2018

Climate change impacts on critical international transportation assets of Caribbean Small Island Developing States (SIDS): the case of Jamaica and Saint Lucia

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Citation/Publisher Attribution

Monioudi, I.N., Asariotis, R., Becker, A. et al. Reg Environ Change (2018) 18: 2211. https://doi.org/10.1007/s10113-018-1360-4

Available at: https://doi.org/10.1007/s10113-018-1360-4

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Regional Environmental Change

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--Manuscript Draft--

Manuscript Number:	REEC-D-17-00537R2
Full Title:	Climate change impacts on critical international transportation assets of Caribbean Small Island Developing States (SIDS): The case of Jamaica and Saint Lucia
Article Type:	S.I. : Small Island and 1.5 Degrees (Thomas)
Keywords:	Climate change, SIDS, Caribbean, international transport, extreme sea levels, dynamic flood modelling
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Funding Information:	
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Additional Information:	
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Climate change impacts on critical international transportation assets of Caribbean Small Island Developing States (SIDS): The case of Jamaica and Saint Lucia

(8733 words, Text: 6933 + Figures and table: 1800 words)

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***** *The views expressed in this contribution are those of the authors and not necessarily those of the United Nations*

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Abstract

This contribution presents an assessment of the potential vulnerabilities to Climate Variability and Change (CV & C) of the critical transportation infrastructure of Caribbean Small Island Developing States (SIDS). It focuses on potential operational disruptions and the coastal inundation forced by CV & C on 4 coastal international airports and 4 seaports in Jamaica and Saint Lucia which are critical facilitators of international connectivity and socioeconomic development. Impact assessments have been carried out under climatic conditions forced by a 1.5 °C Specific Warming Level (SWL) above pre-industrial levels, as well as for different emission scenarios and time periods in the 21st century. Disruptions and increasing costs due to e.g. more frequent exceedance of high temperature thresholds that could impede transport operations are predicted, even under the 1.5 °C SWL, advocated by the Alliance of Small Island States (AOSIS) and reflected as an aspirational goal in the Paris Climate Agreement. Dynamic modelling of the coastal inundation under different return periods of projected extreme sea levels (ESLs) indicates that the examined airports and seaports will face increasing coastal inundation during the century. Inundation is projected for the airport runways of some of the examined international airports and most of the seaports, even from the 100-year extreme sea level under 1.5 °C SWL. In the absence of effective technical adaptation measures, both operational disruptions and coastal inundation are projected to increasingly affect all examined assets over the course of the century.

Keywords: Climate change, SIDS, Caribbean, international transport, extreme sea levels, dynamic flood modelling

1 Introduction

Small Island Developing States (SIDS) face many challenges from Climate Variability and Change (CV & C), prompting the Alliance of Small Island States (AOSIS) to strongly advocate for a cap of 1.5 °C temperature rise above pre-industrial levels (hereafter the 1.5 °C Specific Warming Level - SWL), which has been included as an aspirational target in the 2015 Paris Agreement (Art. 2(a); Benjamin and Thomas 2016). In the Caribbean region, SIDS are particularly exposed due to the high concentration of population, infrastructure, and services at the coast (Rhiney 2015) which will bear the brunt of CV & C impacts in the region, particularly of those associated with: (i) sea level rise (SLR); (ii) potential increases in the destructiveness of tropical cyclones and other extreme events; and (iii) increasing air/sea surface temperatures and coastal water acidification (Simpson et al. 2010; Bender et al. 2010; Nurse et al. 2014; Stephenson and Jones 2017). It has been suggested that the Caribbean States might face climate-related losses in excess of US $ 22 billion annually by 2050 (Bueno et al. 2008).

All SIDS depend on international transportation for accessibility and connectivity and interactions with the global community and markets. The Caribbean SIDS are also major international tourism destinations based on the traditional 'Sun, Sea and Sand (3S)' tourism model (Phillips and Jones 2006), with tourism accounting for between 11 and 79 % of their Gross Domestic Product (UNECLAC 2011; Scott et al. 2012). As international trade and tourism are exclusively facilitated by coastal airports and seaports, these assets form lifelines of the Caribbean socioeconomic development (UNCTAD 2014).

Transport infrastructure and related operations that are situated at the coast are likely to be seriously affected by the impacts of CV & C. Coastal flooding may inundate low-lying coastal airports, whereas higher mean temperatures and more frequent heat waves can affect runways (heat buckling) and aircraft lift, resulting in payload restrictions and disruptions (Coffel 2017); thus, runways may require relocation and/or extension, which may not be always feasible due to topographic constraints. Seaports will be also incrementally affected by SLR and storm events; their quays, jetties and breakwaters may require redesigning and/or strengthening (Takagi et al. 2011; Becker et al. 2013, 2016; Asariotis et al. 2017). Increasing sea levels could alter nearshore flows inducing port scouring and/or silting, whereas changes in the wind and wave regimes may require specific adaptation measures (UNECE 2013). Heavy rainfall can affect services and induce flash floods and landslides that can have an impact on coastal transportation assets and their connecting road network (Fay et al. 2017).

SIDS capacity for adaptation and resilience building with regard to their critical transport infrastructure is constrained by their terrain, unfavorable economies of scale, and the lack of the financial and human resources required to carry out the vulnerability assessments that are necessary to identify requisite adaptation options. Against this background, an UNCTAD Development Account project was carried out to design and test new approaches, in order to develop a methodological framework for assessing climate impacts on the critical coastal transportation assets of Caribbean SIDS (http://unctad.org/en/Pages/DTL/TTL/Legal/Climate-Change-Impacts-on-SIDS.aspx).

Two Caribbean SIDS were selected as case studies: Jamaica and Saint Lucia (Fig. 1). The present contribution presents the assessment of potential vulnerabilities to CV & C of Jamaican and Saint Lucian international airports and seaports, focusing on potential operational disruptions and coastal inundation of these assets caused by changing climatic factors. Assessments have been carried out for the 1.5 °C SWL, as well as for different periods in the present century under different scenarios.

2 The Study Sites

Jamaica (land area 10,990 km^2, population 2.7 million) forms part of an emergent carbonate platform at the northern Nicaraguan Rise (Draper et al. 1994), whereas Saint Lucia (area 616 km^2, population 185,000) is located at the southern section of the 850 km long, Lesser Antilles volcanic 'double' arc (Fig. 1) which is built on mid-Eocene to Holocene volcanics and sediments (Macdonald et al. 2000). As all SIDS, both islands rely heavily on their international airports and seaports for connectivity.

In Jamaica, the assets selected for assessment are: Sangster International Airport (SIA) in the north and Norman Manley International Airport (NMIA) in the south, as well as the Historic Falmouth Cruise Port (HFCP) in the north and the main cargo handling Kingston Freeport and Container Terminal (KCT) in the south (Fig. 1 and "Online Resource 1"). 70 % of international passengers arrive at SIA at Montego Bay, whereas NMIA, located in the capital Kingston, caters mostly for visiting family and business travelers (1.6 million passengers in 2016). SIA is built at the coast; its runway runs parallel to an undulating coastline (average distance 195 m). NMIA covers about 230 hectares and is surrounded by Kingston harbour bay to the north and the open Caribbean Sea to the east and south. Its runway is surrounded by extensive stands of mangroves/saltmarshes. NMIA can only be accessed via the Norman Manley Highway that runs along a low elevation spit, known as the 'Palisadoes road'. HFCP is a major asset for the island's cruise ship industry due to its location and ability to host large cruise vessels, whereas KCT is a regional transhipment hub. HFCP covers a land area of about 11.5 hectares; sea access is provided by an artificial channel through a fringing reef, deep enough to facilitate access of large cruise ships. KCT is located in the large natural Kingston harbour bay and comprises 3 terminals (UNCTAD 2017a).

In Saint Lucia, the assessed critical international transportation assets are: George Charles International Airport (GCIA) and Castries seaport (CSP) located in the capital Castries; and Hewanorra International Airport (HIA) and Vieux Fort Seaport (VFSP), both situated at the southern coast of the island (Fig. 1 and "Online Resource 1"). HIA facilitates about 77 % of all air traffic (840,000 passengers in 2016), serving as the gateway for international long-haul flights, whereas GCIA handles mainly regional flights. CSP and VFSP seaports handle a significant fraction of the total OECS container traffic, with Port Castries being also a major cruise ship destination (677,400 arrivals in 2016). The northern side of the GCIA runway is separated by single lane road from an open sea facing beach (the "Vigie" beach), whereas its western end is bounded by an elevated and armoured coastline. CSP is located in a natural harbour bay; a 12.8 m deep approach channel allows large cruise ships to call. The eastern end of the HIA's runaway is located about 150 m from the shoreline, that forms on a beach fronted by coral reefs; a diverted local river (La Tourney River) runs parallel to the western part of the runway. Finally, VFSP is located about 5km from HIA, surrounded by low-lying land and approached by a narrow road, not ideal for containerised traffic (UNCTAD 2017b).

