

2018

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

Isavela N. Monioudi

Regina Asariotis

See next page for additional authors

Follow this and additional works at: https://digitalcommons.uri.edu/maf_facpubs

**The University of Rhode Island Faculty have made this article openly available.
Please let us know how Open Access to this research benefits you.**

This is a pre-publication author manuscript of the final, published article.

Terms of Use

This article is made available under the terms and conditions applicable towards Open Access Policy Articles, as set forth in our [Terms of Use](#).

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>

This Article is brought to you for free and open access by the Marine Affairs at DigitalCommons@URI. It has been accepted for inclusion in Marine Affairs Faculty Publications by an authorized administrator of DigitalCommons@URI. For more information, please contact digitalcommons@etal.uri.edu.

Authors

Isavela N. Monioudi, Regina Asariotis, Austin Becker, Cassandra Bhat, Danielle Dowding-Gooden, Miguel Esteban, Luc Feyen, Lorenzo Mentaschi, Antigoni Nikolaou, Leonard Nurse, Willard Phillips, David A-Y Smith, Mizushi Satoh, Ulric O'Donnell Trotz, Adonis F. Velegrakis, Evangelos Voukouvalas, Michalis I. Vousdoukas, and Robert Witkop

Regional Environmental Change

Climate change impacts on critical international transportation assets of Caribbean Small Island Developing States (SIDS): The case of Jamaica and Saint Lucia --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 |
| Corresponding Author: | Isavela N Monioudi, Ph.D. University of the Aegean Mytilene, GREECE |
| Corresponding Author Secondary Information: | |
| Corresponding Author's Institution: | University of the Aegean |
| Corresponding Author's Secondary Institution: | |
| First Author: | Isavela N Monioudi, Ph.D. |
| First Author Secondary Information: | |
| Order of Authors: | Isavela N Monioudi, Ph.D. |
| | Regina Asariotis |
| | Austin Becker |
| | Cassandra Bhat |
| | Danielle Dowding-Gooden |
| | Miguel Esteban |
| | Luc Feyen |
| | Lorenzo Mentaschi |
| | Antigoni Nikolaou |
| | Leonard Nurse |
| | Willard Phillips |
| | David A-Y Smith |
| | Mizushi Satoh |
| | Ulric O'Donnell Trotz |
| | Adonis F Velegrakis |
| | Evangelos Voukouvalas |
| | Michalis I Vousdoukas |
| | Robert Witkop |
| Order of Authors Secondary Information: | |
| Funding Information: | |
| 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 |

| | |
|--|--|
| | <p>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.</p> |
| Additional Information: | |
| Question | Response |
| Does your submission belong to a Special Issue currently in preparation for this journal? | Yes |
| If yes, please ensure that your submission occurs according to the approved plans of the respective guest editors. If this is the case, please give the title of the Special Issue and the name of the editors you have been in contact with here. | <p>Special Issue '1.5 °C and Small Island Developing States' edited by:</p> <p>Adelle Thomas, University of The Bahamas Carl-Friedrich Schleussner, Climate Analytics Christopher Reyer, Climate Impacts and Vulnerabilities Mahendra Kumar, Policy and Technical Expert, Climate Change</p> |
| Has your submission been invited to a special issue currently in preparation for this journal? | Yes |
| Please select the special issue your manuscript belongs to. as follow-up to "Has your submission been invited to a special issue currently in preparation for this journal?" | SI has been defined through article type |
| Author Comments: | |

1
2
3
4 **Climate change impacts on critical international transportation assets of Caribbean**
5 **Small Island Developing States (SIDS): The case of Jamaica and Saint Lucia**
6
7
8
9

10 (8733 words, Text: 6933 + Figures and table: 1800 words)
11
12
13

14 Isavela N. Monioudi^{1,a}, Regina Asariotis^{2,b*}, Austin Becker^{3,c}, Cassandra Bhat^{4,d}, Danielle
15 Dowding-Gooden^{5,e}, Miguel Esteban^{6,f}, Luc Feyen^{7,g}, Lorenzo Mentaschi^{7,h}, Antigoni
16 Nikolaou^{1,i}, Leonard Nurse^{8,j}, Willard Phillips^{9,k*}, David A-Y Smith^{5,l}, Mizushi Satoh^{10,m*}, Ulric
17 O'Donnell Trotz^{11,n}, Adonis F. Velegrakis^{1,o}, Evangelos Voukouvalas^{7,p}, Michalis I.
18 Vousdoukas^{7,1,q}, Robert Witkop^{3,r}
19
20
21

22 ¹ *University of the Aegean, Department of Marine Sciences, University Hill, Mytilene, Greece*

23 ² *UNCTAD, Policy and Legislation Section, Division on Technology and Logistics, Geneva, Switzerland*

24 ³ *University of Rhode Island, Department of Marine Affairs, Kingston, United States*

25 ⁴ *ICF, Miami Beach, Florida, United States of America*

26 ⁵ *Smith Warner International Ltd., Kingston, Jamaica*

27 ⁶ *Waseda University, Department of Civil and Environmental Engineering, Shinjuku, Tokyo, Japan*

28 ⁷ *European Commission, Joint Research Centre (JRC), Directorate for Space, Security and Migration
29 Disaster Risk Management Unit, Ispra (VA), Italy*

30 ⁸ *University of the West Indies, Faculty of Science and Technology, Bridgetown, Barbados*

31 ⁹ *UNECLAC, Sustainable Development and Disaster Unit, Port-of-Spain, Trinidad and Tobago*

32 ¹⁰ *UNDP Barbados and the OECS, Bridgetown, Barbados*

33 ¹¹ *Caribbean Community Climate Change Centre, Belmopan, Belize*
34
35
36

37 * *The views expressed in this contribution are those of the authors and not necessarily those of the United
38 Nations*
39

40 ^a imonioudi@marine.aegean.gr, ^b regina.asariotis@unctad.org, ^c abecker@uri.edu,

41 ^d Cassandra.Bhat@icf.com, ^e danielle@smithwarner.com, ^f esteban.fagan@gmail.com,

42 ^g luc.feyen@ec.europa.eu, ^h lorenzo.mentaschi@ec.europa.eu, ⁱ andi_nikolaou@yahoo.com,

