Climate change effects on the biodiversity of the BES islands

Assessment of the possible consequences for the marine and terrestrial ecosystems of the Dutch Antilles and the options for adaptation measures

Alterra-report 2081
ISSN 1566-7197
IMARES-report C118/10

Adolphe O. Debrot and Rob Bugter

Climate change effects on the biodiversity of the BES islands

Commissioned by Ministry of ANF, BO11, Landschap en Platteland, Cluster Terrestrische EHS en Natura 2000, HD3229
Projectcode BO-11-006-000

Climate change effects on the biodiversity of the BES islands

Assessment of the possible consequences for the marine and terrestrial ecosystems of the Dutch Antilles and the options for adaptation measures

Adolphe O. Debrot[1] and Rob Bugter[2]

[1] Imares
[2] Alterra

Alterra-report 2081
IMARES-report C118/10

Alterra Wageningen UR
Wageningen, 2010

Abstract

Debrot, A.O. and R. Bugter, 2010. *Climate change effects on the biodiversity of the BES islands; Assessment of the possible consequences for the marine and terrestrial ecosystems of the Dutch Antilles and the options for adaptation measures*. Wageningen, Alterra, Alterra-report 2081; IMARES-report C118/10. 36 blz.; 10 fig.; 94 ref.

Due to their vulnerability and low capacity to adapt, the impact of climate change on small island nations will be far larger compared to larger countries. The Dutch BES islands (Bonaire, St. Eustatius and Saba) form part of the Caribbean global biodiversity hotspot area. The leeward Dutch islands alone possess some 200 endemic species and subspecies and the three islands count over 120 species that are on the CITES appendices. Since the economy of the Dutch Antilles depends for a large part on tourism and tourism on its turn for a large part on the natural capital of the islands, impacts of climate change on biodiversity will therefore also have important economical consequences.
In this report we review and assess possible consequences of climate change for the biodiversity of the BES islands and present various options for adaptation. It is quite clear that climate change not only poses a severe threat to the ecosystems of the islands, but also to the totality of benefits and services the inhabitants of these islands derive from those ecosystems.

Keywords: Caribbean, Climate change adaptation, Biodiversity risk, Ecosystem services.

Cover: Typical Bonairian cactus-scrub landscape; degraded vegetation and erosion resulting from centuries of overgrazing. Lagoen, Bonaire. Photo Adolphe O. Debrot.

ISSN 1566-7197

The pdf file is free of charge and can be downloaded via the website www.alterra.wur.nl (go to Alterra reports). Alterra does not deliver printed versions of the Alterra reports. Printed versions can be ordered via the external distributor. For ordering have a look at www.boomblad.nl/rapportenservice.

Alterra-report 2081
IMARES-report C118/10
Wageningen, october 2010

Inhoud

Summary

In this report we review and assess possible consequences of climate change for the biodiversity of the Dutch BES islands (Bonaire, Saba and St. Eustatius), and present various options for adaptation. From our review it is quite clear that climate change not only poses a severe threat to the ecosystems of the BES islands, but also to the totality of benefits and services the inhabitants of these islands derive from those ecosystems.
Key changes in climate expected this century include increases in air and sea surface temperature, an increase in sea level and ocean acidity, an increase in the frequency and intensity of storms and hurricanes, general aridification and greater overall unpredictability in weather. The consequences for both terrestrial and marine biodiversity are predicted to be far-reaching.
The principal effects will likely include further losses to the coral reef systems, erosion of coasts and beaches, salinification of ground water sources, losses in hilltop vegetation and flora, soil humus losses and erosion, increases in various disease vectors, changes in ocean currents, fish recruitment and migration, and a stronger foothold for invasive species.

The main areas of environmental policy involving the management of biodiversity are those of land-use planning and zoning, forestry and terrestrial conservation, and marine conservation. As for land-use planning and zoning, main issues of concern will be the introduction of the 'set back' policy for coastal development, the preservation of the full range of key habitats, and sufficient habitat surface area to sustain minimum viable populations for native species. In addition these habitats must be ecologically connected to allow free movement of animals across the habitats they need throughout the different seasons of the year and phases of their life cycle. In terms of forestry and terrestrial conservation policy, the focus will especially need to be on solving the problem of uncontrolled grazing of livestock, and the implementation of reforestation and groundwater conservation. Key issues in marine conservation policy will be to tackle the technically and financially challenging problem of eutrophication and the socially controversial limits to the harvest of reef organisms.

While it is the large industrialized countries that drive man-induced climate change, it is the small island developing states (SIDS) and small coastal states that will suffer the most from climate change. In this respect it may be especially valuable for the BES islands to develop and participate in larger efforts to convince (pressure, lobby) the large industrialized nations to adopt those changes needed in their industrial and energy policies by which to avert the most disastrous scales of global climate change. As the stakes are obviously very high, the BES islands should seek to actively develop and/or participate in such efforts. However, to do this credibly and convincingly will require the islands to develop their own vision and policy and to implement important measures of their own. While the topic of climate change has recently come to the attention of government, preparation and readiness for climate change lags behind.

The main options for local adaptation measures as outlined all come down to just one principle: to 'manage for resilience' of the ecosystems as much as possible by reducing the stress induced by local anthropogenic pressures. This will require proper data and knowledge as well as a proper monitoring of impacts and results. In this, investment in baseline inventories, dedicated research and a monitoring system is essential.

If international resolve falters and precipitous global climatic change cannot ultimately be avoided, large ecological regime shifts may cause ecosystems and species in any given area to become ecologically untenable, and introduced species to become firmly established and impossible to eradicate. If so, it will be important to make hard choices and not waste valuable time and resources fighting lost causes. Therefore, in

the future successful management of natural resources will often require managers and decisions makers to think differently than in the past, to abandon old paradigms and objectives, and to focus more on general ecosystem services than on specific details. Hence our ability and willingness to adaptively 'manage for change' will be critical, as will be the need for effective decision making under conditions of complexity, uncertainty and imperfect knowledge.

1 Introduction and approach

The habitats of the Dutch Antilles are very diverse; they vary from coral reefs, sea grass beds, mangroves and salt ponds, to evergreen coastal woodland vegetations and lush mountaintop elfin forests. Basic biological inventories have been conducted for all islands, including the three discussed here: the BES islands, Bonaire, St. Eustatius and Saba (e.g. Rojer 1997a, b; Freitas et al., 2005).

The islands form part of the Caribbean global biodiversity hotspot area (Myers et al., 2000; Roberts et al., 2002) on the basis of their species richness and high level of endemism. The leeward Dutch islands alone possess some 200 endemic species and subspecies (Debrot, 2006a) and the three islands count over 120 species that are on the CITES appendices.

Compared to larger countries, the impact of climate change on small island nations will be far larger, considering their vulnerability and low capacity to adapt (IPCC, 2007c; Clarke, 2008; FAO, 2008). For instance, the predicted increase in average air temperatures will exert pressure on the energy sector and affect agricultural production, public health and coral reef health as sea surface water temperatures rise concomitantly.

The economy of the Dutch Antilles depends for a large part on tourism (Petit and Prudent, 2008) and tourism on its turn for a large part on the natural capital of the islands (UNEP, 2008). Impacts of climate change on biodiversity will therefore also have important economical consequences. The Bonaire reef is for instance one of the best-preserved reefs in the entire Caribbean, with more than 340 observed fish species, because it has not been devastated by successive tropical storms. The Saba Bank is the largest atoll in the Caribbean Sea and one of the largest in the world. It is characterised by extensive coral reefs and the relative isolation of the Saba Bank has protected it from much human influence and therefore they are among the least disturbed reefs in the Caribbean.

On the basis of the present scientific knowledge regarding global climate, emission scenarios based upon prognoses of world population and economic growth, the IPCC has developed scenarios of future climate development during this century using sophisticated climate models.

The most important consequences that can be expected based on these scenarios (lowest and highest estimates across scenarios, (IPCC, 2007a)) are that:

1. Average air temperature will rise between 1.1 to 6.4 °C.
2. Precipitation will increase in some but decrease in other parts of the world.
3. Global mean sea surface level will rise by 18 - 59 cm.
4. Ocean acidity will rise by 0.14 - 0.35 pH units.

For small islands, a number of possible impacts with serious consequences for biodiversity as well as human activities can be listed. Varying extremes of drought and rainfall will impact groundwater in terms of both quantity and quality. This will have various repercussions for nature, agriculture and horticulture and exacerbate erosion problems. A predicted sea level rise of up to 5mm per year will stress low lying coastal development and put coral reefs, mangroves, saline ecosystems and infrastructure at increased risks for hurricanes, cyclones and storm surges. The strength and frequency of hurricanes may increase as well, placing fragile coastal ecosystems at even more risk. Beaches, an important touristic asset used by man for recreation and by endangered turtles for nesting will erode, thereby impacting both nature and economy. Groundwater resources of fresh water will experience salinification.