Both islands face moderate to high climatic risks; Kreft et al. (2016) ranked Jamaica and Saint Lucia as 53rd and 49th, respectively, out of 180 countries for the period 1996-2015. Since 1850, 135-144 tropical storms and hurricanes have passed within a 300 km radius of the critical transportation assets of Jamaica, with some of them inflicting human losses and serious damage ("Online Resource 2"). Saint Lucia has also been hit by tropical storms/hurricanes that have caused human losses and substantial damages to transportation assets ("Online Resource 3").

In Jamaica, average temperatures range from 24 to 27 °C, increasing by 0.16°C/decade; in recent years, extreme temperatures (33 - 37 °C) are commonly recorded in summer. There is no discernible trend in the mean precipitation, but in recent decades the intensity and occurrence of extreme rainfalls, floods and landslides have been increasing (CARIBSAVE 2012; PIOJ 2012). Winds are typically from E-NE to SE, with both annual and seasonal marine wind speeds increasing since the 1960's (CSGM 2012). SLR records from Cabo Cruz (Fig. 1) shows a rising trend (http://www.psmsl.org/data/obtaining/stations/1910.php) that exceeds the recent Caribbean average trend of 1.76 ± 1.3 mm/yr (Torres and Tsimplis 2013; Nurse et al. 2014).

In Saint Lucia mean daily temperatures are between 23.3 °C and 30.9 °C. Mean annual temperature has been increasing by about 0.16 °C/decade, together with the frequency of warm days and nights. Winds are typically from E-ENE and E-SE and average annual rainfall is about 1265 mm at the coast, but can reach up to 3420 mm in the interior; no long term trends are discernible (CARIBSAVE 2012; ESL 2015). Based on tidal records from Fort-de-France, Martinique (Fig. 1), SLR shows a rising trend since 1976; this has recently accelerated (in 2005-2016), and also exceeds the average trend of the Caribbean basin (http://www.psmsl.org/data/obtaining/stations/1942.php).

3 Methodology

CV & C impacts on the critical international transportation assets of Jamaica and Saint Lucia were estimated by applying the following approaches: (a) an assessment of direct impacts of changing climatic factors on operations, using an '*operational thresholds*' approach; and (b) modelling of the marine inundation of the assets due to extreme sea levels (ESLs) under different scenarios. Impacts under the AOSIS advocated 1.5 °C SWL were assessed. As timelines are important in vulnerability assessments and the planning/design of adaptation measures, the 1.5 °C SWL was translated into date years. The date years when the 1.5 °C SWL will be reached have been projected using the complete ensemble of CMIP5 General Circulation Models (Taylor et al. 2012) and following an approach similar to Alfieri et al. (2017). The analysis projected that the 1.5 °C SWL will be reached by 2033 under the IPCC RCP4.5 and by 2028 under the IPCC RCP8.5 scenarios (see also Taylor 2017). Therefore, ESLs (and resulting coastal inundation) for the 1.5 °C SWL are based on climatic projections for 2030. It should be noted that the results are valid for these date years, since SLR is a time-lagged process and will continue long after temperatures have stabilized (e.g. Jevrejeva et al. 2012). In addition, ESLs and inundation are projected for different periods in the century under different scenarios. In this study, we assess future inundation on the basis of two Representative Concentration Pathways (RCPs): RCP4.5 and RCP8.5. RCP4.5 may be considered as a moderate-emission-mitigation-policy scenario and RCP8.5 as a business-as-usual scenario.

3.1 The 'operational thresholds' approach

Operational thresholds were used to determine the climatic conditions under which facility operations might be impeded. The approach included the following steps. (1) Identification of operational thresholds (e.g. extreme temperatures and rainfall under which facility operations could be severely impaired); as specific facility thresholds were not available, generic thresholds were used. (2) Collation of climatic data. (3) Operational thresholds and climatic projections were compared to assess threshold exceedance frequency. Given the complex topography of the study areas, the spatial resolution of the climatic data is important. Therefore, the Caribbean Community Climate Change Centre's (CCCCC) downscaled climate projections from the RCM PRECIS, available for the SRES A1B scenario, were used (http://clearinghouse.caribbeanclimate.bz). It should be noted that, in terms of both emissions and potential impacts, A1B approximates the RCP6.0 (e.g. van Vuuren and Carter 2014).

3.2 Coastal Inundation

Extreme coastal inundation is driven by ESLs, considered here as the sum of the mean sea level (MSL), the astronomical tide (η_{tide}) and the episodic coastal water level rise (η_{CE}) due to storm surges (SSL) and wave set ups. ESLs for present and future conditions were obtained according to the approach described in Vousdoukas et al. (2018). Projections of SLR were extracted from Hinkel et al. (2014), whereas present-state η_{tide} were obtained from the TOPEX/POSEIDON Global Inverse Solution (Egbert and Erofeeva 2002). Given the focus on extreme events, the maximum tide ($\eta_{tide}^{\max}$) was used. DFLOW FM was then utilized to assess changes in global tidal elevations due to SLR (Vousdoukas et al. 2017). Hindcasts of waves and storm surges (1980-2015) were obtained through dynamic simulations forced by ERA-INTERIM atmospheric conditions. Storm surges were simulated using a flexible mesh setup of the DFLOW FM model (Jagers et al. 2014; Muis et al. 2016), and waves using the third generation spectral wave model WAVEWATCH III (Mentaschi et al. 2017).

Regarding tropical cyclone effects which are not represented in global re-analyses (Hodges et al. 2017), these have been simulated using the DFLOW FM model. The spider-web module (Deltares 2014) was utilized to generate higher resolution atmospheric forcing, considering all tropical cyclone tracks since 1985, available by the IBTrACS best-track archive (Knapp et al. 2010). Each event produced a global dataset of storm surge levels, since the domain of the tropical cyclone simulations is global. These were then combined with those from the ERA-INTERIM reanalysis, selecting the highest value. Cyclone effects on the waves were considered using the peak maxima of H_s measured by altimeter data provided by 6 different satellites (Queffeulou and Croizé-Fillon 2014): ERS-2, ENVISAT, Jason 1 and 2, Cryosat 2 and SARAL-AltiKa. Projected changes in waves and storm surges were estimated through simulations forced by outputs from 6 CMIP5 climate models (Vousdoukas et al. 2018) for 1980-2005 and during the present century under RCP4.5 and RCP8.5. Storm surges and waves result in episodic meteorological coastal water level rises that contribute to ESLs. Given the lack in the detailed nearshore bathymetric/topographic data required to resolve wave nearshore processes, the contribution of waves to ESL is limited to the nearshore wave set-up, not including potential contribution from the wave run-up (see also Section 5).

Offshore H_s, T_p and mean wave direction has been provided by WAVEWATCH III. Offshore wave characteristics vary between islands due to, amongst others, sheltering effects while obstacles which are not resolved by the model resolution are handled by the approach described in Mentaschi et al. (2018). Nearshore conditions (from 50 m water depth) were estimated through wave refraction and shoaling calculations based on the approach described in Part II, Chapter 2 of the Coastal Engineering Manual (CEM 2002). Wave incidence angles were obtained combining the mean wave direction from the model data with the mean shoreline orientation along 500 m long coastline sections, whereas seabed slope in the shoaling and surf zones was assumed as 1.5 %, a widely acceptable generic approximation (CEM 2002). Wave set up was estimated also through a generic approximation in relation to the significant wave height H_s that is based on an analytical solution of standard energy balance and linear wave theory equations (Holthuijsen 2007). More elaborate approaches (e.g. Zijlema et al. 2011; FEMA 2015) would have required detailed nearshore bathymetric information that has not been available for the purposes of the study. Therefore, η_{CE} has been estimated according to:

$$\eta_{\mathrm{CE}} = \mathrm{SSL} + (0.2 \times H_s) \qquad [1]$$

Non-stationary extreme value analysis (Mentaschi et al. 2016) was applied to the η_{CE} time series to obtain values for different return periods, derived for historical and future runs. Final η_{CE} projections were obtained after adjusting the reanalysis values according to the relative changes obtained from the CMIP5 simulations. More details on the approach to estimate ESLs during the present century can be found in Vousdoukas et al. (2017; 2018).

ESLs were projected for the Jamaican and Saint Lucian coasts for the baseline historical period (1995), the 1.5 °C SWL and different periods in the century under different scenarios, for 9 return periods (1, 1/5, 1/10, 1/20, 1/50, 1/100, 1/200, 1/500, 1/1000 years). Inundation maps for the critical transportation assets were obtained following Vousdoukas et al. (2016), using the Lisflood-ACC (LFP) model (e.g. Neal et al. 2011). Simulations were carried out for 2020, 2030, 2040, 2050, 2060, 2080 and 2100 under the examined RCPs.

In Jamaica, simulations were based on the SRTM DTM (1 arcseconds, about 30 m resolution), whereas in Saint Lucia a higher resolution (of about 5 m) DEM (http://www.charim-geonode.net/layers/geonode:dem) was used. Since regional and especially global DEMs are often characterized by vertical bias (e.g. Chirico 2004), bias correction was applied using in situ data of the mean sea level and the terrain elevation, as follows: (i) elevations relative to mean sea level at control areas (i.e. extensive flat areas such as airport runways and seaport berthing docks) were obtained through communication with facility managers and in situ measurements; (ii) the elevation was extracted from the DEM used in the inundation modelling for the same control areas; and (iii) biases were corrected, ensuring that the DEM elevation is always expressed relative to MSL=0 (which is the theoretical datum in the SRTM data). Finally, land hydraulic roughness was derived from land use maps (https://www.esa-landcover-cci.org/).