43 ^j leonard.nurse@cavehill.uwi.edu, ^k willard.phillips@eclac.org, ^l david@smithwarner.com,

44 ^m mizushi.satoh@undp.org, ⁿ utrotz@gmail.com, ^o beachtour@aegean.gr,

45 ^p evangelos.voukouvalas@ext.ec.europa.eu, ^q Michail.VOUSDOKAS@ec.europa.eu,

46 ^r robert_witkop@my.uri.edu
47
48
49

50 **Corresponding author:** Isavela N. Monioudi

51 e-mail: imonioudi@marine.aegean.gr

52 Telephone: +30 6985845864, +30 6937043446

53 Fax: +302251036858
54
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

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

1
2
3
4 framework for assessing climate impacts on the critical coastal transportation assets of Caribbean
5 SIDS (<http://unctad.org/en/Pages/DTL/TTL/Legal/Climate-Change-Impacts-on-SIDS.aspx>).

7 Two Caribbean SIDS were selected as case studies: Jamaica and Saint Lucia (Fig. 1). The present
8 contribution presents the assessment of potential vulnerabilities to CV & C of Jamaican and Saint
9 Lucian international airports and seaports, focusing on potential operational disruptions and coastal
10 inundation of these assets caused by changing climatic factors. Assessments have been carried out
11 for the 1.5 °C SWL, as well as for different periods in the present century under different scenarios.
12
13
14

15 16 **2 The Study Sites**

17
18 Jamaica (land area 10,990 km², population 2.7 million) forms part of an emergent carbonate
19 platform at the northern Nicaraguan Rise (Draper et al. 1994), whereas Saint Lucia (area 616 km²,
20 population 185,000) is located at the southern section of the 850 km long, Lesser Antilles volcanic
21 ‘double’ arc (Fig. 1) which is built on mid-Eocene to Holocene volcanics and sediments (Macdonald et
22 al. 2000). As all SIDS, both islands rely heavily on their international airports and seaports for
23 connectivity.
24
25
26

27 In Jamaica, the assets selected for assessment are: Sangster International Airport (SIA) in the
28 north and Norman Manley International Airport (NMIA) in the south, as well as the Historic Falmouth
29 Cruise Port (HFPC) in the north and the main cargo handling Kingston Freeport and Container
30 Terminal (KCT) in the south (Fig. 1 and “Online Resource 1”). 70 % of international passengers arrive
31 at SIA at Montego Bay, whereas NMIA, located in the capital Kingston, caters mostly for visiting
32 family and business travelers (1.6 million passengers in 2016). SIA is built at the coast; its runway runs
33 parallel to an undulating coastline (average distance 195 m). NMIA covers about 230 hectares and is
34 surrounded by Kingston harbour bay to the north and the open Caribbean Sea to the east and south.
35 Its runway is surrounded by extensive stands of mangroves/saltmarshes. NMIA can only be accessed
36 via the Norman Manley Highway that runs along a low elevation spit, known as the ‘Palisades road’.
37 HFPC is a major asset for the island’s cruise ship industry due to its location and ability to host large
38 cruise vessels, whereas KCT is a regional transshipment hub. HFPC covers a land area of about 11.5
39 hectares; sea access is provided by an artificial channel through a fringing reef, deep enough to
40 facilitate access of large cruise ships. KCT is located in the large natural Kingston harbour bay and
41 comprises 3 terminals (UNCTAD 2017a).
42
43
44
45
46
47
48

49 In Saint Lucia, the assessed critical international transportation assets are: George Charles
50 International Airport (GCIA) and Castries seaport (CSP) located in the capital Castries; and Hewanorra
51 International Airport (HIA) and Vieux Fort Seaport (VFSP), both situated at the southern coast of the
52 island (Fig. 1 and “Online Resource 1”). HIA facilitates about 77 % of all air traffic (840,000 passengers
53 in 2016), serving as the gateway for international long-haul flights, whereas GCIA handles mainly
54 regional flights. CSP and VFSP seaports handle a significant fraction of the total OECS container
55 traffic, with Port Castries being also a major cruise ship destination (677,400 arrivals in 2016). The
56 northern side of the GCIA runway is separated by single lane road from an open sea facing beach (the
57 “Vigie” beach), whereas its western end is bounded by an elevated and armoured coastline. CSP is
58
59
60
61
62
63
64
65

1
2
3
4 located in a natural harbour bay; a 12.8 m deep approach channel allows large cruise ships to call.
5 The eastern end of the HIA's runway is located about 150 m from the shoreline, that forms on a
6 beach fronted by coral reefs; a diverted local river (La Tourney River) runs parallel to the western part
7 of the runway. Finally, VFSP is located about 5km from HIA, surrounded by low-lying land and
8 approached by a narrow road, not ideal for containerised traffic (UNCTAD 2017b).
9

10
11 Both islands face moderate to high climatic risks; Kreft et al. (2016) ranked Jamaica and Saint
12 Lucia as 53rd and 49th, respectively, out of 180 countries for the period 1996-2015. Since 1850, 135-
13 144 tropical storms and hurricanes have passed within a 300 km radius of the critical transportation
14 assets of Jamaica, with some of them inflicting human losses and serious damage ("Online Resource
15 2"). Saint Lucia has also been hit by tropical storms/hurricanes that have caused human losses and
16 substantial damages to transportation assets ("Online Resource 3").
17

18
19 In Jamaica, average temperatures range from 24 to 27 °C, increasing by 0.16°C/decade; in recent
20 years, extreme temperatures (33 - 37 °C) are commonly recorded in summer. There is no discernible
21 trend in the mean precipitation, but in recent decades the intensity and occurrence of extreme
22 rainfalls, floods and landslides have been increasing (CARIBSAVE 2012; PIOJ 2012). Winds are typically
23 from E-NE to SE, with both annual and seasonal marine wind speeds increasing since the 1960's
24 (CSGM 2012). SLR records from Cabo Cruz (Fig. 1) shows a rising trend
25 (<http://www.psmsl.org/data/obtaining/stations/1910.php>) that exceeds the recent Caribbean
26 average trend of 1.76 ± 1.3 mm/yr (Torres and Tsimplis 2013; Nurse et al. 2014).
27
28