Impacts on the marine environment follow from the increase of CO2 concentrations in air and sea, and are the acidification of the oceans, changes in sea surface temperature (SST), and greater dynamics in weather conditions. Climate change and resulting desertification may even affect the Caribbean sea through input of nutrients (particularly iron) that enter the pelagic system via Sahara dust (Garrison et al., 2006; Prospero and Nees, 1986). The precise consequences of these impacts for ecosystem change are not yet clear. However, they may be far reaching and include coral bleaching, diseases, changes in ocean currents and patterns of fish migration and recruitment. Increased ocean acidity will for instance reduce calcification in corals and may even threaten their existence (IPCC, 2007c; Silverman et al., 2009). Since the drivers for these changes are global, local measures will not result in less local impact but may very well serve to reduce ecosystem vulnerability and improve resilience.

In this report the risk that climate change poses to the unusual and extremely important biodiversity of the islands, both in terms of ecological and economical sustainability, are assessed in more detail. In the first section the expected climate change characteristics are described. These are essentially based on the IPCC scenario's, extended with the information available for the Caribbean area. The following description of climate change impacts first evaluates the possible effects of the different climate change pressure factors separately, and then evaluates their possible combined impacts on the islands' vulnerable ecosystems and species. The assessment of impacts is based on a combination of the available information on small islands and the Caribbean area in general and as much specific information on the islands as we could obtain within the limited framework of this project.

2 Predicted climate changes for the Caribbean region

The Caribbean climate in general
The Caribbean climate can be broadly characterized as a tropical climate with dry/wet seasonality. Storms and hurricanes represent the main rainfall source in the Caribbean, as modified at the sub-regional level by orography and elevation (IPCC, 2007b).

Expected climate changes for this century
Air and sea surface temperatures
According to the Small Islands section of the IPCC fourth assessment report, temperatures in the Caribbean region are expected to increase between 1.4 to 3.2 °C this century (local estimates according to A1B scenario; IPCC, 2007b). Since air temperature and sea surface temperature for coastal areas and small island states are closely related, the predicted increases for both are the same (IPCC 2007b; Simpson et al., 2009).

Sea level rise
IPCC estimates a global average sea level rise (SLR) between 0.18 and 0.59m (lowest and highest estimates across scenarios, IPCC 2007a) by the end of this century, with an expected rise for the pacific around the average. However, an UNDP report on modelling climate change impact in the Caribbean region (Simpson et al., 2009) states: *'….. while most studies predict sea level rises in the order of around 1m this century, any departure from the current and projected rate of rise or ice sheet response would make such a prediction an underestimate (Milne et al., 2009). Therefore, it might be prudent to plan for several meters of sea level rise by the end of the century'.* According to the same report the rise in the Caribbean could, due to geophysical reasons, be up to 25% larger than the global average. The Dutch Delta Committee report (Deltacommissie, 2008) adopts a maximum SLR of 1.3 m as the standard on which adaptation measures in the Netherlands should be based. For the BES islands it therefore seems prudent to adopt the same standard with a 25% increase and take a maximum SLR of around 1.6m as a base for the assessment of possible impacts and required adaptations.

Ocean acidity
The estimate for the increase in ocean acidity for the Caribbean region is the same as the global one which is a decrease in pH units of 0.14 to 0.35.

Tropical storms and hurricanes
Globally a likely increase (> 66%) in hurricane intensity with larger peak wind speeds and heavier precipitation (IPCC, 2007b) is predicted. Storm surge height is associated with hurricane intensity and is therefore also likely to increase. The range of inundation and capacity for coastal erosion will increase even more as the sea level rises. The same will be true for tsunamis (Simpson et al., 2009).

Precipitation
There are no clear predictions for the region, although most models predict a decrease in summer precipitation in the Greater Antilles (IPCC, 2007b).

Extreme weather events (floods and droughts)
The number of flood events is expected to increase; the picture for droughts is unclear regionally.

3 Possible impacts on the BES islands and the consequences for biodiversity

3.1 The islands

Together with Curacao and Aruba, Bonaire makes up the leeward islands of the Dutch Antilles. The three islands are located in the South-Eastern part of the Caribbean, of the coast of Venezuela. The islands lie in a climatologically unique part of the Caribbean. Besides being much drier, the main rain season is in the winter (Oct-Jan), whereas in most of the region it falls in summer (May-Oct) (Martis et al., 2002). Due to this the islands have a rare and unique flora and vegetation (Beers et al., 1997, Freitas et al., 2005). In Petit and Prudent (2008), Bonaire is described as relatively flat and arid, and home to cacti, acacia trees and thorny plants, but also to mangroves and salt marshes. Bonaire's marshes are home to an important population of West Indian flamingos (De Boer, 1979) and possess regionally important tern breeding populations (Debrot et al., 2009). The island also has one of the best preserved reefs in the entire Caribbean and the entire coastal zone up to a depth of 60m is included in the National Marine Park of Bonaire.

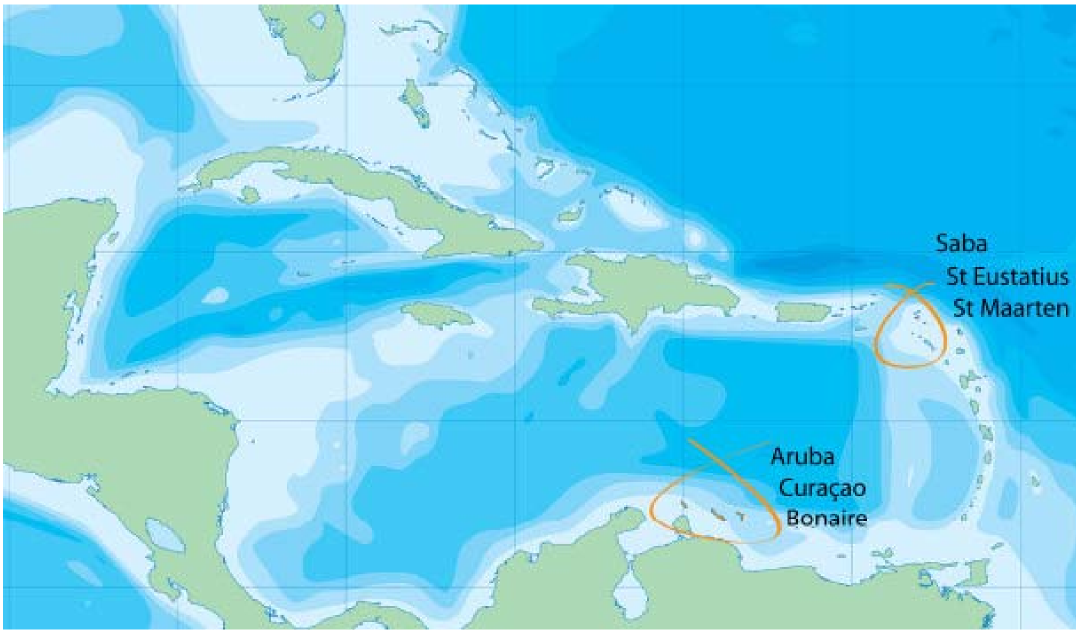


Figure 1
The location of the Dutch Antilles (STENAPA ,2009).

St. Eustatius and Saba belong to the windward Islands which are of volcanic origin and have rugged, lush mountainous landscapes. The climate is more humid and more subject to tropical storms than in the Leeward Islands. The Islands host cloud forests and high altitude tropical rain forests with unique bird species and rare epiphytes.

On the South-East end of St. Eustatius lies a huge dormant volcano with humid forest swathed in clouds. The hilly northern part of the island, with a much drier savannah-like climate, has a completely different flora and fauna. The water surrounding the island contains a network of well preserved patch reefs with a.o. black coral, sea horses and several species of sea turtles. Zeelandia beach is a protected sea turtle nesting site.

Figure 2
Bonaire (Google Earth).

Figure 3
Saba (Google Earth).

Saba is basically the peak of a dormant volcanic cone, topped by lush primary and secondary rain forest. The highest point is 870m above sea level. Located 11km from the island, Saba bank is a large submerged mountain rising from 1800m below sea level to 30m below the sea surface. It is the third largest atoll in the world and the largest in the Caribbean and has a unique flora and fauna with over 200 fish species of which several previously unknown and as many as 20 newly discovered marine plant species that may also be new to science (Lundvall, 2008). Saba National Marine Park includes the whole coastal zone of the island and contains about 13 km^2 of pristine coral reef in the zone between the high tide mark and a depth of 60m.

