes. These adaptation measures are not activities to reduce emissions, but rather actions taken at a local level to protect species, habitats or communities from climate change impacts (see Fish, M.R. and C. Drews. 2009. *Adaptation to climate change: options for marine turtles.* WWF report, San José, pp. 20). Enacting adaptation responses soon will buy time and position sea turtles and their habitats in a better condition to withstand the larger magnitudes of anticipated changes, regardless of when exactly certain thresholds may be reached. The costs of adaptation measures will be less the earlier they are implemented, to the extent that remedial action is minimized.

There are many actions that could be used to reduce the vulnerability of sea turtles and their habitats. The coastlines of many Caribbean countries are under intense pressure from coastal development, which can reduce the suitability of these areas for sea turtles. Measures to restrict beach-side development or to impose construction setback regulations that limit how close buildings are to the high tide line, may prove beneficial in maintaining suitable nesting areas in the advent of sea level rise. Alternatively, climate change adaptation can involve the direct management of sea turtles or their habitats, for example providing artificially shaded areas or restoring natural vegetation for shading, or moving nests to cooler parts of the beach or to hatcheries. Ultimately, the decision to implement any particular adaptation measure will depend on local circumstance and the suitability of the action for those specific logistical and societal conditions. Nevertheless, there are some 'no regrets' strategies that could be put into place now to ensure that sufficient suitable habitat remains in the future to sustain sea turtle populations. At a minimum it is prudent to maximize the potential for sea turtles to naturally adapt by ensuring that a range of nesting conditions are available, both in terms of different beaches and suitable conditions on currently used beaches, preventing the removal of natural vegetation and managing beaches such that the need for beach nourishment is minimized.

Next steps

Alongside changes in temperature and precipitation, an additional threat from climate change to nesting areas comes from sea-level rise, particularly in developed areas. The next project phase will include an analysis of projected change in sea level at a regional level. Furthermore, as more data on regional climate projections, infrastructure distribution and other threats and sea turtle biology become available these will be included in the online vulnerability analysis tool.

To access the interactive GIS tool, or for more information about climate change and marine turtles in Latin America and the Caribbean, visit

www.panda.org/lac/marineturtles/act

or contact

cctortugas@wwfca.org

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Appendix A - Methods

All analyses were carried out in ArcMap (ESRI GIS™). Data were downloaded from http://precis.insmet.cu/eng/Precis-Caribe.htm in ASCII format and converted to raster layers using the ASCII to raster tool.

Country level analysis. To restrict the analysis to just coastal areas, the mean temperature for the coastline of each country was determined using the 'Line Raster Intersection Analysis tool' (Beyer, H. L. 2004. Hawth's Analysis Tools for ArcGIS. Available at http://www.spatialecology.com/htools). Where the coastline of a country intersected more than one raster cell, a length weighted mean for the entire country's coastline was produced.

Nesting areas. Temperature changes for nesting beaches were calculated using the Intersect point tool (Beyer, H. L. 2004. Hawth's Analysis Tools for ArcGIS. Available at http://www.spatialecology.com/htools).