29
30 In Saint Lucia mean daily temperatures are between 23.3 °C and 30.9 °C. Mean annual
31 temperature has been increasing by about 0.16 °C/decade, together with the frequency of warm days
32 and nights. Winds are typically from E-ENE and E-SE and average annual rainfall is about 1265 mm at
33 the coast, but can reach up to 3420 mm in the interior; no long term trends are discernible
34 (CARIBSAVE 2012; ESL 2015). Based on tidal records from Fort-de-France, Martinique (Fig. 1), SLR
35 shows a rising trend since 1976; this has recently accelerated (in 2005-2016), and also exceeds the
36 average trend of the Caribbean basin (<http://www.psmsl.org/data/obtaining/stations/1942.php>).
37
38

39 40 41 42 43 44 **3 Methodology**

45
46 CV & C impacts on the critical international transportation assets of Jamaica and Saint Lucia were
47 estimated by applying the following approaches: (a) an assessment of direct impacts of changing
48 climatic factors on operations, using an '*operational thresholds*' approach; and (b) modelling of the
49 marine inundation of the assets due to extreme sea levels (ESLs) under different scenarios. Impacts
50 under the AOSIS advocated 1.5 °C SWL were assessed. As timelines are important in vulnerability
51 assessments and the planning/design of adaptation measures, the 1.5 °C SWL was translated into
52 date years. The date years when the 1.5 °C SWL will be reached have been projected using the
53 complete ensemble of CMIP5 General Circulation Models (Taylor et al. 2012) and following an
54 approach similar to Alfieri et al. (2017). The analysis projected that the 1.5 °C SWL will be reached by
55 2033 under the IPCC RCP4.5 and by 2028 under the IPCC RCP8.5 scenarios (see also Taylor 2017).
56 Therefore, ESLs (and resulting coastal inundation) for the 1.5 °C SWL are based on climatic
57
58
59
60
61
62
63
64
65

1
2
3
4 projections for 2030. It should be noted that the results are valid for these date years, since SLR is a
5 time-lagged process and will continue long after temperatures have stabilized (e.g. Jevrejeva et al.
6 2012). In addition, ESLs and inundation are projected for different periods in the century under
7 different scenarios. In this study, we assess future inundation on the basis of two Representative
8 Concentration Pathways (RCPs): RCP4.5 and RCP8.5. RCP4.5 may be considered as a moderate-
9 emission-mitigation-policy scenario and RCP8.5 as a business-as-usual scenario.

13 **3.1 The ‘operational thresholds’ approach**

14
15 Operational thresholds were used to determine the climatic conditions under which facility
16 operations might be impeded. The approach included the following steps. (1) Identification of
17 operational thresholds (e.g. extreme temperatures and rainfall under which facility operations could
18 be severely impaired); as specific facility thresholds were not available, generic thresholds were used.
19 (2) Collation of climatic data. (3) Operational thresholds and climatic projections were compared to
20 assess threshold exceedance frequency. Given the complex topography of the study areas, the spatial
21 resolution of the climatic data is important. Therefore, the Caribbean Community Climate Change
22 Centre’s (CCCC) downscaled climate projections from the RCM PRECIS, available for the SRES A1B
23 scenario, were used (<http://clearinghouse.caribbeanclimate.bz>). It should be noted that, in terms of
24 both emissions and potential impacts, A1B approximates the RCP6.0 (e.g. van Vuuren and Carter
25 2014).

32 **3.2 Coastal Inundation**

33
34 Extreme coastal inundation is driven by ESLs, considered here as the sum of the mean sea level
35 (MSL), the astronomical tide (η_{tide}) and the episodic coastal water level rise (η_{CE}) due to storm surges
36 (SSL) and wave set ups. ESLs for present and future conditions were obtained according to the
37 approach described in Vousdoukas et al. (2018). Projections of SLR were extracted from Hinkel et al.
38 (2014), whereas present-state η_{tide} were obtained from the TOPEX/POSEIDON Global Inverse Solution
39 (Egbert and Erofeeva 2002). Given the focus on extreme events, the maximum tide (η_{tide}^{max}) was used.
40 DFLOW FM was then utilized to assess changes in global tidal elevations due to SLR (Vousdoukas et
41 al. 2017). Hindcasts of waves and storm surges (1980-2015) were obtained through dynamic
42 simulations forced by ERA-INTERIM atmospheric conditions. Storm surges were simulated using a
43 flexible mesh setup of the DFLOW FM model (Jagers et al. 2014; Muis et al. 2016), and waves using
44 the third generation spectral wave model WAVEWATCH III (Mentaschi et al. 2017).

45
46 Regarding tropical cyclone effects which are not represented in global re-analyses (Hodges et al.
47 2017), these have been simulated using the DFLOW FM model. The spider-web module (Deltares
48 2014) was utilized to generate higher resolution atmospheric forcing, considering all tropical cyclone
49 tracks since 1985, available by the IBTrACS best-track archive (Knapp et al. 2010). Each event
50 produced a global dataset of storm surge levels, since the domain of the tropical cyclone simulations
51 is global. These were then combined with those from the ERA-INTERIM reanalysis, selecting the
52 highest value. Cyclone effects on the waves were considered using the peak maxima of H_s measured

1
2
3
4 by altimeter data provided by 6 different satellites (Queffeuilou and Croizé-Fillon 2014): ERS-2,
5 ENVISAT, Jason 1 and 2, Cryosat 2 and SARAL-AltiKa. Projected changes in waves and storm surges
6 were estimated through simulations forced by outputs from 6 CMIP5 climate models (Vousdoukas et
7 al. 2018) for 1980-2005 and during the present century under RCP4.5 and RCP8.5. Storm surges and
8 waves result in episodic meteorological coastal water level rises that contribute to ESLs. Given the
9 lack in the detailed nearshore bathymetric/topographic data required to resolve wave nearshore
10 processes, the contribution of waves to ESL is limited to the nearshore wave set-up, not including
11 potential contribution from the wave run-up (see also Section 5).
12
13