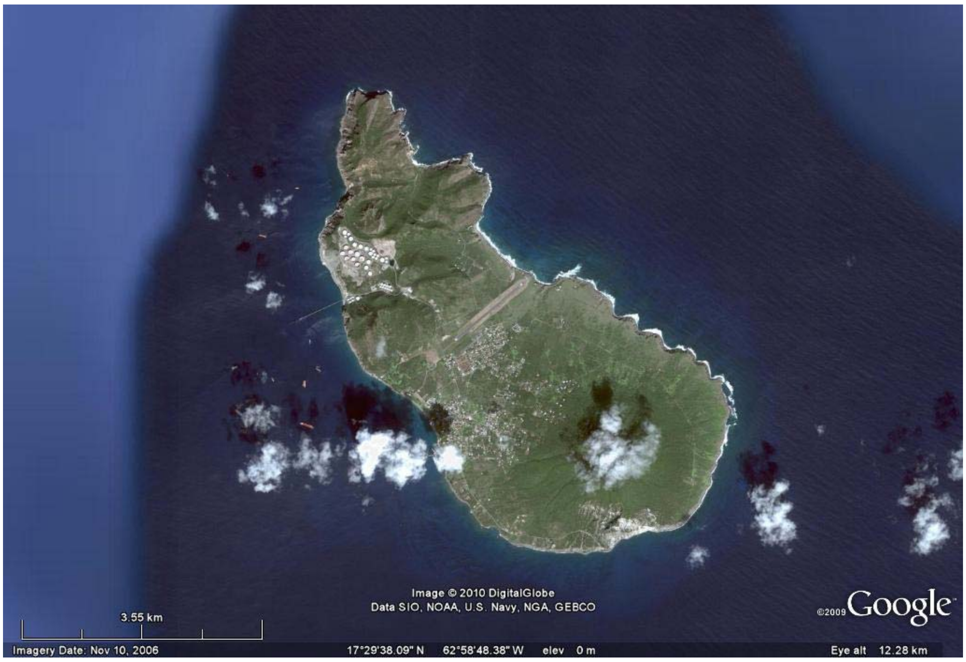


Figure 4 St Eustatius (Google earth).

3.2 Possible impact of pressure factors resulting from climate change

The possible impacts are discussed separately for the marine and terrestrial (including fresh water) environments.

A) Increase in temperature of air and sea surface

Terrestrial impacts

a) Decline of mountain vegetation

Montane vegetation on all islands depends for its water largely on condensation when warm humid air is pushed up slope to reach its dew point. Thanks to this process of 'adiabatic cooling' the upper slopes of the islands often have a much more lush vegetation than the areas below at sea level. Plants common here include ferns, bromeliads, mosses and orchids (e.g. Stoffers, 1956; Freitas et al., 2005). The Caribbean has already become warmer and drier (Peterson et al., 2002) and that trend is expected to continue. When air temperature rises, so will the height at which rising air reaches its dew point. Every degree of temperature coincides roughly with 100 meters of altitude. Montane altitude and habitat surface area is very limited and the species requiring montane special conditions can only 'migrate' upwards to a limited extent. This means that the most lush montane vegetations of the islands and the many species contained therein will be reduced or disappear altogether. The greatest impact can be expected on Saba and St. Eustatius where the elfin forest will be at greatest risk. However, rare hilltop habitat and species on Bonaire will be at risk as well.

Figure 5
Lichens (hanging from trees), ferns and orchids growing on hilltops in Bonaire will experience difficulties (Photo: A. Debrot).

b) Reductions in soil humus

Humus (partially broken-down organic material, principally from leaf fall) plays an important role in soil water retention, and its preservation in soils is critically affected by environmental temperatures. Increased air temperatures will negatively impact humus retention capability of soils and can thereby negatively influence both natural vegetations and agriculture. All three islands are potentially vulnerable.

c) Potential increase in diseases

Increased temperatures affect life cycle times in disease vectors and can increase the risk of tropical diseases that affect man and nature. Young animals and plant seedlings are generally known to be more vulnerable to heat stress than larger adult animals. An increase in heat stress may impact reproductive success in plants and animals and also make them more vulnerable to various kinds of disturbance. All three islands are vulnerable.

d) Changed timing for interactions

A general risk resulting from climate change is the risk of critical changes in the timing of interactions between species, for instance between pollinators and seed dispersers and their host species. Also, seasonal food availability for species may be affected or food plants may decrease or disappear. This extra stress factor might particularly endanger species of the elfin forests on Saba and St. Eustatius where the largest changes can be expected. On Bonaire, for example, the endangered yellow-shouldered parrot (*Amazona barbadensis*) is very much dependent on crops of candelabra cacti and pods of the tree *Prosopis juliflora*, for reproduction and in the dry season. Island wide mortalities have frequently been caused by food shortages during prolonged droughts (Voous, 1983).

e) *Potential increase in invasive species*

The Global Invasive Species Programme (GISP) considers invasive species to be the single largest threat to biodiversity in island ecosystems (GISP 2008). Climate change, and in particular increasing temperatures, may enhance the opportunity by non-native species to become invasive because the resistance of the original ecosystem against them is weakened while conditions for invasive species improve. Although islands are by their nature not very susceptible to invasions, the increased international trade, sea and air traffic and tourism make them increasingly reachable and vulnerable. Also, a change in wind patterns could lead to the spread of wind-born invasive species (Petit and Prudent, 2008).

Figure 6

Invasive plants: rubber vine, Cryptostegia grandiflora, (big shiny leaves) and corallita, Antigonon leptopus, (pink flowers), Saba (Photo: A. Debrot).

f) Changes in ocean currents may change food availability for some shore and sea birds

Changes in climate and weather can potential influence ocean current with a possible disastrous effect on food availability for sea birds. See also the same point in the next section on marine effects.

Marine impacts

a) *Coral bleaching and disease*

Increased water temperatures of oceans resulting from global warming can have huge effects on reef ecosystems (e.g. Crabbe, 2008). The most direct evidence of the impact of climate warming on Caribbean marine biodiversity has been widespread 'bleaching' of its reef-building corals (Donner et al., 2007), also in the Dutch Caribbean (e.g. Lundvall, 2008; Nagelkerken, 2007). Bleaching refers to the loss of a coral's natural colour (often hues of green and brown) caused by the expulsion of symbiotic algae (zooxanthellae). This leaves the coral very pale to brilliant white in appearance. Bleaching, which leaves the coral vulnerable without its symbiotic energy source, can be a response to many different stresses, including salinity changes, excessive light, toxins and microbial infection. However, increase in sea surface temperature (SST) is the most common cause of bleaching. Bleaching reduces coral resistance to diseases, growth and regeneration capabilities (Meesters and Bak, 1993).

b) *Oxygen depletion (fish mortalities, dead anoxic deep sea)*

Beside mortalities in corals, in recent years also several outbursts took place of localized and even regional reef fish mass mortalities (Buurt, 1981a, b,; Williams and Bunkley-Williams, 2000). Most often, several to a whole range of reef species are affected, among which commercially valuable species. Mass mortalities appear to be most common during the warm third and fourth quarters of the year (Debrot, unpublished data). In Curacao, localized fish mortalities are common during the hot dry season in areas with restricted water flow, such as coastal lagoons, which serve as nursery habitat for many species. With higher temperatures, oxygen depletion in such areas with restricted water flow will exacerbate, leading to even more frequent fish mortality.

c) Increase in diseases

Perhaps the most profound and widespread changes in Caribbean coral reefs in the past 30 years have been caused by diseases of corals and other organisms (Williams and Bunkley-Williams, 2000). In recent decades, an unprecedented array of new diseases has emerged, severely affecting coral reefs. The reasons for this sudden emergence and rapid spread of reef diseases throughout the Caribbean are not well understood. Possibly bleaching may affect coral resistance to diseases (Meesters and Bak, 1993; Croquer and Weil, 2009). Diseases have been observed all across the Caribbean, even on the most remote coral reefs, far from islands influence. 'Black-band, 'white-plague diseases' and 'yellow blotch (yellow-band)' syndromes are most frequent infections. These infections are alarming as they can infect different species, spread fast and typically result in the death of the affected corals. Especially *Acropora* species in the Caribbean have been decimated. This may be related to temperature stress, whether or not associated with global climate change. Other stresses such as high nutrients and sedimentation may similarly alter the balance between the coral and its resident microbial flora (Harvell et al., 2007).

d) Population blooms of poisonous organisms

In recent years several localized and even regional outbursts of reef fish mass mortalities (Buurt, 1981a, b; Williams and Bunkley-Williams, 2000), possibly caused by botulism poisoning or other disease agents. Again, within the EEZ, the principal area for which coral reef fish mortalities are a concern is the Saba Bank. As ecosystems are destabilized, swarms of predator resistant and undesirable reef species will occur more frequently (e.g. Debrot and Nagelkerken, 1997).

e) *Changing current flow: impact on fish recruitment and migrations*

The coral reef ecosystems of the Dutch Caribbean depend on clear, nutrient poor sea water. Most reef organisms further experience a sensitive larval stage in which they are dispersed via currents. The current patterns in the Caribbean have been persistent oceanographic features, important in providing ecological connectivity within and between areas and habitats dispersed throughout the region. Ecological connectivity for coral reefs is an emergent field of study and is not well understood but certainly critical to all aspects of ecosystem health. Changes in climate and weather can potentially impact currents in terms of either direction or speed and may have unprecedented effects on the ecosystems which depend on them. It could for instance affect the southern Caribbean wind-induced upwelling upon which the Venezuelan sardine fishery, the largest fishery of the Caribbean, is based (Sturm, 1991). This in turn could have economic and ecological consequences in terms of fish migration and the protection of cetaceans in the southern Caribbean.

B) Sea level rise

Terrestrial impacts

a) Salinification of groundwater.