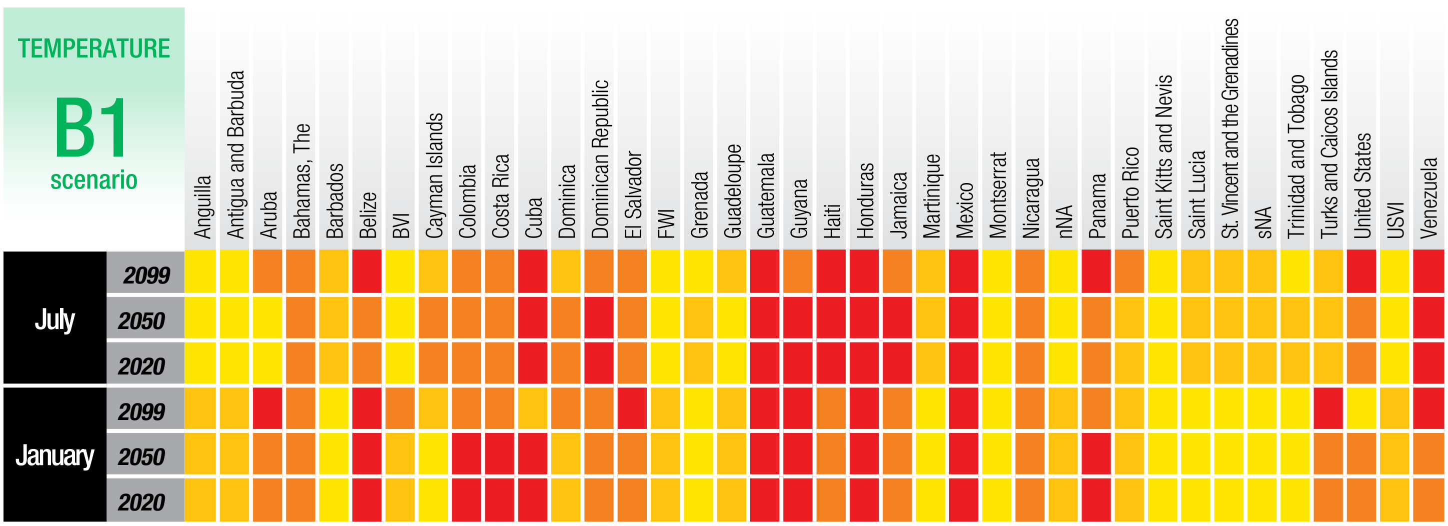
Appendix B - Climate projections by country:

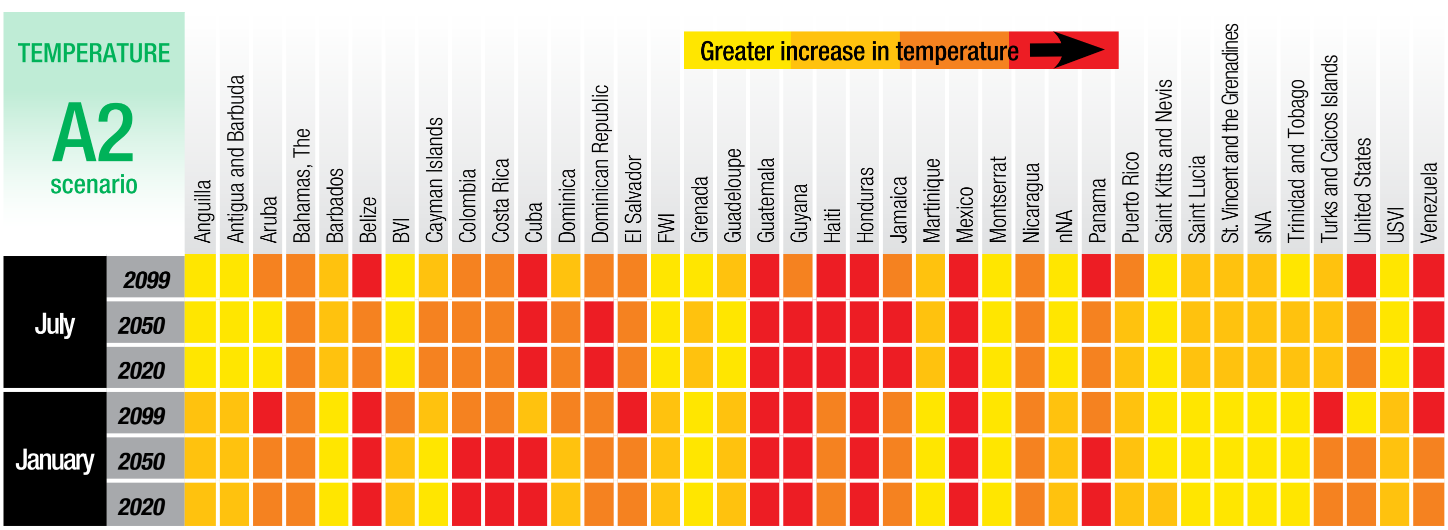
For the purpose of analysis some islands were grouped as follows: Cayman Islands (Cayman Brac, Little Cayman, Grand Cayman) the French West Indies (FWI) (St Martin and St Barthélemy), the northern Netherlands Antilles (nNA) (St Maarten, Saba and St Eustatius) and the southern Netherlands Antilles (Bonaire and Curaçao).