14
15 Offshore H_s , T_p and mean wave direction has been provided by WAVEWATCH III. Offshore wave
16 characteristics vary between islands due to, amongst others, sheltering effects while obstacles which
17 are not resolved by the model resolution are handled by the approach described in Mentaschi et al.
18 (2018). Nearshore conditions (from 50 m water depth) were estimated through wave refraction and
19 shoaling calculations based on the approach described in Part II, Chapter 2 of the Coastal Engineering
20 Manual (CEM 2002). Wave incidence angles were obtained combining the mean wave direction from
21 the model data with the mean shoreline orientation along 500 m long coastline sections, whereas
22 seabed slope in the shoaling and surf zones was assumed as 1.5 %, a widely acceptable generic
23 approximation (CEM 2002). Wave set up was estimated also through a generic approximation in
24 relation to the significant wave height H_s that is based on an analytical solution of standard energy
25 balance and linear wave theory equations (Holthuijsen 2007). More elaborate approaches (e.g.
26 Zijlema et al. 2011; FEMA 2015) would have required detailed nearshore bathymetric information
27 that has not been available for the purposes of the study. Therefore, η_{CE} has been estimated
28 according to:
29
30
31
32
33
34
35

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

36
37
38 Non-stationary extreme value analysis (Mentaschi et al. 2016) was applied to the η_{CE} time series
39 to obtain values for different return periods, derived for historical and future runs. Final η_{CE}
40 projections were obtained after adjusting the reanalysis values according to the relative changes
41 obtained from the CMIP5 simulations. More details on the approach to estimate ESLs during the
42 present century can be found in Vousdoukas et al. (2017; 2018).
43
44
45

46
47 ESLs were projected for the Jamaican and Saint Lucian coasts for the baseline historical period
48 (1995), the 1.5 °C SWL and different periods in the century under different scenarios, for 9 return
49 periods (1, 1/5, 1/10, 1/20, 1/50, 1/100, 1/200, 1/500, 1/1000 years). Inundation maps for the critical
50 transportation assets were obtained following Vousdoukas et al. (2016), using the Lisflood-ACC (LFP)
51 model (e.g. Neal et al. 2011). Simulations were carried out for 2020, 2030, 2040, 2050, 2060, 2080
52 and 2100 under the examined RCPs.
53
54

55
56 In Jamaica, simulations were based on the SRTM DTM (1 arcseconds, about 30 m resolution),
57 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
58 characterized by vertical bias (e.g. Chirico 2004), bias correction was applied using in situ data of the
59
60
61
62
63
64
65

1
2
3
4 mean sea level and the terrain elevation, as follows: (i) elevations relative to mean sea level at
5 control areas (i.e. extensive flat areas such as airport runways and seaport berthing docks) were
6 obtained through communication with facility managers and in situ measurements; (ii) the elevation
7 was extracted from the DEM used in the inundation modelling for the same control areas; and (iii)
8 biases were corrected, ensuring that the DEM elevation is always expressed relative to MSL=0 (which
9 is the theoretical datum in the SRTM data). Finally, land hydraulic roughness was derived from land
10 use maps (<https://www.esa-landcover-cci.org/>).

15 **4. Results**

16 **4.1 Climatic operational thresholds**

17
18
19
20
21 The ability of airport and seaport staff to safely work outdoors depends on the Heat Index, i.e. a
22 combination of temperature and relative humidity. According to NOAA
23 (http://www.nws.noaa.gov/om/heat/heat_index.shtml), temperatures over 30.6 °C and 32.5 °C
24 combined with 80 % relative humidity present ‘high’ and ‘very high’ risks, respectively. Our analysis
25 suggests that, under the 1.5 °C SWL, staff working outdoors at the Jamaican and Saint Lucian
26 international transportation assets could be at ‘high’ risk for 5 and 2 days/year, respectively. Under a
27 standard SRES A1B scenario transient warming scenario, such days could increase to 30 and 55
28 days/year, respectively, by 2081-2100 (Table 1).

29
30
31
32 Higher temperatures will reduce aircraft lift, requiring reduced payloads and/or longer runways
33 (Coffel et al. 2017). Take-off length requirements vary by aircraft type. In this study, the temperature
34 thresholds beyond which aircraft used in the area will require runways longer than those currently
35 available at the Jamaican and Saint Lucian airports have been estimated, together with the number of
36 days over the threshold. For example, it was found that under the 1.5 °C SWL, Boeing 737-800
37 aircraft (Boeing 2013), which serve all studied airports, will have to decrease their take-off load for 65
38 days/year at SIA and 24 days/year at NMIA, whereas by the 2070s and under SRES A1B such days
39 could increase at least twofold for SIA and fourfold for NMIA (Table 1). As the maximum temperature
40 projections are available at a daily scale (as all used model projections), the degree of operational
41 disruptions that also depends on the duration of extreme heat during the day and on air traffic
42 schedules could not be detailed further. It should be noted that, the example in Table 1 refers to a
43 medium size/range aircraft that requires less lengthy runways than the long-haul aircrafts serving
44 Caribbean routes (e.g. the Boeing 777 series, UNCTAD (2017a)); therefore, the results shown in Table
45 1 are likely to represent conservative estimations of such operational disruptions. Finally, the
46 projections assume no targeted aircraft design changes.

47
48
49
50
51
52
53
54 Extreme heat can also raise energy demand/costs for heating, ventilation and cooling (HVAC)
55 systems. According to a generic standard, 1 °C warming will result in a 5 % increase in energy
56 requirements (assuming current technology) (IDB 2015). Using a temperature rise of about 0.7 °C
57 between the pre-industrial and the baseline (1986-2005) periods (Hawkins et al. 2017), increases in
58 energy requirements were estimated for 0.8, 1.3 and 3 °C temperature increases above the baseline,
59
60
61
62
63
64
65