Salinification, driven by freshwater extraction, has been previously described as a serious problem in the Dutch Antilles, for Curacao, and has had long lasting consequences for the vegetation and on agriculture (Henriquez, 1962). The groundwater fed water systems of Bonaire have been described as of generally poor quality (Grontmij and Soghrea, 1968; Rowbottom and Winkel, 1979), but harbour rare, significantly endemic crustacean and freshwater fish fauna, including IUCN Red List 'vulnerable' species *Typhlatya monae* (Debrot, 2003a,b; Hulsman et al., 2008). This fauna is opportunistic and able to survive at varying salinities but may be vulnerable to large scale intrusion of saltwater. Many important habitats with evergreen vegetation, especially in the low-lying southern part Bonaire (Freitas et al., 2005) may get lost or greatly altered.

b) Coastal erosion and inundation

Low-lying coastal infrastructure and habitats will be at increased risk from extreme ocean conditions, including the RAMSAR and IBA flamingo habitat in south Bonaire and the industrial salt works (Wells and Debrot, 2008). See also the next section on marine effects.

Because of their character as high volcanic islands, and the fact that little infrastructure is located close to the shore, Saba and St. Eustatius will be less vulnerable to sea level rise. However, the already existing coastal erosion problems (Debrot and Sybesma, 2000) will be increase for both islands and the port facilities will experience greater hurricane risk.

Figure 7
Beach erosion due to loss of shallow reefs leaves historic plantation buildings like those of Washington Slagbaai Park on Bonaire vulnerable. In 1999 waves from distant hurricane Lenny devastated the plantation complex and it had to be rebuilt (Photo: A. Debrot).

Marine Impacts

a) Coral reefs

The Coral reefs of the Netherlands Antilles are zoned benthic communities and form an important coastal defence against waves. They are already quite vulnerable to extreme weather (Meyer et al., 2003; Bries et al., 2004) and will only become more so with greater water depth in shallow areas.

Figure 8
Species-packed reefs of Bonaire (Photo: D. Slijkerman).

b) Mangroves

In the Dutch Antilles, mangroves are found in protected waters at the edge of land where fresh surface and groundwater enters the sea and where salinity is not excessive. They are likewise vulnerable to sea level rise and can be expected to die back with rising water levels. Mangroves are not found in Saba or St. Eustatius due to the absence of wave-protected habitat. In Bonaire they are practically only found in Lac Bay.

The mangrove forests on Bonaire are currently severely threatened by increased sedimentation due to agricultural practices (Debrot, Meesters and Slijkerman, 2010). Basically, an increased sedimentation can help mangroves to adapt to a sea level rise, but the current rate is much too large.

c) Beaches

Both St. Eustatius and Bonaire possess important sea turtle nesting sandy beaches. Four species of turtle nest on these islands (Leatherback turtle, Green turtle, Hawksbill turtle and Loggerhead turtle). These beaches will experience increased erosion and put these endangered species even more at risk.

Figure 9
Nesting green turtle (Photo: A. Debrot).

d) Salina flamingo foraging habitat
Bonaire possesses important flamingo nesting habitat in the form of natural and semi natural saline lagoons known as 'Salinas'. These provide food for flamingos based on their annual cycle of salinities ranging from brackish to hypersaline conditions, as required for healthy populations of brine shrimp and brine fly (De Boer, 1979). Leaky salinas (with a too large inflow of seawater) do not produce effective hypersaline conditions. Therefore sea level rise will threaten the functioning of these flamingo feeding areas.

C) Increasing ocean acidity

The increase of atmospheric CO_2 is accelerating as a result of worldwide human activities. CO_2 is taken up by oceans, leading to lower pH, and this lowers the saturation of carbonate and magnesium minerals. These minerals are needed for the skeletons of many marine organisms, such as corals and shells (Kleypas et al., 2006). Recent measurements suggest that increasing temperature stress and a declining saturation state of seawater aragonite may be diminishing the ability of corals to deposit calcium carbonate (De'ath et al., 2009; Bak and Meesters, 2009). This is troubling because one of the important ecosystem functions of coral reefs is defence of the coastline. With reduced growth rates, mortalities due to disease and bleaching, and increased damage by severe weather, the likelihood that coral reef accretion will keep up with sea level rise and continue to protect the shoreline decreases. This is especially important for the mangrove forest in Lac bay on Bonaire, which now largely depends on a coastal reef for its protection against hurricane damage.

Ocean acidification is due to world wide CO_2 emissions, and cannot be solved by local management plans. Local species however respond in different ways to acidification. Therefore, at the local level, an important goal for management is to help optimize the natural resilience of the ecosystem (Hoegh-Guldberg et al., 2007; Hoegh-Guldberg et al., 2008). By increasing ecosystem resilience, environmental perturbations will less likely lead to ecosystem collapse and ecosystem components will more quickly recover from adverse impacts.

D) Change in power, frequency and pattern of hurricanes

Hurricanes are among the most powerful storms on earth and can cause large scale destruction to nature. Saba and St. Eustatius are located within the hurricane belt and hurricane conditions are experienced on the average once every 4-5 years. For the leeward Dutch islands, including Bonaire hurricane frequency is much lower and occurs roughly once every 100 years (Meteo, 2010). Nevertheless, it appears that in recent years the 'hurricane belt' is moving south, which places the Leeward islands and also Bonaire at increased hurricane risk.

Terrestrial impacts

a) Impact on forests

Hurricanes can severely damage tropical forests (Basnet et al, 1993; Lugo, 2000) and with a predicted increase in force and possibly frequency recovery time will diminish. Combined with the other climate change pressures, this can have devastating effects on the elfin forests of Saba and St. Eustatius.

b) Impact on coastal systems

Combined with sea level rise and the resulting diminishing protection from coastal reefs, the effect of hurricanes on coastal systems is expected to increase considerably (a.o. Petit and Prudent, 2008). Beach erosion is one of the main problems, which on BES islands can especially affect sea turtle nesting grounds. The other impacted system is the mangrove forests, which is discussed in the next section.

Marine impacts

Hurricanes and tropical storms are the most frequent natural pressures affecting reef ecosystems (Gardner et al., 2005). They constitute a defining factor in the structuring and functioning of marine and coastal ecosystems, and are always an important factor to include when evaluating reef ecosystems. Hurricanes are natural events from which coral reefs can recover, if the ecosystem is resilient enough. However, even in best case scenario's, recovery of severely damaged reefs may take a decade or more after the fiercest storms. The windward Dutch Caribbean is impacted frequently while the Leeward Dutch islands are impacted less. Hurricanes are devastating to the reefs of the Leeward Dutch islands (Bries et al.; 2004). Climate change is believed to ultimately result in an increase in the number and magnitude of hurricanes and their impact on reefs is likely to increase. This is especially a risk to the Bonaire reef, which is at this moment one of the best preserved in the entire Caribbean due to the low frequency of hurricane damage (Petit and Prudent, 2008: DCNA, 2008).

Figure 10
Hurricane Lenny impacting the shore of Curacao, November 1999. (Photo: H. Goilo).

E) Increased variability in rainfall and drought

Terrestrial impacts

a) Phenology of ecological processes confused

When seasons change there is a possibility that plants will fruit and flower at the wrong time and thereby waste energy and nutrients on aborted flowers and fruit set. While both animals and plants oftentimes react opportunistically in the tropics due to less pronounced seasonality, many animals appear to cue their reproduction to periods of special food availability. These may include the flamingo, the endangered Bonaire yellow-shouldered parrot, and the rare barn owl of Bonaire, as well as raptors such as the caracara and the white-tailed hawk. If these animals have young at a time when they have miscalculated the food supply, then reproductive success may be compromised. At present it is unclear if species can adapt.

b) Plant and animal mortalities due to droughts and flooding

More plants will be at risk due to either excesses or shortages of water. Periods of prolonged droughts take their toll, just as periods of excess rain fall when tree roots get waterlogged and loosened or die, causing large trees and columnar cacti to topple over. Unpredictable excesses of rainfall will result in more flooding and potential destruction of flood control infrastructure (especially dams), and result in less effective penetration of groundwater, more runoff, increased erosion, and even dust which is already an environmental hinder to man in Bonaire but with unknown effects on nature (Nolet and Van der Veen, 2009).

c) Increased fire risk due to drier conditions

Increased fire risk is a general threat resulting from long dry periods. Although nothing specific for the Caribbean region was found, increased risks will certainly apply to the lower regions of all three Islands. Moreover, the upward shift of the rain forest zone due to general temperature increase that is expected on Saba and St. Eustace will probably result in a very significant expansion of the dry zone vulnerable to fires.

d) Insufficient recovery time between extreme weather events

In general, an increase in extreme weather events decreases recovery time for all ecosystems. Effects will especially apply to the ecosystems that are already stressed due to other pressures.

Marine impacts

Sedimentation impacts on coral reefs

Extreme rainfall, especially in combination with a preceding drought, will cause an extreme increase in terrestrial run-off. The coral reefs are particularly vulnerable to the sediment that runoff entails (Rogers, 1990). While the Saba Bank has no adjoining terrestrial habitat and is therefore not vulnerable to terrestrial runoff or groundwater leaching, the coastal reefs of all three islands are vulnerable and impacted by sedimentation.