4. Results

4.1 Climatic operational thresholds

The ability of airport and seaport staff to safely work outdoors depends on the Heat Index, i.e. a combination of temperature and relative humidity. According to NOAA (http://www.nws.noaa.gov/om/heat/heat_index.shtml), temperatures over 30.6 °C and 32.5 °C combined with 80 % relative humidity present ‘high’ and ‘very high’ risks, respectively. Our analysis suggests that, under the 1.5 °C SWL, staff working outdoors at the Jamaican and Saint Lucian international transportation assets could be at ‘high’ risk for 5 and 2 days/year, respectively. Under a standard SRES A1B scenario transient warming scenario, such days could increase to 30 and 55 days/year, respectively, by 2081-2100 (Table 1).

Higher temperatures will reduce aircraft lift, requiring reduced payloads and/or longer runways (Coffel et al. 2017). Take-off length requirements vary by aircraft type. In this study, the temperature thresholds beyond which aircraft used in the area will require runways longer than those currently available at the Jamaican and Saint Lucian airports have been estimated, together with the number of days over the threshold. For example, it was found that under the 1.5 °C SWL, Boeing 737-800 aircraft (Boeing 2013), which serve all studied airports, will have to decrease their take-off load for 65 days/year at SIA and 24 days/year at NMIA, whereas by the 2070s and under SRES A1B such days could increase at least twofold for SIA and fourfold for NMIA (Table 1). As the maximum temperature projections are available at a daily scale (as all used model projections), the degree of operational disruptions that also depends on the duration of extreme heat during the day and on air traffic schedules could not be detailed further. It should be noted that, the example in Table 1 refers to a medium size/range aircraft that requires less lengthy runways than the long-haul aircrafts serving Caribbean routes (e.g. the Boeing 777 series, UNCTAD (2017a)); therefore, the results shown in Table 1 are likely to represent conservative estimations of such operational disruptions. Finally, the projections assume no targeted aircraft design changes.

Extreme heat can also raise energy demand/costs for heating, ventilation and cooling (HVAC) systems. According to a generic standard, 1 °C warming will result in a 5 % increase in energy requirements (assuming current technology) (IDB 2015). Using a temperature rise of about 0.7 °C between the pre-industrial and the baseline (1986-2005) periods (Hawkins et al. 2017), increases in energy requirements were estimated for 0.8, 1.3 and 3 °C temperature increases above the baseline, i.e. for the 1.5 °C SWL and for 2 and 3.7 °C temperature increases since the pre-industrial levels, respectively (Table 1). It was found that for the Jamaican seaports, the 1.5 °C SWL (2030) will increase the baseline energy requirements by 4 % for 214 days/year, whereas a 3.7 °C rise (2081-2100) will increase energy requirements by 15 % for 215 days/year. Saint Lucia seaports are projected to experience similar trends (Table 1). Extreme rainfall can severely limit visibility and inhibit operations (e.g. crane operations at commercial seaports). Future disruptions due to intense (> 20 mm/day) and very heavy rainfall (> 50 mm/day) are projected not to differ significantly from those of the baseline period (Table 1). Strong winds can prevent aircraft take-off and landing (with a generic passenger aviation threshold of 11.2 m/s) and affect the manoeuvrability and berthing of ships at seaports; winds over 18 m/s (40.3 mph) may force seaport shutdowns. Our projections show that future winds will not appreciably affect airport and seaport operations on the basis of these thresholds (but see also Nurse 2013).

It appears that most operational problems for the Jamaican and Saint Lucian critical coastal transportation assets (apart from coastal inundation) will be due to rising temperatures, with rainfall and wind effects projected to have minor impacts. However, as the climate projections from the CCCCC database do not include the effects of tropical storms/hurricanes, these estimates might be considered as conservative. Also, facility-specific operational sensitivities that cannot be captured by generic thresholds (e.g. the disruptive effects of wind and wave directional changes on ship berthing) may increase operational disruptions. In any case, large increases in operational disruptions are projected, even under the AOSIS advocated 1.5 °C SWL.

4.2 Extreme sea levels and coastal inundation

Projected ESLs are higher in Jamaica than in Saint Lucia (Fig. 2). In Jamaica, the baseline 100-year ESL (ESL_{100}), i.e. the combination of the SLR, tides and the 100-year η_{CE} has been estimated as 1.96 m, whereas in Saint Lucia the baseline 100-year ESL has been estimated as 1.29 m. ESLs in Jamaica under the 1.5 °C SWL are projected as 1.43, 1.60, 1.88 and 2.14 m for the 10-, 20-, 50-, and 100-year event, respectively (Fig. 2a); an increase of about 0.17 m is projected compared to baseline for the 100-year event. In Saint Lucia, ESL_{100} is estimated as 1.41 m under the 1.5 °C SWL. In both islands ESLs are projected to increase during the century, with the rise being faster under RCP8.5 (Fig. 2b).

Estimation of the contributions of each of the components of the ESLs and their time evolution has shown that whereas η_{CE} is the primary ESL contributor; its dominance will decrease in the course of the century. For example, contributions of SLR, tides ($\eta_{tide}^{\max}$) and η_{CE} to the ESL_{100} under the 1.5 °C SWL in Jamaica have been estimated as about 7 %, 10 % and 83 % (for both RCP scenarios), whereas in Saint Lucia, the estimates are 10 %, 20 % and 70 %, respectively. However, η_{CE} is projected not to change much over the course of the century. In Jamaica, for example, the contributions of SLR, tides ($\eta_{tide}^{\max}$) and η_{CE} to the ESL_{100} change between the baseline and the 1.5 °C SWL have been estimated as about 81 %, 5.1 % and 14 % (RCP 4.5) and 89 %, 5 % and 6 % (RCP8.5), respectively; for Saint Lucia, such estimates have been 80 %, 17 % and 3 % (RCP 4.5) and 80 %, 16 % and 4 % (RCP8.5), respectively. As the century progresses SLR is expected to gather pace and dominate further the ESL increases (“Tables S5 and S6, Online Resource 4”).

The return periods of the extreme sea levels (ESLs) form fundamental design parameters for coastal transportation infrastructure and/or any proposed technical adaptation measures. Thus, the evolution of the return periods of extreme sea levels has been estimated for different periods in the 21st century. Our results suggest that the ESL return periods will significantly decrease over time (Fig. 2c, d). In Jamaica, the baseline ESL_{100} will occur every 50 years under 1.5 °C SWL. By 2080, under RCP8.5 the baseline 100-year event will occur about every 9 years (Fig. 2c) Our results also indicate that the 100-year event projected under the 1.5 °C SWL will occur about every 6-7 years by 2100, under RCP8.5 (“see also Table S4, Online Resource 4”). In Saint Lucia, the ESL return periods are projected to decrease faster than in Jamaica. Under the 1.5 °C SWL, the baseline 100-year event will occur about every 10 years, occurring every year after the early 2040s (Fig. 2d). The 100-year event projected under the 1.5 °C SWL will occur about every 20 years by 2050 under RCP4.5.

In Jamaica, the low elevation of the SIA runway (approximately 1.2 - 1.4 m above MSL) will make it increasingly vulnerable to coastal inundation during extreme events. Modelling results show that, even under the 1.5°C SWL, the 100-year event will cause considerable flooding (Fig. 3). By 2050 under RCP4.5, similar flooding is projected for the 50-year event (ESL_{50}). NMIA, located in Kingston harbour bay, is less prone to coastal inundation, as its runway has an elevation in excess of 2 m and is also adjacent to mangroves/saltmarshes that can reduce storm impacts. Both the NMIA and SIA airports have experienced shutdowns during extreme events (“Online Resource 2”), with the disruptions in NMIA being mostly associated with the inundation of the coastal airport access road; this road has been recently raised and armoured, but not yet tested under a powerful event.

Under the 1.5 SWL, some areas of the KCT seaport are projected to be flooded under the 100-year event, whereas by 2100 extensive areas will be affected (Fig. 4). Access roads are also projected to be vulnerable to flooding. KCT has been previously vulnerable to extreme events, including strong winds, energetic waves and terrestrial flash floods which have driven large volumes of debris into the harbour (“Online Resource 2”). Finally, modelling results suggest that the HFCP cruise port will be very moderately affected until the 2080s, even by events with return periods in excess of 200 years. However, it appears that the low-lying access roads will be increasingly vulnerable to flooding; according to port officials (pers. comm., S. Rhoden), this is already a problem, as is berthing under certain wind and swell waves.