1
2
3
4 i.e. for the 1.5 °C SWL and for 2 and 3.7 °C temperature increases since the pre-industrial levels,
5 respectively (Table 1). It was found that for the Jamaican seaports, the 1.5 °C SWL (2030) will increase
6 the baseline energy requirements by 4 % for 214 days/year, whereas a 3.7 °C rise (2081-2100) will
7 increase energy requirements by 15 % for 215 days/year. Saint Lucia seaports are projected to
8 experience similar trends (Table 1). Extreme rainfall can severely limit visibility and inhibit operations
9 (e.g. crane operations at commercial seaports). Future disruptions due to intense (> 20 mm/day) and
10 very heavy rainfall (> 50 mm/day) are projected not to differ significantly from those of the baseline
11 period (Table 1). Strong winds can prevent aircraft take-off and landing (with a generic passenger
12 aviation threshold of 11.2 m/s) and affect the manoeuvrability and berthing of ships at seaports;
13 winds over 18 m/s (40.3 mph) may force seaport shutdowns. Our projections show that future winds
14 will not appreciably affect airport and seaport operations on the basis of these thresholds (but see
15 also Nurse 2013).
16
17
18
19
20

21 It appears that most operational problems for the Jamaican and Saint Lucian critical coastal
22 transportation assets (apart from coastal inundation) will be due to rising temperatures, with rainfall
23 and wind effects projected to have minor impacts. However, as the climate projections from the
24 CCCCC database do not include the effects of tropical storms/hurricanes, these estimates might be
25 considered as conservative. Also, facility-specific operational sensitivities that cannot be captured by
26 generic thresholds (e.g. the disruptive effects of wind and wave directional changes on ship berthing)
27 may increase operational disruptions. In any case, large increases in operational disruptions are
28 projected, even under the AOSIS advocated 1.5 °C SWL.
29
30
31
32
33

34 **4.2 Extreme sea levels and coastal inundation**

35
36 Projected ESLs are higher in Jamaica than in Saint Lucia (Fig. 2). In Jamaica, the baseline 100-year
37 ESL (ESL_{100}), i.e. the combination of the SLR, tides and the 100-year η_{CE} has been estimated as 1.96
38 m, whereas in Saint Lucia the baseline 100-year ESL has been estimated as 1.29 m. ESLs in Jamaica
39 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
40 event, respectively (Fig. 2a); an increase of about 0.17 m is projected compared to baseline for the
41 100-year event. In Saint Lucia, ESL_{100} is estimated as 1.41 m under the 1.5 °C SWL. In both islands ESLs
42 are projected to increase during the century, with the rise being faster under RCP8.5 (Fig. 2b).
43
44
45
46

47 Estimation of the contributions of each of the components of the ESLs and their time evolution
48 has shown that whereas η_{CE} is the primary ESL contributor; its dominance will decrease in the course
49 of the century. For example, contributions of SLR, tides (η_{tide}^{max}) and η_{CE} to the ESL_{100} under the 1.5 °C
50 SWL in Jamaica have been estimated as about 7 %, 10 % and 83 % (for both RCP scenarios), whereas
51 in Saint Lucia, the estimates are 10 %, 20 % and 70 %, respectively. However, η_{CE} is projected not to
52 change much over the course of the century. In Jamaica, for example, the contributions of SLR, tides
53 (η_{tide}^{max}) and η_{CE} to the ESL_{100} change between the baseline and the 1.5 °C SWL have been estimated as
54 about 81 %, 5.1 % and 14 % (RCP 4.5) and 89 %, 5 % and 6 % (RCP8.5), respectively; for Saint Lucia,
55 such estimates have been 80 %, 17 % and 3 % (RCP 4.5) and 80 %, 16 % and 4 % (RCP8.5),
56
57
58
59
60
61
62
63
64
65

1
2
3
4 respectively. As the century progresses SLR is expected to gather pace and dominate further the ESL
5 increases (“Tables S5 and S6, Online Resource 4”).
6

7 The return periods of the extreme sea levels (ESLs) form fundamental design parameters for
8 coastal transportation infrastructure and/or any proposed technical adaptation measures. Thus, the
9 evolution of the return periods of extreme sea levels has been estimated for different periods in the
10 21st century. Our results suggest that the ESL return periods will significantly decrease over time (Fig.
11 2c, d). In Jamaica, the baseline ESL₁₀₀ will occur every 50 years under 1.5 °C SWL. By 2080, under
12 RCP8.5 the baseline 100-year event will occur about every 9 years (Fig. 2c) Our results also indicate
13 that the 100-year event projected under the 1.5 °C SWL will occur about every 6-7 years by 2100,
14 under RCP8.5 (“see also Table S4, Online Resource 4”). In Saint Lucia, the ESL return periods are
15 projected to decrease faster than in Jamaica. Under the 1.5 °C SWL, the baseline 100-year event will
16 occur about every 10 years, occurring every year after the early 2040s (Fig. 2d). The 100-year event
17 projected under the 1.5 °C SWL will occur about every 20 years by 2050 under RCP4.5.
18
19
20
21
22

23 In Jamaica, the low elevation of the SIA runway (approximately 1.2 - 1.4 m above MSL) will make
24 it increasingly vulnerable to coastal inundation during extreme events. Modelling results show that,
25 even under the 1.5°C SWL, the 100-year event will cause considerable flooding (Fig. 3). By 2050 under
26 RCP4.5, similar flooding is projected for the 50-year event (ESL₅₀). NMIA, located in Kingston harbour
27 bay, is less prone to coastal inundation, as its runway has an elevation in excess of 2 m and is also
28 adjacent to mangroves/saltmarshes that can reduce storm impacts. Both the NMIA and SIA airports
29 have experienced shutdowns during extreme events (“Online Resource 2”), with the disruptions in
30 NMIA being mostly associated with the inundation of the coastal airport access road; this road has
31 been recently raised and armoured, but not yet tested under a powerful event.
32
33
34
35

36 Under the 1.5 SWL, some areas of the KCT seaport are projected to be flooded under the 100-
37 year event, whereas by 2100 extensive areas will be affected (Fig. 4). Access roads are also projected
38 to be vulnerable to flooding. KCT has been previously vulnerable to extreme events, including strong
39 winds, energetic waves and terrestrial flash floods which have driven large volumes of debris into the
40 harbour (“Online Resource 2”). Finally, modelling results suggest that the HFCP cruise port will be
41 very moderately affected until the 2080s, even by events with return periods in excess of 200 years.
42 However, it appears that the low-lying access roads will be increasingly vulnerable to flooding;
43 according to port officials (pers. comm., S. Rhoden), this is already a problem, as is berthing under
44 certain wind and swell waves.
45
46
47
48