4 Possible adaptation measures

Many of the global changes expected on the basis of climate change predictions are beyond the direct control of small island nation. Nevertheless, anticipating the changes ahead, it is possible to prepare for some of them. Critical is to enhance ecosystem resilience by reducing as much as possible local sources of anthropogenic stress.

Key policy areas impinging on climate change issues include industrial, energy, transportation, and public heath, as well as environmental policy. Key areas of environmental policy in turn are

- Land-use planning and zoning
- Forestry and terrestrial conservation policy
- Marine conservation policy

Land-use planning and zoning

Implement coastal setback policy
Sea coasts are highly dynamic and infrastructure placed close to the sea often runs the risk of being destroyed during severe weather and washed onto the reef. Human construction in the shore zone further disrupts and stresses many natural features that help to protect the coast, such as reefs, mangroves and dune vegetation. Therefore, more and more, coastal setback, in which buildings and human infrastructure is set back from the coast, is used to reduce and avert economic and environmental risks (IUCN, 2007; UNESCO, 2010). Furthermore, the coral reefs of the BES islands are generally distributed in a narrow band along the coasts of the islands. This even means that the coast forms an integral part of the reef landscape that also serves an important corridor function for animals that use both the land and sea (e.g. land crabs, the hermit crab, amphidromous freshwater fishes and shrimp). Incorporating the mitigation of coastal setback into land-use planning and zoning is a simple tool to greatly reduce ecological and economic risks.

Preserve the full diversity of habitats
Ecological functioning and resilience depends on preserving all habitats that organisms in a community need during their life cycle. Therefore, land use planning and zoning should seek to preserve the various representative habitats. Identification and description of the critical habitats, and where they are located is an essential prerequisite. In this, vegetation maps for terrestrial areas are critical. However, only for Bonaire is vegetation map available (Freitas et al., 2005). Preliminary work on vegetation maps for Saba and St. Eustatius has been done but needs to be completed.

Preserve sufficient area of each habitat type
To support minimum viable populations (MVP's) of endemic and endangered species it is not only necessary to provide all the various habitats, but also sufficient habitat to sustain genetically viable populations (Soule and Simberloff, 1986). Not only can MVP's vary from species to species, but the habitat requirements per individual species also vary greatly, depending especially on size of the animal, territorial behaviour and the likes.

Ensure habitat connectivity
In addition to preserving sufficient of each habitat, it is also critical for these habitats to be well connected to each other so that ecological processes can function. In the design of conservation areas it is therefore important to cluster the habitats together in large areas, in this way voiding borders as much as possible (Soule and Simberloff, 1985). In other areas connectivity can be achieved through implementation of corridors.

Forestry and terrestrial conservation policy

Control feral grazing

Feral grazing is a serious problem on all three BES islands (Coblentz, 1980; Brink, 1998; Debrot and Sybesma, 2000, Freitas et al., 2005). Even though it is illegal to let livestock roam freely, this has become the accepted practice on all three islands. Loose animals, principally goats, and on Bonaire also donkeys, roam uncontrolled and without limit. The animals damage the vegetation, enhance erosion, generate dust and cause a loss of topsoil, raid gardens and constitute a hazard to traffic. On the isle of St. Eustatius measures are being taken now to reduce the number of free ranging animals. Invasive species, such as the rubber vine, *(Cryptostegia grandiflora)* on Bonaire, and Saba, and corallita, (*Antigonon leptopus*) on Bonaire, Saba and St. Eustatius are strongly associated with disturbance by man and livestock (Winkel, 2003). This is a most serious terrestrial conservation issue on all three islands and has wide economic and ecological consequences. It greatly impairs the ecological resilience of ecosystems, which is the best hope against climate change. On Bonaire a large part of the flora is threatened with extinction in the coming decades if this issue is not dealt with.

Reforestation and freshwater conservation

Reforestation has been done successfully on Curacao and Bonaire in recent years using simple and inexpensive methods. It can be used to replenish endangered species, tackle erosion problems, restore ecosystem functioning, and as a basis for agroforestry (Debrot, 2009a). An economically integrated reforestation plan has been developed for Saba and presented to the Saba island council (Debrot, 2006). Particularly in the rural areas of Bonaire damming water has always been an important tool in agriculture to conserve water and stimulate water penetration into the ground.

Marine conservation policy

Eutrophication

Coral reefs are very sensitive to nutrient enrichment. Several studies have been done to this aspect in the Dutch Caribbean (Gast et al., 1998, 1999; Duyl et al., 2002). Measurements on Bonaire indicate that nutrient enrichment of coastal waters due to seepage of wastewater from the urban area of Kralendijk is a true menace to coral reef development. Based on this, a sewage treatment system is under construction to treat most waste water.

Overfishing

Coral reefs are extremely sensitive to overfishing (Roberts, 1995b) and can hardly support even subsistence level fishing (Coblentz, 1997). Overfishing in these islands, including Bonaire and the Saba Bank has led to the disappearance of large groupers (Debrot and Criens, 2005; Toller et al., 2010) like the Nassau grouper and the Goliath grouper, many of which are now regionally threatened. This overfishing may make the reefs vulnerable to invasive species such as, *Pterois volitans*, the lionfish, which is now spreading rapidly on the reefs of Bonaire, Saba and St. Eustatius.

Aside from laws against spear fishing, there are virtually no other controls on fishing effort, methods, or target species on any of the three islands. Such measures are dearly needed in support of conservation and fishery management. Most effective are the use of marine reserves (Roberts et al, 2001, 2005), the Saba Marine Park has been successful (Roberts, 1995a). The data needed for assessment of fish reserves are limited and they are easy to enforce and for fishermen to understand. Bonaire has recently introduced this concept to the BES.

5 Synthesis and conclusion

Our present state of knowledge makes it perfectly clear that climate change not only poses a severe threat to the ecosystems of the BES islands, but also to the benefits the inhabitants derive from them, especially in the form of coastal defence and income from tourism. Climate change pressures do not have a local origin and can therefore not be reduced by local efforts. However, the main problem for ecosystems in coping with these pressures is that the systems' adaptation capacity is or could be insufficient. About the only way open to locally reduce the risk of damage is to invest in improving the adaptation capacity, which can be achieved by reducing other (local man-induced) pressures as much as possible.

The general options for reducing pressures on the most valuable and vulnerable ecosystems and are synthesized below.

i) Coastal zones

The mangrove forest and salt pans on Bonaire, the Flamingo and Sea turtle populations and the coastal reefs on Saba and Bonaire are all mainly threatened by the combination of sea level rise, increased force and frequency of hurricanes and pressure from (over-)exploitation of coastal and agricultural ecosystems. mangrove forests can however possibly keep up with sea level rise and, when sedimentation rates are reduced. If their adaptive capacity is indeed optimal, both systems could therefore take away much of the risk to themselves and also to other sectors because they would then retain their coastal protection capacity. To achieve this adaptive capacity should be maximized by reducing the main local stresses, specifically those induced by sedimentation and nutrient enrichment. To maximize the adaptation to sea level rise of the mangrove forest, a certain degree of sedimentation is probably required. However, in the present situation, a far too high sedimentation rate is one of the largest threats to the forest. But careful management and monitoring, backed up by research can possibly optimize the sedimentation rate for adaptation and maximize resilience. The salt marshes and salt pan system on the other hand clearly need to be adapted by investments in their infrastructure.

ii) *Coral reefs*

The coral reefs in the area are at this moment still relatively undamaged and well preserved, and are therefore extremely important for biodiversity as well as responsible for a large part of the income from tourism (Bueno et al., 2008). However, coral reefs will experience increasing stress from sea level temperature and increase in acidity and will therefore need the largest possible reduction in pressures from other sources to keep their capacity to adapt and to recover from extreme events as hurricanes intact. The main options to do so are again a reduction of the sedimentation and nutrient inflow, coastal building setback as well as the reduction of fishing.

iii) *The forests on Saba and St. Eustatius*

The elfin forests of Saba and St. Eustatius will mainly suffer from the general increase in temperature that will drive them uphill, but will also be threatened by higher occurrence of weather extremes like droughts and hurricanes, invasive species and probably by a higher fire risk in the lower regions. The combination of these factors will make the forest extremely vulnerable and, again, the only possible adaptation measure is to reduce other stress factors like feral grazing, reduction of water availability, erosion and commercial exploitation as much as possible in order to keep their resilience as high as possible.

iv) Bonaire's terrestrial nature

On Bonaire, being lower and much drier than the other islands, salinification of ground water, an increased fire risk during droughts and erosion due to extreme rainfall probably are important extra risk factors to the terrestrial systems. All three can basically be reduced by proper land and water management and by the reduction of (over) exploitation of resources by mainly agriculture and animal husbandry practices.