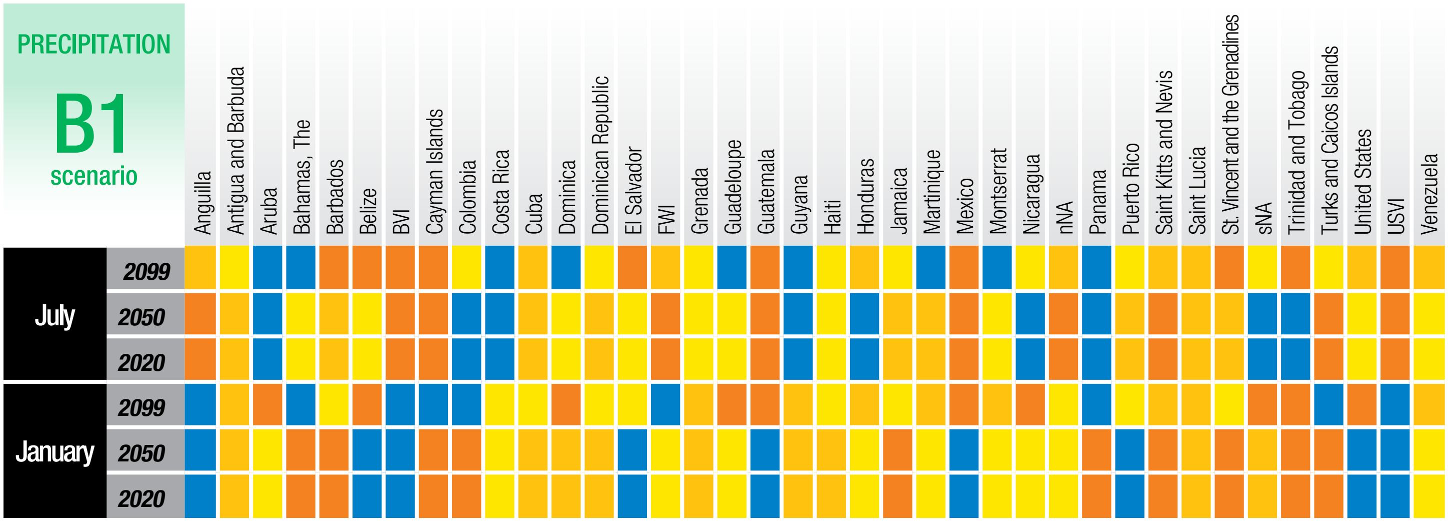
For a comparison of country values, each country was ranked from 1 - 4 based on the quartile ranges. Lighter colours represent lower ranks and darker colours higher ranks.