49 In Saint Lucia, the results (Fig. 5) show that several low-lying bay areas are under increased flood
50 risk (ICF GHK 2012), including the areas where the critical assets are located. Under the 1.5 °C SWL,
51 GCIA appears vulnerable to the 100-year event mostly at its northern side (Vigie beach), as the
52 western end of the runway is located at an elevated and armoured coastline. As the century
53 progresses, its vulnerability will increase (Fig. 5). Vigie beach, located only 30 m away from the
54 airport fence, has been projected to face also substantial beach erosion (UNCTAD 2017b); this will
55 further increase coastal inundation. Hewanorra International Airport (HIA) appears vulnerable at its
56 eastern (seaward) edge. There, the runway is projected to be inundated at lengths of about 150, 130,
57
58
59
60
61
62
63
64
65

1
2
3
4 and 380 m from the 100-year event under the 1.5 °C SWL, the 50-year event in 2050 under RCP4.5
5 and the 100-year event in 2100 under RCP8.5, respectively (Fig. 5). Until now, HIA has been mainly
6 impacted by strong rainfall events that, in some cases, forced overflowing of the redirected La
7 Tourney river (Fig. 5, “Online Resource 3”) resulting in severe airport flooding.
8
9

10 Port Castries (CSP) is projected to be severely affected by the 100-year event under the 1.5 °C
11 SWL. Coastal flooding will impact its docks, inundate its berths, cargo sheds and cruise ship facilities
12 and cause flooding of the city, the nation’s capital Castries. Later in the century, and under both RCP
13 scenarios tested, CSP flooding is projected to deteriorate in the absence of effective adaptation
14 measures. CSP has already experienced damages during extreme events, involving its breakwater
15 armor, revetment, fencing and roofing (“Online Resource 3”). Finally, the Vieux Fort Seaport (VFSP)
16 appears vulnerable to coastal flooding under all tested scenarios, a marked deterioration from the
17 present situation as reported by the facility managers (UNCTAD 2017b).
18
19
20
21
22

23 **5 Discussion**

24
25 Our projections show that critical transportation assets of the studied Caribbean SIDS will face
26 increasing operational disruptions and coastal inundation under climate change, even under the 1.5
27 °C SWL, which according to projections will regrettably be reached by the early 2030s. With regard to
28 operational disruptions, these are projected to be mostly due to rising temperatures, with rainfall
29 and wind changes (in relation to the baseline) projected to have small impacts. As regards coastal
30 inundation, some of the critical transportation assets in both countries have been projected to face
31 severe coastal flooding under the extreme sea levels forced by the 1.5 °C SWL; this is projected to
32 deteriorate and affect more assets later in the century. Saint Lucian ports and airports appear to be
33 generally more vulnerable to inundation than ports and airports in Jamaica. In this context it should
34 be noted that the lack of appropriate alternative locations, particularly in Saint Lucia, may have
35 driven asset placement in low-lying areas.
36
37
38
39
40

41 Our results show that η_{CE} is the primary ESL contributor, with its contribution ranging between
42 62 and 90 % of total ESL under the 1.5 °C SWL depending on the return periods and the RCP scenario.
43 Its contribution is projected to decrease in the course of the century, as SLR will become larger
44 whereas both future storm surge levels and wave set ups are projected to change very little (“see
45 Tables S5 and Table S6, Online Resource 4”). Therefore, future increases in the ESLs in Jamaica and
46 Saint Lucia are projected to be dominated by SLR (e.g. Vitousek et al. 2017; Vousdoukas et al. 2018).
47
48
49

50 The analysis of coastal hazards included dynamic projections of components and inundation
51 simulations using a hydrological model. However data availability and the long temporal window of
52 the study imposed some inevitable constraints in the employed approach, which are pointed out to
53 the reader. ESL estimation was based on the maximum tide, an approach which omits spring/neap
54 tidal variations and thus tends to overestimate ESLs. The timing of spring tides is rather deterministic,
55 but this is not the case for the timing of the climate extremes obtained from CMIP5 GCMs. For the
56 same RCP, different GCM ensembles can show substantial variability in the sequencing of
57
58
59
60
61
62
63
64
65

1
2
3
4 meteorological conditions. As a result, simulations would have to be repeated, with the tidal timing
5 probably varying in a Monte Carlo fashion, in order to capture the full probability range of
6 coincidence between extreme events and high tides. Such an approach would imply prohibitive
7 computational load, and was not employed.
8
9

10 Wave contributions to η_{CE} are considered only in the form of an increase in coastal sea level
11 due to wave set up. However, waves also transfer substantial momentum to the coast that may drive
12 coastal erosion (Vousdoukas et al. 2012b) and overwashing and/or breaching of coastal dunes and
13 dykes (Roelvink et al. 2009; McCall et al. 2010; Lynett et al. 2010), and damage structures (e.g.
14 Oumeraci 1994; Takagi et al. 2011; UNECE 2013). Such processes have not been included in the
15 analysis for the following reasons. Nearshore wave transformation requires both computationally
16 expensive modelling and accurate (nearshore) bathymetric information. Studies that consider climate
17 change impacts involve the analysis of several combinations of scenarios, including amongst others,
18 greenhouse gas emissions, time windows and return periods; such modelling would be prohibitive in
19 terms of computational loads. In addition, detailed bathymetric information is not available for the
20 study areas, both for the present and certainly for future conditions; nearshore morphology is very
21 dynamic, constantly changing under natural and anthropogenic factors. Wave run up heights, are not
22 included, even though they can be important drivers of coastal inundation (Stockdon et al. 2006;
23 Vousdoukas et al. 2012a; Perini et al. 2016; Monioudi et al. 2017), as they are sensitive to the
24 constantly changing beach-face slope (Vousdoukas 2012a). Therefore, consideration of waves refers
25 only to contributions of wave setup to ESLs and does not include wave run up and wave impacts on
26 coastal structures, as well as the spatio-temporal variability of impacts due to interactions with the
27 nearshore bathymetry and structures. In order to address these issues, high resolution coastal
28 bathymetric/topographic surveys are recommended for the Jamaican and Saint Lucia assets, so that
29 the full impacts of waves on these assets could be assessed under the present conditions.
30
31
32
33
34
35
36
37
38