General conclusions

While it is the large industrialized countries that drive man-induced climate change, as indicated previously, it is the small island developing states (SIDS) and small coastal states that will suffer the most from climate change (IPCC, 2007c; Clarke, 2008; FAO 2008, Mertz et al., 2009). Whole nations in the Pacific will likely be flooded and even cease to exist. In this respect it may be especially valuable for the BES islands to develop and participate in larger efforts to convince the large industrialized nations to adopt those changes needed in their industrial and energy policies by which to avert the most disastrous scales of climate change. As the stakes are obviously very high, the BES islands should seek to actively develop/participate in such efforts. However, to do this credibly and convincingly will require the islands to assess and model the risks and consequences to greater detail and to implement important measures of their own. Lately the government of the Netherlands Antilles, has been giving some attention to the topic of climate change in the form of inquiries (e.g. Debrot, 2009b), participation in regional conferences (e.g. DBB, 2009) and by preparations to install a national interdepartmental climate change commission (ICK, NA, 2010). Nevertheless, as is the case for developing countries in general (Mertz et al., 2009), the islands still lag far behind in their preparation and readiness for climate change, certainly as compared to their kingdom partner The Netherlands (De Bruin et al., 2009).

The main threat climate change poses to the biodiversity of the BES islands is obviously to the coral reefs which have great global importance for biodiversity protection as well as local importance for economy and coastal defence. Apart from that, the threats to the elfin forests with their many endemic species, to the mangrove forest of Lac bay and to the populations of specific endangered species like flamingos and sea turtles are of great importance. Options for local adaptation measures all come down to just one thing: to 'manage for resilience' of the ecosystems as much as possible by reducing the stress induced by local pressures. Since biodiversity and local economy and well being are inseparably linked, this will be beneficial for the sustainability of the island's communities as well. However, proper management of the biodiversity of the islands requires proper data and knowledge as well as a proper monitoring of impacts and results. Since there are large gaps in all three, investment in inventories, dedicated research as well as in an extensive monitoring system is recommended.

Nevertheless if, due to faltering international resolve, precipitous global climatic change cannot be averted, improving ecological resilience can only help delay or postpone the inevitable, and will certainly not be sufficient to ensure continued existence of all natural systems or species. In regime shifts, ecosystems and species in any given area may become ecologically untenable, and introduced species may become firmly established and impossible to eradicate. If so, it will be important to make hard choices and not waste valuable time and resources fighting lost causes. Traditional conservation paradigms, based on assumptions of stability and stasis, and past climatic conditions, and the mantra of 'managing for resilience' is more and more proving inadequate and insufficient (West et al., 2009). In the future, successful management of natural resources will often require managers and decisions makers to think differently than in the past, thereby abandoning their old paradigms and objectives, and to focus more on general ecosystem services than on specific details (Baron et al., 2009). The ability and willingness to 'manage for change' will be critical (West et al., 2009), as will be the need for effective decision making under conditions of complexity, uncertainty and imperfect knowledge, by means of an active adaptive learning approach (e.g. Fernandes et al., 2005).

References

Bak, R.P.M., G. Nieuwland and E.H. Meesters, 2009. Coral growth rates revisited after 31 years: what is causing lower extension rates in *Acropora palmata*? Bull. Mar. Scdi. 84(3): 287-294.

Baron, J. S., L. Gunderson, C. D. Allen, E. Fleishman, D. McKenzie, L. A. Meyerson, J. Oropeza and N. Stephenson, 2009. Options for National Parks and Reserves for Adapting to Climate Change. Environmental Management 44: 1033-1042.

Basnet K., G.E. Likens, F.N. Scatena and A.E. Lugo, 1992. Hurricane Hugo: damage to a tropical rain forest in Puerto Rico. Journal of Tropical Ecology 8, 47-55.

Beers, C.E., J. de Freitas and P. Ketner, 1997. Landscape ecological vegetation map of the island of Curaçao, Netherlands Antilles. Publication Foundation for Scientific Research in the Caribbean Region: 138. 54 pp.

Boer, de, B.A. 1979. Flamingos on Bonaire and in Venezuela. Stinapa Doc. Ser. 3., Carmabi, Curaçao.

Bries, J.M., A.O. Debrot and D.L. Meyer, 2004. Damage to the leeward reefs of Curaçao and Bonaire, Netherlands Antilles from a rare storm event: Hurricane Lenny, November, 1999. Coral Reefs 23: 297-307.

Brink, T. van den, 1998. Forestry policies in the Netherlands Antilles and Aruba. In: Forestry policies in the Caribbean, Vol. 2: Reports of 28 selected countries and territories, pp. 395-460. FAO Forestry Paper 137/2. FAO, Rome.

Bruin, K, de, R.B. Dellink, A. Ruijs, L. Bolwidt, A. van Buuren, J. Graveland, R. S. de Groot, P. J. Kuikman, S. Reinhard, R.P. Roetter, V.C. Tassone, A. Verhagen and E.C. van Ierland, 2009. Adapting to climate change in The Netherlands: an inventory of climate adaptation options and ranking of alternatives. Climatic Change (2009) 95:23-45.

Bueno, R., C. Herzfeld, E. Stanton and F. Ackerman, 2008. The Caribbean and Climate Change: The Costs of Inaction. Stockholm Environment Institute - US Center Global Development and Environment Institute, Tufts University.

Buurt, G. van, 1981a. A report on observed recent mortalities in the Netherlands Antilles as they relate to the regional problem. Proc. Ad hoc GCFI Symposium Unusual mass fish mortalities in the Caribbean and Gulf of Mexico: 9-14.

Buurt, G. van, 1981b. The 1980 fish kills in Curacao, Bonaire and Aruba and their relation to the regional problem. Kristof VI-2: 1-8.

Clarke, J., 2008. Review of the Economics of Climate Change (RECC) Project Phase I Activity. Report #2, Draft, Prepared for Economic Commission for Latin America and the Caribbean (ECLAC) Port-of-Spain. 50 pp.

Coblentz, B.E., 1980. Goat problems in the national parks of the Netherlands Antilles. 16 pp.
Coblentz, B.E., 1997. Subsistence Consumption of Coral Reef Fish Suggests Non-Sustainable Extraction. Cons. Biol. 11(2): 559-561.

Crabbe, M.J.C., 2008 Climate change, global warming and coral reefs: Modelling the effects of temperature. Computational Biology and Chemistry, 32(5), 311-314.

Croquer, A. and E. Weil, 2009. Changes in Caribbean coral disease prevalence after the 2005 bleaching event. Diseases of Aquatic Organisms 87(1-2): 33-43.

DBB (Directie Buitenlandse Betrekkingen, Nederlandse Antillen), 2009. Country overview. Proceedings ECLAC Expert Meeting on Climate Change, 13 februari 2009, Barbados. 19 pp.

DCNA, 2008. Dutch Caribbean Nature Alliance, Annual Report 2008. DCNA, Kralendijk, Bonaire. 56 pp.

De'ath. G., J.M. Lough and K.E. Fabricius, 2009. Declining coral calcification on the Great Barrier Reef Science 323: 116-119.

Debrot, A.O., 2003a. The freshwater shrimps of Curaçao, West Indies (Decapoda, Caridea). *Crustaceana* 76: 65-76.

Debrot, A.O., 2003b. A review of the freshwater fishes of Curaçao, with comments on those of Aruba and Bonaire. Car. J. Sci. 39: 100-108.

Debrot, A.O., 2006a. Preliminary checklist of extant endemic taxa of Aruba, Bonaire and Curaçao, Leeward Antilles. Carmabi Report, Carmabi, Curaçao. 28 pp.

Debrot, A.O., 2006b. Reforestation for Saba. Carmabi powerpoint presentation for the Saba island council.

Debrot, A.O., 2009a. Ten years of successful reforestation in Curacao and Bonaire. Carmabi powerpoint presentation.

Debrot, A.O., 2009b. Climate Change in the Dutch Caribbean: Ecological consequences, risks, measures, and recommendations. Presentation to Parliament of the Netherlands Antilles (2009).

Debrot, A.O., C. Boogerd and D. van den Broeck, 2009. Chapter 24. The Netherlands Antilles III: Curaçao and Bonaire. Pp. 207-215. In: P.E. Bradley and R.L. Norton (eds.) Breeding seabirds of the Caribbean. Univ. Press, Florida.

Debrot, A.O., S.R. Criens, 2005. Reef fish stock collapse documented in Curaçao, Netherlands Antilles, based on a preliminary comparison of recreational spear fishing catches half a century apart. 32nd AMLC (Abstract).

Debrot, A., E.H. Meesters and D. Slijkerman, 2010. Assessment of Ramsar site Lac Bonaire. IMARES Wageningen UR report number C066/10, 31 pp.
Debrot, A.O. and I.A. Nagelkerken, 1997. An unusual recruitment swarm of the balloonfish (*Diodon holocanthus*) in the leeward Dutch Antilles, 1994. Car. J. Sci. 33: 284-286.