In Saint Lucia, the results (Fig. 5) show that several low-lying bay areas are under increased flood risk (ICF GHK 2012), including the areas where the critical assets are located. Under the 1.5 °C SWL, GCIA appears vulnerable to the 100-year event mostly at its northern side (Vigie beach), as the western end of the runway is located at an elevated and armoured coastline. As the century progresses, its vulnerability will increase (Fig. 5). Vigie beach, located only 30 m away from the airport fence, has been projected to face also substantial beach erosion (UNCTAD 2017b); this will further increase coastal inundation. Hewanorra International Airport (HIA) appears vulnerable at its eastern (seaward) edge. There, the runway is projected to be inundated at lengths of about 150, 130, and 380 m from the 100-year event under the 1.5 °C SWL, the 50-year event in 2050 under RCP4.5 and the 100-year event in 2100 under RCP8.5, respectively (Fig. 5). Until now, HIA has been mainly impacted by strong rainfall events that, in some cases, forced overflowing of the redirected La Tourney river (Fig. 5, "Online Resource 3") resulting in severe airport flooding.

Port Castries (CSP) is projected to be severely affected by the 100-year event under the 1.5 °C SWL. Coastal flooding will impact its docks, inundate its berths, cargo sheds and cruise ship facilities and cause flooding of the city, the nation's capital Castries. Later in the century, and under both RCP scenarios tested, CSP flooding is projected to deteriorate in the absence of effective adaptation measures. CSP has already experienced damages during extreme events, involving its breakwater armor, revetment, fencing and roofing ("Online Resource 3"). Finally, the Vieux Fort Seaport (VFSP) appears vulnerable to coastal flooding under all tested scenarios, a marked deterioration from the present situation as reported by the facility managers (UNCTAD 2017b).

5 Discussion

Our projections show that critical transportation assets of the studied Caribbean SIDS will face increasing operational disruptions and coastal inundation under climate change, even under the 1.5 °C SWL, which according to projections will regrettably be reached by the early 2030s. With regard to operational disruptions, these are projected to be mostly due to rising temperatures, with rainfall and wind changes (in relation to the baseline) projected to have small impacts. As regards coastal inundation, some of the critical transportation assets in both countries have been projected to face severe coastal flooding under the extreme sea levels forced by the 1.5 °C SWL; this is projected to deteriorate and affect more assets later in the century. Saint Lucian ports and airports appear to be generally more vulnerable to inundation than ports and airports in Jamaica. In this context it should be noted that the lack of appropriate alternative locations, particularly in Saint Lucia, may have driven asset placement in low-lying areas.

Our results show that η_{CE} is the primary ESL contributor, with its contribution ranging between 62 and 90 % of total ESL under the 1.5 °C SWL depending on the return periods and the RCP scenario. Its contribution is projected to decrease in the course of the century, as SLR will become larger whereas both future storm surge levels and wave set ups are projected to change very little ("see Tables S5 and Table S6, Online Resource 4"). Therefore, future increases in the ESLs in Jamaica and Saint Lucia are projected to be dominated by SLR (e.g. Vitousek et al. 2017; Vousdoukas et al. 2018).

The analysis of coastal hazards included dynamic projections of components and inundation simulations using a hydrological model. However data availability and the long temporal window of the study imposed some inevitable constraints in the employed approach, which are pointed out to the reader. ESL estimation was based on the maximum tide, an approach which omits spring/neap tidal variations and thus tends to overestimate ESLs. The timing of spring tides is rather deterministic, but this is not the case for the timing of the climate extremes obtained from CMIP5 GCMs. For the same RCP, different GCM ensembles can show substantial variability in the sequencing of meteorological conditions. As a result, simulations would have to be repeated, with the tidal timing probably varying in a Monte Carlo fashion, in order to capture the full probability range of coincidence between extreme events and high tides. Such an approach would imply prohibitive computational load, and was not employed.

Wave contributions to η_{CE} are considered only in the form of an increase in coastal sea level due to wave set up. However, waves also transfer substantial momentum to the coast that may drive coastal erosion (Vousdoukas et al. 2012b) and overwashing and/or breaching of coastal dunes and dykes (Roelvink et al. 2009; McCall et al. 2010; Lynett et al. 2010), and damage structures (e.g. Oumeraci 1994; Takagi et al. 2011; UNECE 2013). Such processes have not been included in the analysis for the following reasons. Nearshore wave transformation requires both computationally expensive modelling and accurate (nearshore) bathymetric information. Studies that consider climate change impacts involve the analysis of several combinations of scenarios, including amongst others, greenhouse gas emissions, time windows and return periods; such modelling would be prohibitive in terms of computational loads. In addition, detailed bathymetric information is not available for the study areas, both for the present and certainly for future conditions; nearshore morphology is very dynamic, constantly changing under natural and anthropogenic factors. Wave run up heights, are not included, even though they can be important drivers of coastal inundation (Stockdon et al. 2006; Vousdoukas et al. 2012a; Perini et al. 2016; Monioudi et al. 2017), as they are sensitive to the constantly changing beach-face slope (Vousdoukas 2012a). Therefore, consideration of waves refers only to contributions of wave setup to ESLs and does not include wave run up and wave impacts on coastal structures, as well as the spatio-temporal variability of impacts due to interactions with the nearshore bathymetry and structures. In order to address these issues, high resolution coastal bathymetric/topographic surveys are recommended for the Jamaican and Saint Lucia assets, so that the full impacts of waves on these assets could be assessed under the present conditions.

On the basis of the above, the employed approach may underestimate asset vulnerability. However, in climate change studies, missing data can result in additional uncertainty and, thus, wave effects are often omitted (e.g. Garner et al. 2017; Hauer et al. 2016). Notwithstanding the above constraints, the present study provides a first assessment of the vulnerability to CV & C of critical transportation assets in Caribbean SIDS. Results could be improved if facility specific operational thresholds, high resolution DEMS and accurate nearshore bathymetric information were available.

Coastal transportation assets could also be directly and indirectly impacted by additional hazards and their combinations, making multi-hazard assessments (e.g. Forzieri et al. 2016) necessary for effective adaptation planning. In Saint Lucia, flash floods and landslides are historical hazards, as most of the roads traverse areas of high or extreme landslide risk. As a result, landslide densities of up to 1.75/km (average density 0.75/km) have been recorded for the main road connecting HIA with the capital Castries and the major tourist resorts located at the northwestern coast of the island (Fig. 1) (UNCTAD 2017b). These landslides can seriously compromise the connectivity of the international tourist gateways with urban centers and tourist resorts, demanding redundancy adaptation options. Finally, since international transportation is a demand-driven industry, indirect impacts may arise from the impacts of CV & C on the capital/product of other economic sectors, such as the tourism industry. 3S' island tourism destinations, such as the Caribbean SIDS, are likely to be subjected to deteriorating beach erosion (UNCTAD 2017b) which can have severe implications for the beach carrying capacity for leisure and, ultimately, for tourism-related transportation demand.

Generally, coastal inundation is projected to increasingly impact the critical international transportation assets (and their access roads) of both countries and detailed research is required to identify the most effective adaptation options (Giardino et al. this issue). Here it should be noted that coastal flood protection measures under a changing climate can be designed utilizing different approaches, such as integrating safety factors and/or climate change robustness factors (i.e. applying the precautionary principle), exploratory modeling for different future scenarios, robust decision making and pathway planning (e.g. Klijn et al. 2015a). However, building fail-safe systems i.e. setting the climate change robustness at too high a level and, thus, over-engineering coastal defenses could be very costly (e.g. Narayan et al. 2016). Instead, building systems that would fail in a safe way ('safe-fail') and that easily recover and/or can be upgraded after failure might be considered (Klijn et al. 2015b)

Given the physiographic, climatic and developmental similarity of Jamaica and Saint Lucia to the remainder of the Caribbean SIDS, it is expected that the impacts of CV & C will present large challenges to the international transportation assets and connectivity of most Caribbean (and other) SIDS. This could severely compromise the achievement of several of the Sustainable Development Goals (SDGs), notably, SDG 9, 13 and 1.5, which form an integral part of the international community's agreed 2030 Sustainable Development Agenda.

6 Conclusions

The study results show high and increasing potential vulnerabilities to climatic changes of the critical international transportation assets (airports and seaports) of Jamaica and Saint Lucia involving both operational disruptions and coastal inundation from extreme events. Severe impacts are projected, even under the AOSIS advocated temperature increase cap of 1.5 °C (SWL) which will be reached in the early 2030s. These will deteriorate significantly in the course of the century.

Operational disruptions arising from climatic factor changes are projected to be mostly due to rising temperatures, with rainfall and wind changes having minor impacts; however, projections did not account for tropical storms. In addition, considerable, varied and increasing coastal inundation of the assets is also projected, with the Sangster International Airport (SIA) in Jamaica and the Saint Lucian airports and seaports being the most vulnerable.

In the absence of timely planning and implementation of requisite adaptation measures, the projected impacts of climate variability and change on critical transport infrastructure may have serious implications for the connectivity of SIDS to the international community and global markets, as well as broad economic and trade-related repercussions, which may severely compromise the sustainable development prospects of these vulnerable nations. Against this background, further research, including detailed technical studies, as well as collaborative concerted action at all levels are urgently required.

Acknowledgments

The authors gratefully acknowledge the support received under UN Development Account Project 1415O (sidsport-climateadapt.unctad.org). Also acknowledged with thanks is the support by the Disaster Risk Management Unit of the Joint Research Centre of the European Commission. The study benefitted from valuable discussions with participants at two national workshops, in Saint Lucia (24-26 May 2017) and in Jamaica (30 May-1 June 2017), and a regional workshop in Barbados (5-7 December 2017) which are also gratefully acknowledged.