39 On the basis of the above, the employed approach may underestimate asset vulnerability.
40 However, in climate change studies, missing data can result in additional uncertainty and, thus, wave
41 effects are often omitted (e.g. Garner et al. 2017; Hauer et al. 2016). Notwithstanding the above
42 constraints, the present study provides a first assessment of the vulnerability to CV & C of critical
43 transportation assets in Caribbean SIDS. Results could be improved if facility specific operational
44 thresholds, high resolution DEMs and accurate nearshore bathymetric information were available.
45
46
47

48 Coastal transportation assets could also be directly and indirectly impacted by additional hazards
49 and their combinations, making multi-hazard assessments (e.g. Forzieri et al. 2016) necessary for
50 effective adaptation planning. In Saint Lucia, flash floods and landslides are historical hazards, as
51 most of the roads traverse areas of high or extreme landslide risk. As a result, landslide densities of
52 up to 1.75/km (average density 0.75/km) have been recorded for the main road connecting HIA with
53 the capital Castries and the major tourist resorts located at the northwestern coast of the island (Fig.
54 1) (UNCTAD 2017b). These landslides can seriously compromise the connectivity of the international
55 tourist gateways with urban centers and tourist resorts, demanding redundancy adaptation options.
56
57
58
59
60
61
62
63
64
65

1
2
3
4 from the impacts of CV & C on the capital/product of other economic sectors, such as the tourism
5 industry. 3S' island tourism destinations, such as the Caribbean SIDS, are likely to be subjected to
6 deteriorating beach erosion (UNCTAD 2017b) which can have severe implications for the beach
7 carrying capacity for leisure and, ultimately, for tourism-related transportation demand.
8
9

10 Generally, coastal inundation is projected to increasingly impact the critical international
11 transportation assets (and their access roads) of both countries and detailed research is required to
12 identify the most effective adaptation options (Giardino et al. this issue). Here it should be noted that
13 coastal flood protection measures under a changing climate can be designed utilizing different
14 approaches, such as integrating safety factors and/or climate change robustness factors (i.e. applying
15 the precautionary principle), exploratory modeling for different future scenarios, robust decision
16 making and pathway planning (e.g. Klijn et al. 2015a). However, building fail-safe systems i.e. setting
17 the climate change robustness at too high a level and, thus, over-engineering coastal defenses could
18 be very costly (e.g. Narayan et al. 2016). Instead, building systems that would fail in a safe way ('safe-
19 fail') and that easily recover and/or can be upgraded after failure might be considered (Klijn et al.
20 2015b)
21
22
23
24
25

26 Given the physiographic, climatic and developmental similarity of Jamaica and Saint Lucia to the
27 remainder of the Caribbean SIDS, it is expected that the impacts of CV & C will present large
28 challenges to the international transportation assets and connectivity of most Caribbean (and other)
29 SIDS. This could severely compromise the achievement of several of the Sustainable Development
30 Goals (SDGs), notably, SDG 9, 13 and 1.5, which form an integral part of the international
31 community's agreed 2030 Sustainable Development Agenda.
32
33
34
35

36 **6 Conclusions**

37

38 The study results show high and increasing potential vulnerabilities to climatic changes of the
39 critical international transportation assets (airports and seaports) of Jamaica and Saint Lucia involving
40 both operational disruptions and coastal inundation from extreme events. Severe impacts are
41 projected, even under the AOSIS advocated temperature increase cap of 1.5 °C (SWL) which will be
42 reached in the early 2030s. These will deteriorate significantly in the course of the century.
43
44
45

46 Operational disruptions arising from climatic factor changes are projected to be mostly due to
47 rising temperatures, with rainfall and wind changes having minor impacts; however, projections did
48 not account for tropical storms. In addition, considerable, varied and increasing coastal inundation of
49 the assets is also projected, with the Sangster International Airport (SIA) in Jamaica and the Saint
50 Lucian airports and seaports being the most vulnerable.
51
52

53 In the absence of timely planning and implementation of requisite adaptation measures, the
54 projected impacts of climate variability and change on critical transport infrastructure may have
55 serious implications for the connectivity of SIDS to the international community and global markets,
56 as well as broad economic and trade-related repercussions, which may severely compromise the
57 sustainable development prospects of these vulnerable nations. Against this background, further
58
59
60
61
62
63
64
65

1
2
3
4 research, including detailed technical studies, as well as collaborative concerted action at all levels
5 are urgently required.
6
7

8 9 **Acknowledgments**

10
11 The authors gratefully acknowledge the support received under UN Development Account
12 Project 14150 (sidsport-climateadapt.unctad.org). Also acknowledged with thanks is the support by
13 the Disaster Risk Management Unit of the Joint Research Centre of the European Commission. The
14 study benefitted from valuable discussions with participants at two national workshops, in Saint Lucia
15 (24-26 May 2017) and in Jamaica (30 May-1 June 2017), and a regional workshop in Barbados (5-7
16 December 2017) which are also gratefully acknowledged.
17
18
19
20