Debrot, A.O. and J. Sybesma, 2000. The Dutch Antilles. Chapter 38. In C.R.C. Sheppard (ed.), Seas at the Millennium: an Environmental Evaluation, Vol. I Regional Chapters: Europe, The Americas and West Africa, pp. 595-614. Elsevier, Amsterdam.
Deltacommissie, 2008. Samen werken met water. Een land dat leeft, bouwt aan zijn toekomst. Bevindingen van de Deltacommissie 2008. Secretariaat Delta-commissie. ISBN/EAN 978-90-9023484-7.

Donner, S.D., T.R. Knutson and M. Oppenheimer, 2007. Model-based assessment of the role of human-induced climate change in the 2005 Caribbean coral bleaching event. Proceedings of the National Academy of Sciences of the United States of America 104 (13): 5483-5488.

Duyl, F.C. van, G.J. Gast, W. Steinhoff, S. Kloff, M.J.W. Veldhuis and R.P.M. Bak, 2002. Factors influencing the short-term variation in phytoplankton composition and biomass in coral reef waters. Coral Reefs 21: 293-306.

FAO, 2008. Climate change and food security in Pacific Island countries. FAO, Rome, 2008, 266 pp.

Fernandes, L. et al., 2005. Establishing Representative No-Take Areas in the Great Barrier Reef: Large-Scale Implementation of Theory on Marine Protected Areas. Cons. Biol. 19(6): 1733-1744.

Freitas, J.A. de, B.S.J. Nijhof, A.C. Rojer and A.O. Debrot, 2005. Landscape ecological vegetation map of the island of Bonaire (Southern Caribbean). Royal Netherlands Academy of Arts and Sciences, Amsterdam. 64 pp. (+ maps).

Gardner, T.A., I.M. Cote, J.A. Gill, A. Grant, A.R. Watkinson, 2005. Hurricanes and Caribbean coral reefs: Impacts, recovery patterns and role in long-term decline. Ecology, 86(1), pp. 174-184.

Garrison V.H., W.T. Foreman, S. Genualdi, D.W. Griffin, C.A. Kellogg, M.S. Majewski, A. Mohammed, A. Ramsubhag, E.A. Shinn, S.L. Simonich and G.W. Smith, 2006. Saharan dust – a carrier of persistent organic pollutants, metals and microbes to the Caribbean? Rev. Biol. Trop. 54 (Suppl. 3): 9-21.

Gast, G.J., P.J. Jonkers, F.C. van Duyl and R.P.M. Bak, 1999. Bacteria, flagellates and nutrients in island fringing reef waters: influence of the ocean, the reef and eutrophication. Bull. Mar. Sci. 65:523-538.

Gast, G.J., S. Wiegman, E. Wieringa, F.C. van Duyl and R.P.M. Bak, 1998. Bacteria in coral reef water types: removal of cells, stimulation of growth and mineralization. Mar. Ecol. Progr. Ser. 167: 37-45.

GISP, 2008. Implementing the Global Strategy on Invasive Species. Annual Narrative & Financial Report. The Global Invasive Species Programme, Nairobi, Kenya.

Grontmij and Sogreah, 1968. *Water and land resources development plan for the islands of Aruba, Bonaire and Curaçao*. Rept. (for) Central Govt. Neth. Antilles, Curaçao – *Vol B*. Inventory of land and water resources 155 pp., ill. *Vol C.* Present and possible water and land use, 135 pp., ill.

Harvell, D., E. Jordan-Dahlgren, S. Merkel, E. Rosenberg, L. Raymundo, G. Smith, E. Weil, B. Willis,2007. Coral disease, environmental drivers, and the balance between coral and microbial associates. Oceanography, 20(1), 172-195.

Henriquez, P. C 1962. *Problems relating to hydrology, water conservation, erosion control, reforestation and agriculture in Curac¸ao*. Uitgaven van de Natuurwetenschappelijke Werkgroep Nederlandse Antillen No. 14, Curac¸ao, Netherlands Antilles. 54 pp.

Hoegh-Guldberg, O., P.J. Mumby, A.J. Hooten, R.S. Steneck, P. Greenfield, E. Gomez, C.D. Harvell, P.F. Sale, A.J. Edwards, K. Caldeira, N. Knowlton, C.M. Eakin, R. Iglesias-Prieto, N. Muthiga, R.H. Bradbury, A. Dubi, M.E. Hatziolos (2007) Coral reefs under rapid climate change and ocean acidification. *Science*, 318(5857), 1737-1742.

Hoegh-Guldberg, O., P.J. Mumby, A.J. Hooten, R.S. Steneck, P. Greenfield, E. Gomez, D.R. Harvell, P.F. Sale, A.J. Edwards, K. Caldeira, N. Knowlton, C.M. Eakin, R. Iglesias-Prieto, N. Muthiga, R.H. Bradbury, A. Dubi, M.E. Hatziolos (2008) Coral adaptation in the face of climate change - Response. *Science*, 320(5874), 315-316.

Hulsman, H., R. Vonk, M. Aliabadian, A. O. Debrot and V. Nijman. 2008. Effect of introduced species and habitat alteration on the occurrence and distribution of euryhaline fishes in fresh- and brackish-water habitats on Aruba, Bonaire and Curaçao (South Caribbean). *Contrib. Zool.* 77(1): 45-52.

ICK, NA. (Interdepartmentale Commissie voor Klimaatverandering, Nederlandse Antillen). 2010. *Een eerste aanzet voor het ontwikkelen van een beleid betreffende klimaatverandering voor de Nederlandse Antillen*. 3 pp.

IPCC 2007a Synthesis report

IPCC 2007b WG1 Science base report

IPCC 2007c WG2 Impacts, Adaptation and Vulnerability report

IUCN 2007. Best practice guidelines for establishment of a coastal green belt. IUCN, Sri Lanka Country Office, 8 pp.

Kleypas, J.A., R.A. Feely, V.J. Fabry, C. Langdon, C.L. Sabine, L.L. Robbins (2006) *Impacts of Ocean Acidification on Coral Reefs and Other Marine Calcifiers: A Guide for Future Research, report of a workshop held 18-20 April 2005,* St. Petersburg, FL. In: t.N.O.a.A.A.a.t.U.S.G.S. National Science Foundation (Ed). sponsored by NSF, NOAA, and the U.S. Geological Survey, 88 p.

Lundvall, S. 2008. *Saba Bank Special Marine Area Management Plan 2008*: 94.
Lugo, E. A. 2000. Effects and outcomes of Caribbean hurricanes in a climate change scenario. The Science of the Total Environment 262, 253-251

Martis, A., G. J. van Oldenborgh and G. Burgers. 2002. Predicting rainfall in the Dutch Caribbean- more than El Niño? *Int. J. climatology* 22: 1219-1234.

Meesters, E.H., R.P.M. Bak (1993) Effects of coral bleaching on tissue regeneration potential and colony survival. *Mar. Ecol. Prog. Ser.*, 96, 189-198.

Mertz, O., K. Halsnæs, J. E. Olesen and K. Rasmussen 2009. Adaptation to Climate Change in Developing Countries. Environmental Management 43:743–752

Meteo (Meteorological Service of the Netherlands Antilles and Aruba). 2010. *Hurricanes and tropical storms in the Netherlands Antilles and Aruba*. 38 pp.

Milne, G.A., Gehrels, W.R., Hughes, C.W. and Tamisiea, M.E. (2009). *Identifying the causes of sea-level change.* Nature Geoscience 2: 471 – 478.

Myers, N., Mittermeier, R. A., C. G. Mittermeier, G. A. B. da Fonseca and J. Kent. 2000. *Biodiversity hotspots for conservation priorities.* Nature 403:853-858.

Meyer, D. L., J. M. Bries, B. J. Greenstein and A. O. Debrot. 2003. Preservation of in situ reef framework in regions of low hurricane frequency: Pleistocene of Curaçao and Bonaire, southern Caribbean. *Lethaia* 36: 273-285.

Nagelkerken, I (2007) Relationship between anthropogenic impacts and bleaching-associated tissue mortality of corals in Curaçao (Netherlands Antilles). *Revista de Biologia Tropical* 54 (Suppl. 3): 31-44 .

Nolet, C. and M. van der Veen. 2009. Stofonderzoek Bonaire 2009. Stichting Kibrahacha/Wageningen UR, 103 pp.

Peterson, T. C. 2002. Recent changes in climate extremes in the Caribbean region *J. Geophysical Res*. 107, ACL 16:1-9.

Petit, J. & G. Prudent 2008. *Climate Change and Biodiversity in the European Union Overseas Entities*. IUCN, Brussels, 178pp.

Prospero, J.M. & R.T. Nees. 1986. Impact of the North African drought and El Niño on mineral dust in the Barbados trade winds. *Nature* 320: 735-738.

Roberts, C. M. 1995a. Rapid build-up of fish biomass in a Caribbean marine reserve. *Cons. Biol*. 9(4): 815-826.

Roberts, C. M. 1995b. Effects of fishing on the ecosystem structure of coral reefs. *Cons. Biol*. 9(5): 988-995.
Roberts, C. M. et al. 2002. Marine biodiversity hotspots and conservation priorities for tropical reefs. *Science* 295:1280-1284.