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Figure captions

Fig. 1 Location of the critical transportation assets of Jamaica and Saint Lucia. Key: SIA, Sangster International Airport; HFCP, Historic Falmouth Cruise Port; NMIA, Norman Manley International Airport; KCT, Kingston Freeport and Container Terminal; HIA, Hewanorra International Airport; VFSP, Vieux Fort Seaport; GCIA, George Charles International Airport; and CSP, Port Castries ("see also Online Resource 1"). The location of the tide gauges in Cuba and Martinique is also shown. Digital Elevation Model data from SRTM DTM were used for the 2 islands; Caribbean bathymetric data from GEBCO_2014 Grid, http://www.gebco.net/

Fig. 2 Time evolution of Extreme Sea Levels (ESLs; defined as the sum of the mean sea level, the maximum astronomical tide and the episodic water level rise due to storm surge and wave set up) in relation to their baseline return periods for the 20- 50- and 100-year event, under RCP4.5 and RCP8.5, and for Jamaica (a, c) and Saint Lucia (b, d). The stippled line represents the projected year the 1.5 °C temperature increase since the pre-industrial period is reached

Fig. 3 Inundation of Sangster International Airport (SIA) (a, c, e) and Norman Manley International Airport (NMIA) (b, d, f) under the 100-year event and 1.5 °C SWL (a, b), the 50-year event in 2050 under RCP4.5 (c, d) and the ESL_{100} in 2100, under RCP8.5 (e, f). Inundation simulations followed Vousdoukas et al. (2016), using the Lisflood-ACC (LFP) model. DEM resolution is of about 5 m. DEM was corrected for vertical biases; elevation is expressed relative to MSL=0

Fig. 4 Inundation of Kingston Freeport and Container Terminal (KCT) (a, c, e) and Historic Falmouth Cruise Port (HFCP) (b, d ,f) under the 100-year event and 1.5 °C SWL (a, b), the 50-year event in 2050 under RCP4.5 (c, d), and the ESL_{100} in 2100 under RCP8.5 (e, f)

Fig. 5 Inundation of (a, c, e) George Charles International Airport (GCIA) and Castries Seaport (CSP) and (b, d, f) Hewanorra International Airport (HIA) and Vieux Fort Seaport (VFSP) under the 100-year event and 1.5 °C SWL (a, b), the 50-year event in 2050 under RCP4.5 (c, d) and the ESL_{100} in 2100 under RCP8.5 (e, f)

Table captions

Table 1 Days of disruptions projected for the Jamaica and Saint Lucia airports and seaports. Heat Index is a measure of the human feeling of heat when relative humidity is factored in with the actual air temperature (http://www.nws.noaa.gov/om/heat/heat_index.shtml). Aircraft take-off length requirements according to the manufacturer manuals. Estimations for aircraft lift assume no related design advances. Impacts in energy costs and crane operation were based on generic thresholds from IDB (2015). Note: Temperature related disruptions are assessed for temperature increases in relation to the 1986-2005 (baseline) average that was about 0.7 °C above the pre-industrial level

Reply to reviewers' comments

Comments from the editor

For your guidance, any comments from the subject editor and/or the reviewers are appended below and in the attached pdf. Please also note that it now seems as if your "results and discussion" section consists now of section 4.1 and 4.2 as results and 4.3 as discussion. Please clarify this further. If only 4.3 is the discussion section, then it should be labelled "5. Discussion"

Authors: We have labelled the sections according to the editor's suggestions.

If you decide to revise the work, you need to submit a list of changes or a rebuttal against each point which has been raised along with your revised manuscript. Note that all instructions for authors, as published on our website, need to be followed also for the revision.

Please ensure that the revised paper follows all our published instructions for authors, including reference formatting (with doi-numbers where available). Also make sure to provide good illustrations, following our instructions.

Figures should contain only essential information, and be designed to allow reproduction in small format. Where possible, provide explanatory text elements in figure and table captions and not in the figure itself, making sure all acronymys are explained (even if they are also in the text).

Authors: We have formatted the manuscript according to the journal's style

In order to allow for quick processing, I ask you to submit the revised version by 05 May 2018. To submit a revision, go to https://reec.editorialmanager.com/ and log in as an Author. You will see a menu item call Submission Needing Revision. You will find your submission record there.

With kind regards,

Christopher Reyer

Chief Editor

Regional Environmental Change

Dear authors,

many thanks for the resubmission of your manuscript. It has now been seen by three reviewers again. You will see that while the reviewers acknowledge the improvement of your manuscript, they still have considerable concerns regarding the coastal inundation methodology. Please take great care in addressing these concerns in your resubmission.

Note that I have set the a 12 days deadline for your resubmission in order to allow for a consideration of your resubmitted manuscript before May 15. I understand that this is a very tight timeline. Please let me know if it is not feasible for you to address the comments with the scientific rigour required and we shall extend your deadline accordingly.

Best Regards,

Carl

Authors: We would like to thank the editor for his suggestions and we did our best to address the reviewers' comments on time.

Reviewer #3

This contribution explains interesting aspects on the impacts of sea level rise on Low Elevation Coastal Zones (LECZ) in Caribbean SIDS. Reviewer One points out reservations subject to change with regards to the analysis of inundation modeling. While most of these points have been addressed within the revision, we suggest adding the following improvements which will significantly enhance the quality of this paper.

In the discussion, a statement should be added explaining how wave heights may vary around islands. Potentially, sheltering effects become important when calculating impacting wave energies.

Authors: Information on the way waves are considered in the methodology has been extended (Section 3.2, 3rd paragraph) according to suggestions from both reviewers.

The calculation of offshore wave heights should be explained in more detail. At the moment, it is unclear how regional model outputs were obtained and validated (Section 3.2).

Authors: Recently a paper describing in detail the methodology to obtain the projections of SLR, tides, waves and storm surges has been accepted in Nature Communications and is in production stage and we are citing it in the revision (Vousdoukas et al., 2018). In addition there is a paper dedicated to the wave projections (Mentaschi et al., 2017), and another also explaining the methodology (Vousdoukas et al., 2017). The number of previous publications is indicative of the amount of work involved in generating these projections, combining different models, scenarios, etc. Therefore, we think that would be impossible to describe the procedures in detail, taking also into account the space limitations. Still, we have added additional clarifications on the estimations of the ESL components (e.g. in Section 3.2, 3rd paragraph). We are also confident that, following publication of the Nature Communications paper, the reader can have all information to follow the methodology in detail.

Wave directions and power may change during different spatial and temporal scales; we suggest adding statements reflecting on this.

Authors: We have used WAVEWATCH III that does capture different scales as the reviewer mentions. In any case, we now refer to spatio-temporal scaling in the revised discussion on wave effects added in this revision (Section 5, 4th paragraph).

Finally, a few sentences explaining field sites will be useful. Section 2 is very broad scale and lacks detail of local environmental specifications - These may become important when considering future shoreline adjustments to external forcing.

Authors: In response to this comment, we have added additional relevant information (Section 2, 2nd and 3rd paragraphs)

Overall, a general rework of the manuscript is recommended for correcting minor orthographic mistakes.

Authors: We went through the paper carefully and such mistakes have been eliminated

Once all these points have been addressed to the reviewer satisfaction, I take no issue for publication of this article in 'Regional Environmental Change'.

Reviewer #1:

General

The revised paper describes a methodology that disregards the significant effect of waves in hurricane damage in coastal areas.

The importance of wave action is part of proven flood mapping methodologies by FEMA and others. FEMA uses the concept of Base Flood Elevation, which includes the wave crest and has been shown to be appropriate for evaluation of coastal storm damage. ESL, as defined by the authors, is insufficient to assess vulnerability in coastal areas where waves are expected to impact facilities during extreme events. The authors try to justify this omission, without discussing the limitations of the proposed method, as opposed to recommending that their method be used in cases where wave effects are not expected to be significant. Unfortunately, I disagree with their response.

Authors: We agree with the reviewer in all his statements about the importance of waves and many of the authors have substantial experience in monitoring and modelling nearshore wave processes (including wave run up), erosion and hazard in different environmental settings (Broekema et al., 2016; Schimmels et al., 2012; Vousdoukas, 2014; Vousdoukas et al., 2012a; Vousdoukas et al., 2014; Vousdoukas et al., 2009a; Vousdoukas et al., 2009b; Vousdoukas et al., 2012b; Velegrakis et al 2016). We also acknowledge that waves in flooded areas during an *extreme event can assault coastal transportation assets in a manner that these assets are not designed for (UNECE 2013).*

However in climate change studies there is: (i) a general lack in nearshore seabed and swash zone bathymetric/topographic and sedimentary information to set up the models as well as inherent uncertainties involving such information in the future and under a changing climate; and (ii) a need to assess several scenarios during multiple time windows that act as bottlenecks to the amount of detail in terms of the methodology applied. We would like also to refer to recent studies on climate change hazards published in high impact journals which for that reason have neglected waves (Garner et al. 2017; Hauer et al. 2016), although they focused on the US coast where data availability is far better than in the Caribbean SIDS.