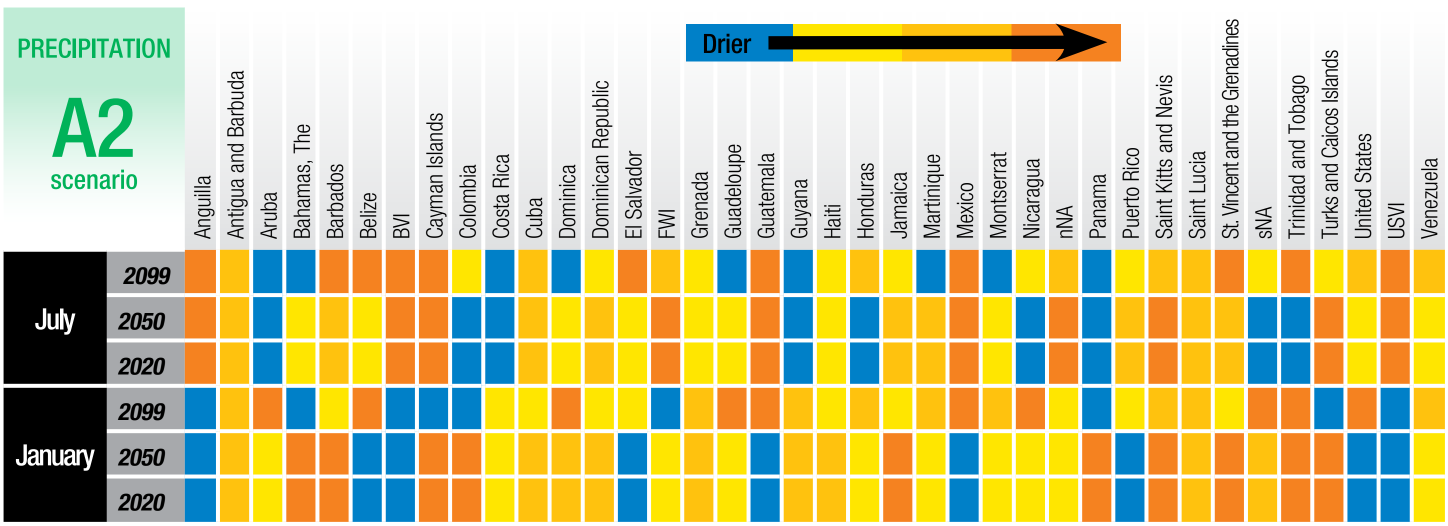
Table 2 Range of projected change in temperature and precipitation in the Wider Caribbean between 1961-1990 and 2020, 2050 and 2099 for two months and two emissions scenarios.

		TEMPERATURE		PRECIPITATION	
		A2	*B1*	*A2*	*B1*
2020	January	0.44 - 0.97	0.39 - 0.87	-1.78 - 0.14	-1.60 - 0.12
	July	0.41 - 1.41	0.37 - 1.26	-1.68 - 1.39	-1.51 - 1.25
2050	January	0.92 - 2.06	0.70 - 1.55	-3.78 - 0.29	-2.86 - 0.22
	July	0.87 - 2.99	0.66 - 2.26	-3.57 - 2.95	-2.69 - 2.23
2099	January	1.89 - 4.63	1.15 - 2.88	-2.29 - 3.07	-1.40 - 1.86
	July	1.95 - 6.47	1.18 - 3.94	-5.50 - 3.38	-3.34 - 2.06






PRECIPITATION
B1
scenario
Anguilla
Antigua and Barbuda
Aruba
Bahamas, The
Barbados
Belize
BVI
Cayman Islands
Colombia
Costa Rica
Cuba
Dominica
Dominican Republic
El Salvador
FWI
Grenada
Guadeloupe
Guatemala
Guyana
Haiti
Honduras
Jamaica
Martinique
Mexico
Montserrat
Nicaragua
nNA
Panama
Puerto Rico
Saint Kitts and Nevis
Saint Lucia
St. Vincent and the Grenadines
sNA
Trinidad and Tobago
Turks and Caicos Islands
United States
USVI
Venezuela
July
2099
2050
2020
January
2099
2050
2020


PRECIPITATION
A2
scenario
Drier
Anguilla
Antigua and Barbuda
Aruba
Bahamas, The
Barbados
Belize
BVI
Cayman Islands
Colombia
Costa Rica
Cuba
Dominica
Dominican Republic
El Salvador
FWI
Grenada
Guadeloupe
Guatemala
Guyana
Haiti
Honduras
Jamaica
Martinique
Mexico
Montserrat
Nicaragua
nNA
Panama
Puerto Rico
Saint Kitts and Nevis
Saint Lucia
St. Vincent and the Grenadines
sNA
Trinidad and Tobago
Turks and Caicos Islands
United States
USVI
Venezuela
July
2099
2050
2020
January
2099
2050
2020

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- conserving the world's biological diversity
- ensuring that the use of renewable natural resources is sustainable
- promoting the reduction of pollution and wasteful consumption

WWF Central America
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