Roberts, C. M., J. P. Hawkins and F. R. Gell. 2005. The role of marine reserves in achieving sustainable fisheries. *Phil. Trans. R. Soc. B*, 360, 123-132.

Roberts, C. M., J. A. Bohnsack, F. Gell, Julie P. Hawkins, R. Goodridge. 2001. Effects of Marine reserves on Adjacent Fisheries *Science* 294: 1920-1923.

Rogers, C. S. 1990. Responses of coral reefs and reef organisms to sedimentation. *Mar. Ecol. Progr. Ser* 62: 185-202.

Rojer, A. 1997a. *Biologische Inventarisatie van Saba.* KNAP-project 96-10. Carmabi Report 1997, 41 pp + 54 bijl.

Rojer, A. 1997b. *Biologische Inventarisatie van St. Eustatius*. KNAP Project 96-10. Carmabi Report 1997, 44 pp + 51 bijl.

Rowbottom, R. J. and C. W. Winkel. 1979. *Well survey Bonaire*. Department of Agriculture Curaçao. 42 pp.

Silverman, J. , B. Lazar, L. Cao, K. Caldeira, and J. Erez. 2009. Coral reefs may start dissolving when atmospheric CO2 doubles. *Geophys. Res. Lett.* 36:

Simpson, M.C., Scott, D., New, M., Sim, R., Smith, D., Harrison, M., Eakin, C.M., Warrick, R., Strong, A.E., Kouwenhoven, P., Harrison, S., Wilson, M., Nelson, G.C., Donner, S., Kay, R., Geldhill, D.K., Liu, G., Morgan, J.A., Kleypas, J.A., Mumby, P.J., Christensen, T.R.L., Baskett, M.L., Skirving, W.J., Elrick, C., Taylor, M., Bell, J., Rutty, M., Burnett, J.B., Overmas, M., Robertson, R.7 and Stager, H., (2009) *An Overview of Modeling Climate Change Impacts in the Caribbean Region with contribution from the Pacific Islands*, United Nations Development Programme (UNDP), Barbados, West Indies

Soulé, M. E. and D. Simberloff. 1986. What do genetics and ecology tell us about the design of nature reserves? *Biol. Cons* 35: 19-40.

STENAPA 2009. St. Eustatius National Parks Foundation, Annual Report 2008. STENAPA, Oranjestad, St. Eustatius, 77 pp.

Stoffers, A. L. 1956. The vegetation of the Netherlands Antilles. Publications Foundation Scientific Research

Suriname Netherlands Antilles 15, Utrecht, The Netherlands.

Sturm, M. G. de L. 1991. The living resources of the Caribbean Sea and adjacent areas. Car. Mar. Stud. (1&2): 18-44.

Toller, W, A. O. Debrot, M. J. A. Vermeij and P. C. Hoetjes. 2010. *Reef Fishes of Saba Bank, Netherlands Antilles: Assemblage Structure across a Gradient of Habitat Types.* PlosOne 5(5): e9207,1-13.
UNEP (United Nation Environment Programme), 2008. *Climate Change in the Caribbean and the Challenge of Adaptation*. UNEP Regional Office for Latin America and the Caribbean, Panama City, Panama.

UNESCO 2010. Environment and development in coastal regions and small islands. CSI info 4. www.unesco.org/csi/pub/info/info49.htm.

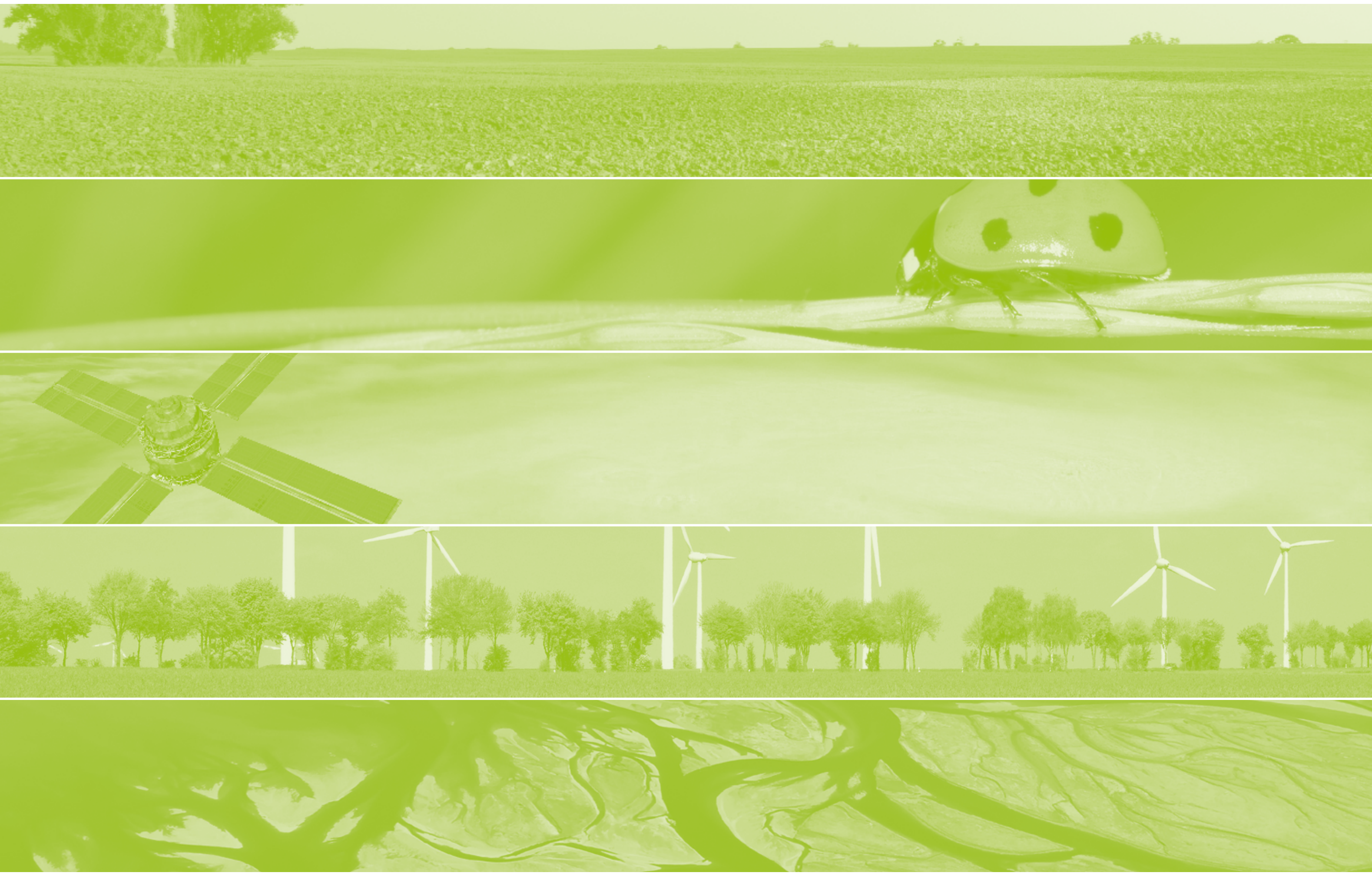
Voous, K.H., 1983. *Birds of the Netherlands Antilles* . Zutphen: De Walburg Pers.

Wells, J. and Debrot, A.O. 2008. Bonaire. Pp. 95-102. In: D. C. Wege and V. Anadon-Irizarry. Important Bird Areas in the Caribbean: key sites for conservation. Cambridge, UK: BirdLife International (BirdLife Conservation Series 15).

West, J. M, S. H. Julius, P. Kareiva, C. Enquist, J. J. Lawler, B. Petersen, A. E. Johnson and M. R. Shaw. 2009. U.S. Natural Resources and Climate Change: Concepts and Approaches for Management Adaptation Environmental Management 44:1001–1021.

Williams, E. H. and L. Bunkley-Williams. 2000. Marine major ecological disturbances of the Caribbean. The Infectious Diseases Review 2000(3): 110-127.

Winkel, F. 2003. *Distribution and densities of Cryptostegia grandiflora in natural areas of Curacao.* Carmabi/Univ. Wageningen Report 6 pp.



Alterra is part of the international expertise organisation Wageningen UR (University & Research centre). Our mission is 'To explore the potential of nature to improve the quality of life'. Within Wageningen UR, nine research institutes – both specialised and applied – have joined forces with Wageningen University and Van Hall Larenstein University of Applied Sciences to help answer the most important questions in the domain of healthy food and living environment. With approximately 40 locations (in the Netherlands, Brazil and China), 6,500 members of staff and 10,000 students, Wageningen UR is one of the leading organisations in its domain worldwide. The integral approach to problems and the cooperation between the exact sciences and the technological and social disciplines are at the heart of the Wageningen Approach.

Alterra is the research institute for our green living environment. We offer a combination of practical and scientific research in a multitude of disciplines related to the green world around us and the sustainable use of our living environment, such as flora and fauna, soil, water, the environment, geo-information and remote sensing, landscape and spatial planning, man and society.

More information: www.alterra.wur.nl/uk