Still we acknowledge the significance of the point raised and we have tried to include an improved and more extensive discussion of the constraints in the methodology as well as to make clear that wave run up and power can have additional impacts (see Section 5, 4th and 5th paragraphs). We also made it clear in different sections that estimations involve only wave set up contributions and not of wave run up (e.g. Section 3.2, 2nd paragraph). We also acknowledge that the previous Methodology and Discussion sections were not sufficiently clear and missing certain aspects; in the revised manuscript we have addressed these issues.

Comment 1

The authors disregard the importance of wave effects in flood maps. The authors have not addressed the request to compare their method and assumptions to the extensive experience of US FEMA and their flood mapping methodologies (R1-2 and R1-4). As such, discussion in section 4.3 is considered insufficient.

Authors: We would like to clarify that the applied methodology omits wave run up effects but not wave effects overall. Moreover, although authors have the expertise to conduct an analysis that will involve such effects (see also previous comment), detailed analysis as prescribed by US (FEMA) requires data that are not available, both for present and future conditions. Still as mentioned previously, we have clarified the issue in the Methodology Section (Section 3.2, see e.g. beginning of the 1st and the end of the 2nd paragraphs) and extended the relevant discussion (Section 5, 4th and 5th paragraph) according to the reviewer's comments.

In section 4.3 of the paper and in response to R1-2, the authors imply that waves are not significant for inundation mapping because they act at a smaller temporal scale. This answer implies that only continuous flooding (still water level) is important, which is not accurate. The answer disregards the fact that coastal hazard analysis in the US and Australia (subject to tropical cyclones) is predicated on the proven fact that wave impacts matter.

Authors: We acknowledge that the text was not written clearly, but we never argued that waves are not significant. This is the reason that we include them, while this is not the case for most climate change studies (see also discussion in Vousdoukas et al., 2016). We have now tried to make it clear in different Sections (Sections 3.2, 4 and 5).

Further to question their response, simplified models and assumptions based on experience (which are part of the FEMA standard methodology) provide practical solutions to the inclusion of the effects described in the response to R1-2. Disregarding wave effects in the methodology underestimates vulnerability evaluations, so this methodology is not adequate to assess vulnerability in coastal areas where wave effects should be expected.

Authors: See previous replies.

Comment 2

The authors justify omissions of major physical effects in the fact that they cannot obtain data. This does not seem an appropriate explanation in a scientific paper that proposes a methodology to assess vulnerability.

Authors: The reviewer does not take into account that the aim of our methodology/study has been to assess vulnerability under certain scenarios of climate change and well into the future and not to conduct a detailed assessment of the present day vulnerability that will be required for the planning/design of effective technical adaptation measures. In the latter case, detailed data on nearshore bathymetry, swash zone and facility topography would have been required, together with the collection/analysis of time series of nearshore directional wave and flow information to drive and validate the models; high frequency monitoring of the storm effects would also be required to evaluate the actual wave effects on coastal morphodynamics. Such studies require very substantial human and financial resources and, ultimately, also rely on assumptions involving the stationarity of the coastal bathymetry/topography under a storm event.

As, however, our purpose has been to provide an assessment under different scenarios of climate change such an analysis could not be undertaken, not only due to the non-availability of the necessary present day information, but also due the uncertainties involving the future nearshore topography under a changing climate. Moreover, we think that the computational effort involved for such an assessment, as well as inherent uncertainties in the climate change projections do not support the undertaking of such projections. Nevertheless, we acknowledge that we should have discussed these issues in more detail, which we now do in the revised manuscript (Sections 5, 4th and 5th paragraphs).

Because the method is proposed to assess infrastructure, and those are a finite number of sites and each one has a limited spatial scale, surveys should be recommended to obtain accurate data. The fact that they may not be readily available to a researcher does not justify omitting significant physical effects in a general recommended methodology. The authors also justify omitting critical physical phenomena in the assumption that future morphology cannot be predicted. Their position may be arguable on a sandy beach, but is not true on hard bottom areas and most overland flooding conditions. In any case, the authors do not demonstrate that the potential errors of considering wave effects in the nearshore with uncertain shoreline morphology are higher than the certain errors of not accounting for wave impacts. The reviewer's opinion is certainly different.

Authors: A recommendation for high resolution coastal bathymetric/topographic surveys is now included, as suggested by the reviewer (Section 5, end of the 4th paragraph). We do not fully agree with the reviewer that hard seabed morphology is easily predicted. Hard nearshore seabeds can be altered by erosion/sedimentation and certainly affect the evolution of the coastline (e.g. Velegrakis et al., 2016); in any case, many of the studied assets (e.g. GCIA and HIA in St Lucia and SIA in Jamaica) are partially fronted by beaches, the morphology of which the reviewer acknowledges may be difficult to predict. Secondly, in the case of defended coastlines (as is the case of the western margin of GCIA runway and of the studied seaports), the likelihood of change in the next 20 years (not to mention by the end of the century) is rather high due to storm damages and improvements/modifications, among others (e.g. Asariotis et al., 2017). Finally, collection of the necessary data needed to resolve these issues will require large financial and human resources which have not been available for the present study. See also the response to previous comment.

Comment 3

The conclusion that "ESL increases are mostly controlled by MSLR" may be the result of the assumption that "waves do not matter".

Authors: We think that the reviewer misread/misinterpreted our statement. Our finding that "<u>ESL increases</u> are mostly controlled by mean sea level rise", is logical since future mean sea level rise is > 0.5 m in some cases whereas minor changes are projected for tides, waves and storm surges in this area (see also Vitousek et al., 2017). We have the feeling that the reviewer misread our statement to mean that '<u>ESL is mostly controlled by MSLR</u>", which is obviously not correct. Although mean sea level and its rise may control the magnitude and temporal changes of the other ESL components, it forms only a fraction of the overall ESL value as shown in Fig. 2; the baseline 100-year ESL event has been projected as 1.96 and 1.29 m above the baseline mean sea level, for Jamaica and Saint Lucia, respectively.

As it appears that our statement could be misread, the manuscript (Section 4.2, 2nd paragraph) has been redrafted and Tables S5 and S6 (Online resource 4) redone, so as to make our findings clearer.

Had wave impacts been considered, the results would have shown that wave heights will increase with MSLR. It can be shown that the influence of sea level rise on the total flood elevation (including wave crest elevation) is more than the nominal increase in mean sea level, even disregarding storm intensity effects. When calculating the base flood elevation following FEMA guidelines, adding the effect of SLR results in an increase of the BSE of up to 2 times the nominal SLR (this ratio varies, but exceeds 1.5 and a simple and conservative rule of thumb is 2).This impact of SLR on waves is not exposed by this methodology, because wave effects are omitted entirely.

Authors: The comment implies that SLR will increase nearshore water depths, and decrease wave attenuation, resulting in higher wave power reaching the coast. While there is no doubt that SLR will affect tides and waves/storm surges, predicting that effect at large spatial and temporal scales remains a challenge for several reasons. The most sensitive point is that, as previous studies highlight, SLR will probably drive shoreline retreat, and previous studies have shown that *the extent of shoreline retreat will modulate changes in astronomical (Idier et al., 2017; Pickering et al., 2017) and/or meteorological water level variations (Du et al., 2018). SLR effects can even reverse in extreme retreat scenarios; which could lead to higher attenuation. That could be the case also for waves (e.g. when flat terrains will become permanently inundated and will result in extensive flat submerged areas). All the above are difficult to predict, as natural long-term shoreline evolution is a complex process per se, and it becomes even more challenging when human interventions are involved.*

As we have stated in our previous replies as well as in the manuscript itself, we have included wave effects (e.g. the wave set up) that could be predicted with reasonable accuracy. Potential effects from wave run up and wave impacts that are not included are now clearly referred to in the manuscript (e.g. Section 5, 4th paragraph).

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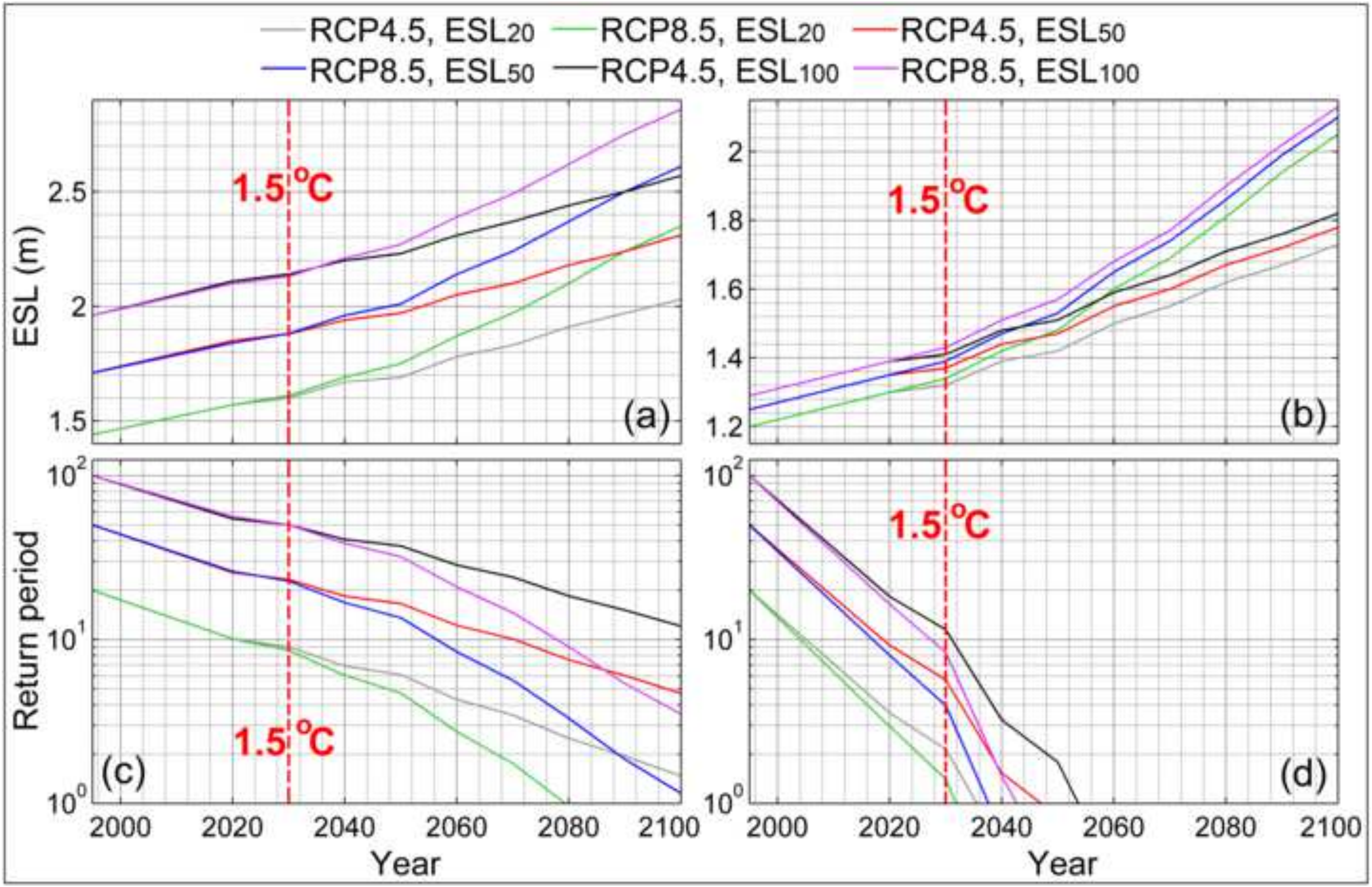
Figure1

Esri, Garmin, Gebco, NOAA NGDC, and other contributors
National Imagery and Mapping Agency (NIMA) World Port Index, 2002


RCP4.5, ESL20
RCP8.5, ESL20
RCP4.5, ESL50
RCP8.5, ESL50
RCP4.5, ESL100
RCP8.5, ESL100
ESL (m)
2.5
2
1.5
1.5 °C
(a)
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1.8
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1.4
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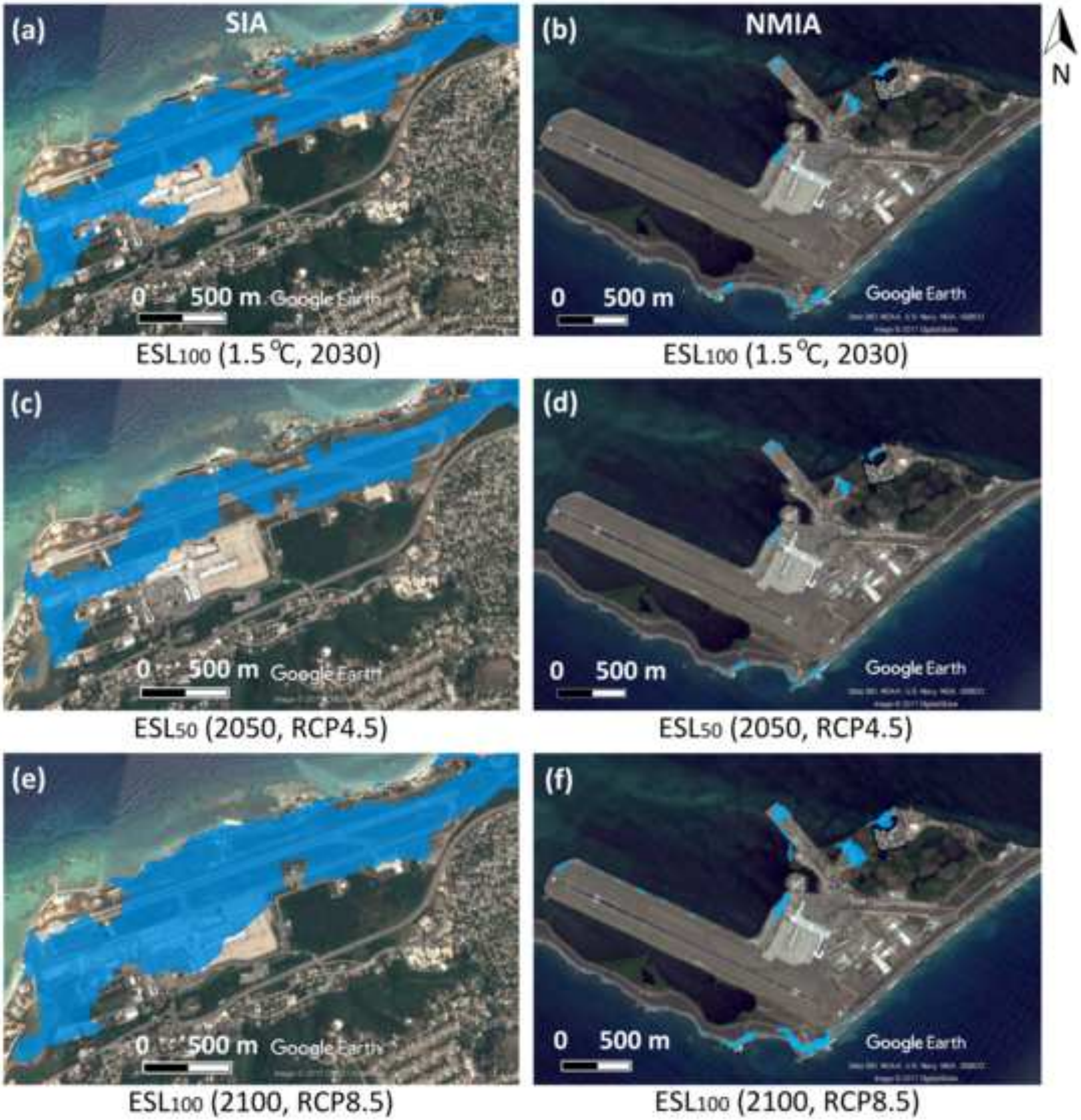


ESL_{100} (1.5 °C, 2030)

ESL_{100} (1.5 °C, 2030)

ESL_{50} (2050, RCP4.5)

ESL_{50} (2050, RCP4.5)

ESL_{100} (2100, RCP8.5)

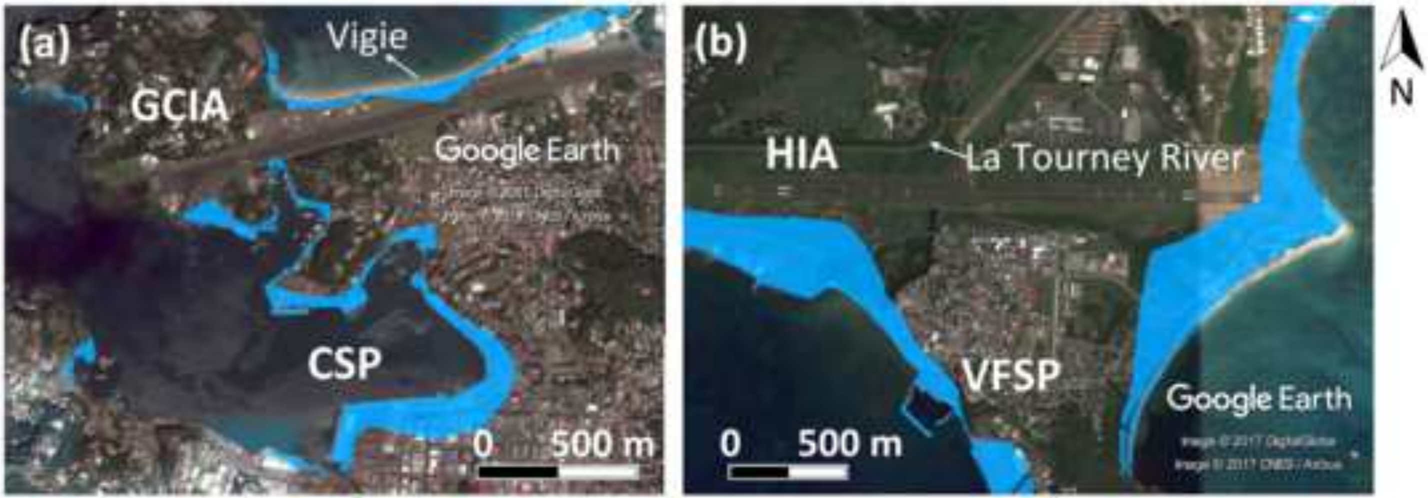
ESL_{100} (2100, RCP8.5)

Figure4

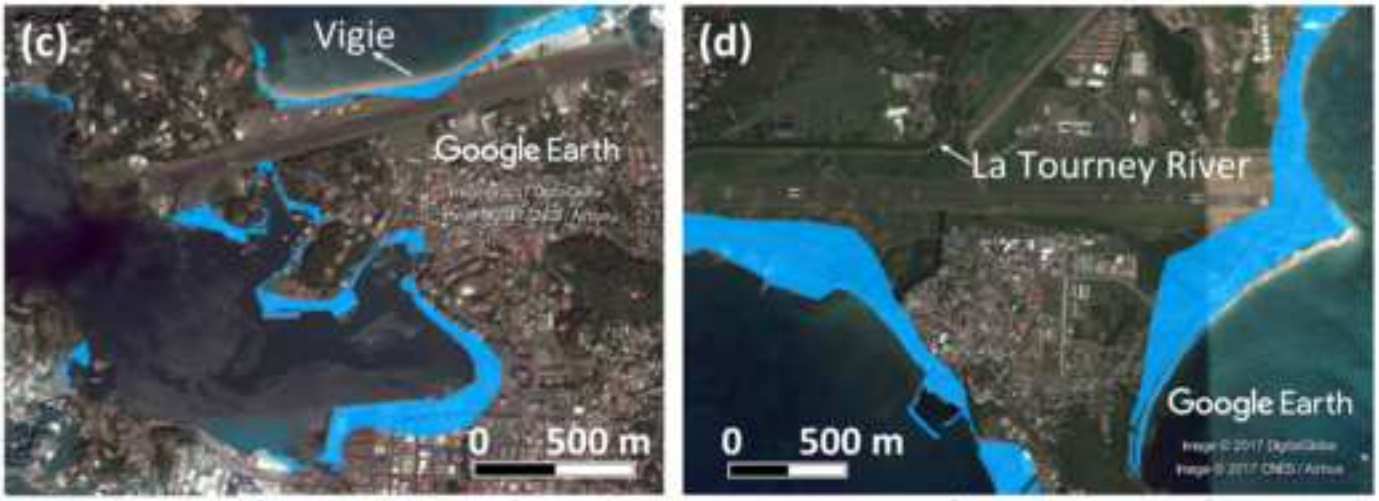
ESL$_{100}$ (1.5 °C, 2030) ESL$_{100}$ (1.5 °C, 2030)

ESL$_{50}$ (2050, RCP4.5) ESL$_{50}$ (2050, RCP4.5)

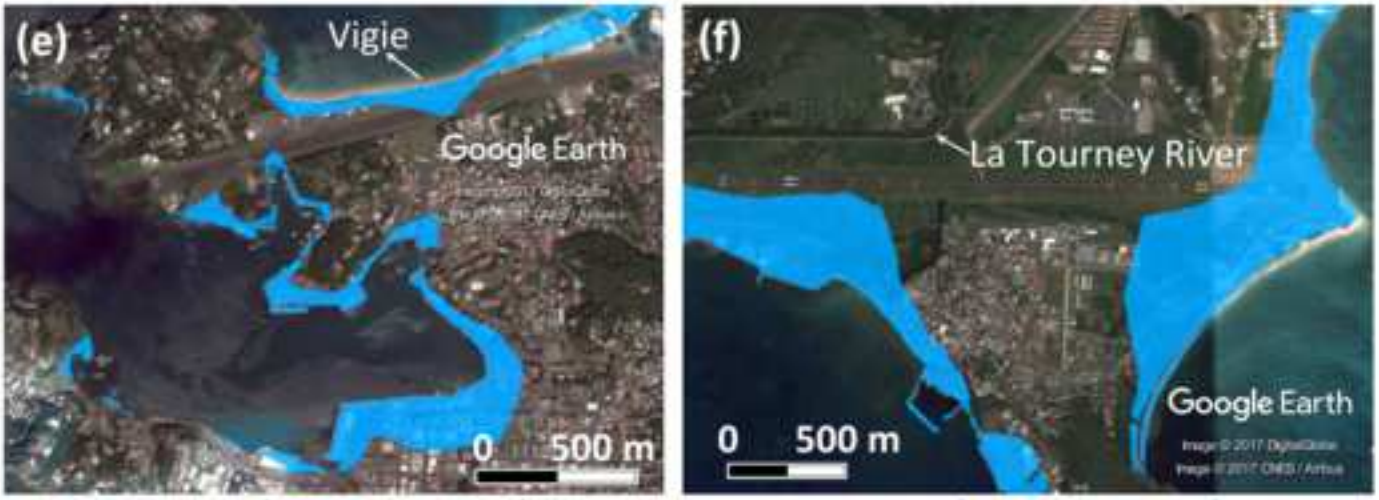
ESL$_{100}$ (2100, RCP8.5) ESL$_{100}$ (2100, RCP8.5)



ESL_{100} (1.5 °C, 2030) ESL_{100} (1.5 °C, 2030)



ESL_{50} (2050, RCP4.5) ESL_{50} (2050, RCP4.5)



ESL_{100} (2100, RCP8.5) ESL_{100} (2100, RCP8.5)

Table1

Climate Stressor	**Sensitivity**	**Threshold**	**Disruptions (average days/year)**					
			1986-2005	**2006-2030**	***2030***	**2031-2055**	**2056-2080**	**2081-2100**
JAMAICA								
Extreme Heat	Employee ability to work safely outdoors in airports and seaports	Heat Index (NOAA) over 39.4 °C (103 °F), resulting from 30.6 °C (87.1 °F) and 80 % relative humidity presents 'high' risk	4.40	5.76	***5.00***	13.45	22.21	29.67
		Heat Index (NOAA) over 46 °C (115 °F) resulting from 32.5 °C (90.5 °F) and 80 % relative humidity presents 'very high risk'	0.05	0.12	***1.00***	1.95	4.88	10.89
	Aircraft take-off length requirements	Boeing 737-800 aircrafts will have to reduce their full payload to take off from SIA in temperature over 33.2 °C	23.70	44.92	***65.00***	84.91	138.75	183.78
		Boeing 737-800 aircrafts will have to reduce their full payload to take off from NMIA in temperatures over 34.1 °C	5.35	14.64	***24.00***	44.41	99.25	146.00
	Energy costs in seaports	0.8 °C warming from baseline = 4 % increase if temperature exceeds 30.3 °C (1986-2005 (baseline) average: 29.5 °C)	145.20	177.36	***214.00***	216.73	271.46	303.44
		1.3 °C warming = 6.5 % increase if temperature exceeds 30.8 °C	121.50	153.44	***182.00***	196.41	248.50	286.61
		3 °C warming = 15 % increase if temperature exceeds 32.5 °C	47.25	74.92	***97.00***	117.95	168.96	214.83
Precipitation	Inhibits crane operation in seaports	Intense rainfall (e.g. > 20 mm/day)	3.70	3.60	***0.00***	4.59	4.00	3.11
		Very heavy rainfall (e.g. >50 mm/day)	0.90	0.64	***0.00***	1.45	0.92	0.89
SAINT LUCIA								
Extreme Heat	Employee ability to work safely outdoors in airports and seaports	Heat Index (NOAA) over 39.4 °C (103 °F), resulting from 30.6 °C (87.1 °F) and 80 % relative humidity presents 'high' risk	1.25	1.96	***2.00***	11.86	29.13	55.33
		Heat Index (NOAA) over 46 °C (115 °F) resulting from 32.5 °C (90.5 °F) and 80 % relative humidity presents 'very high risk'	0.00	0.00	***0.00***	0.59	2.42	9.06
	Aircraft take-off length requirements	Boeing 737-500 aircrafts will have to reduce their full payload to take off from HIA in temperatures over 31.2 °C	0.55	0.96	***0.00***	10.64	31.38	69.72
		Boeing 737-800 aircrafts will have to reduce their full payload to take off from HIA in temperatures over 34.5 °C	0.00	0.00	***0.00***	0.00	0.04	1.33
	Energy costs in seaports	0.8 °C warming from baseline = 4 % increase if temperature exceeds 30.3 °C (1986-2005 (baseline) average: 26.8 °C)	80.55	114.32	***168.00***	225.50	322.13	355.72
		1.3 °C warming = 6.5 % increase if temperature exceeds 28.1 °C	49.05	71.76	***113.00***	161.59	279.58	343.61
		3 °C warming = 15 % increase if temperature exceeds 29.8 °C	5.90	9.72	***18.00***	40.32	98.54	182.78
Precipitation	Inhibits crane operation in seaports	Intense rainfall (e.g., > 20 mm/day)	48.20	44.60	***51.00***	45.55	46.88	48.00
		Very heavy rainfall (e.g. >50 mm/day)	0.45	0.72	***1.00***	1.05	0.54	0.83

Electronic Supplementary Material