21 **References**

- 22
23
24 Alfieri L, Bisselink B, Dottori F, Gustavo N, de Roo A, Salamon P, Wyser K, Feyen L (2017) Global
25 projections of river flood risk in a warmer world. *Earth's Future* 5:171–182.
26 doi:10.1002/2016EF000485
- 27 Asariotis R, Benamara H, Mohos-Naray V (2017) Port Industry Survey on Climate Change Impacts and
28 Adaptation. UNCTAD/SER.RP/2017/18
- 29 Becker A, Acciaro M, Asariotis R, Cabrera E, Cretegnny L, Crist P, Esteban M, Mather A, Messner S,
30 Naruse S, NG AKY, Rahmstorf S, Savonis M, Song DW, Stenek V, Velegrakis AF (2013) A note on
31 climate change adaptation for seaports: A challenge for global ports, a challenge for global society.
32 *Climatic Change* 120:683–695. doi:10.1007/s10584-013-0843-z
- 33 Becker A, Chase NTL, Fischer M, Schwegler B, Mosher K (2016) A method to estimate climate-critical
34 construction materials applied to seaport protection. *Global Environmental Change* 40:125–136.
35 doi:10.1016/j.gloenvcha.2016.07.008
- 36 Benjamin L, Thomas A (2016) 1.5 °C to stay alive? AOSIS and the long term temperature goal in the
37 Paris Agreement. *IUCNAEL e-Journal*. <http://www.iucnael.org/en/e-journal/current-issue>.
38 Accessed 10 May 2017
- 39 Bender MA, Knutson TR, Tuleya RE, Sirutis JJ, Vecchi GA, Garner ST, Isaac MH (2010) Modeled impact
40 of anthropogenic warming on the frequency of intense Atlantic hurricanes. *Science* 327:454–458.
41 doi:10.1126/science.1180568
- 42 Boeing (2013) 737 Airplane Characteristics for Airport Planning.
43 <http://www.boeing.com/assets/pdf/commercial/airports/acaps/737.pdf>. Accessed 10 May 2017
- 44 Bueno R, Herzfeld C, Stanton E, Ackerman F (2008) The Caribbean and Climate Change. The costs of
45 inaction. Stockholm Environment Institute — US Center Global Development and Environment
46 Institute, Tufts University. <http://ase.tufts.edu/gdae/Pubs/rp/Caribbean-full-Eng.pdf>. Accessed 6
47 June 2017
- 48 CARIBSAVE (2012) The CARIBSAVE Climate Change Risk Atlas – Climate Change Risk Profile for Saint
49 Lucia. Final draft Country Risk Profile. Caribbean Community Climate Change Centre.
50 <http://dms.caribbeanclimate.bz/M-Files/openfile.aspx?objtype=0&docid=5047>. Accessed 06
51 September 2016
- 52 CEM (2002) Coastal Engineering Manual. U.S. Army Corps of Engineers, Washington, DC
- 53 Chirico PG (2004) An evaluation of SRTM, ASTER, and contour based DEMs in the Caribbean region.
54 Proceedings of the URISA 2004 Caribbean GIS conference, Barbados, 2004. URISA- The Association
55 for GIS Professionals, Des Plaines, IL, pp 209-219
56
57
58
59
60
61
62
63
64
65

- 1
2
3
4 Coffel ED, Thompson TR, Horton, RM (2017) The impacts of rising temperatures on aircraft takeoff
5 performance. *Climatic Change*. doi:10.1007/s10584-017-2018-9
6
7 CSGM (2012) State of the Jamaican Climate 2012: Information for Resilience Building (Summary for
8 Policymakers). Report to the Planning Institute of Jamaica (PIOJ). Climate Studies Group, Mona,
9 Kingston, Jamaica
10
11 Deltares (2014) Delft3D-FLOW: Simulation of multi-dimensional hydrodynamic flows and transport
12 phenomena, including sediments. User Manual. 3.15.34158 edn. Deltares, Delft, The Netherlands
13
14 Draper G, Jackson TA, Donovan SK (1994) Geologic Provinces of the Caribbean Region. *Caribbean
15 Geology: An Introduction*, U.W.I. Publishers' Association, Kingston, pp 3-12
16
17 Egbert GD, Erofeeva SY (2002) Efficient Inverse Modeling of Barotropic Ocean Tides. *Journal of
18 Atmospheric and Oceanic Technology* 19:183-204. doi:10.1175/1520-
19 0426(2002)019<0183:EIMOBO>2.0.CO;2
20
21 ESL (2015) Impact Assessment and National Adaptation Strategy and Action Plan to Address Climate
22 Change in the Tourism Sector, Saint Lucia. Caribbean Community Climate Change Centre (CCCCC)
23 and the Government of Saint Lucia (GoSL), EU-GCCA Caribbean Support Project, pp 111
24
25 Fay M, Andres LA, Fox CJE, Narloch UG, Straub S, Slawson MA (2017) Rethinking infrastructure in
26 Latin America and the Caribbean: spending better to achieve more. Washington DC: World Bank
27 Group.
28 [http://documents.worldbank.org/curated/en/676711491563967405/Rethinking-infrastructure-in-
29 Latin-America-and-the-Caribbean-spending-better-to-achieve-more](http://documents.worldbank.org/curated/en/676711491563967405/Rethinking-infrastructure-in-Latin-America-and-the-Caribbean-spending-better-to-achieve-more). Accessed 20 August 2017
30
31 FEMA (2015) Guidance for Flood Risk Analysis and Mapping: Coastal Wave Setup. Federal Emergency
32 Management Agency Guidance Document 44.
33 [https://www.fema.gov/media-library-data/1451318472953-
34 ecb5bd1400a8c9cfe3ff7fe64c4daf21/Coastal_Wave_Setup_Guidance_Nov_2015.pdf](https://www.fema.gov/media-library-data/1451318472953-ecb5bd1400a8c9cfe3ff7fe64c4daf21/Coastal_Wave_Setup_Guidance_Nov_2015.pdf). Accessed 5
35 March 2018
36
37 Forzieri G, Feyen L, Russo S, Vousdoukas M, Alfieri L, Outten S, Migliavacca M, Bianchi A, Rojas R, Cid
38 A (2016) Multi-hazard assessment in Europe under climate change. *Climatic Change* 137:105-119.
39 doi:10.1007/s10584-016-1661-x
40
41 Garner AJ, Mann ME, Emanuel KA, Kopp RE, Lin N, Alley RB, Horton BP, DeConto RM, Donnelly JP,
42 Pollard D (2017) Impact of climate change on New York City's coastal flood hazard: Increasing
43 flood heights from the preindustrial to 2300 CE. *Proceedings of the National Academy of Sciences*
44 114:11861-11866
45
46 Giardino A, Nederhoff C, Vousdoukas MI (2018) Coastal hazard risk assessment for small islands:
47 assessing the impact of climate change and disaster reduction measures on Ebeye (Marshall
48 Islands). *Journal of Regional Environmental Change* (accepted)
49
50 Hauer ME, Evans JM, Mishra DR (2016) Millions projected to be at risk from sea-level rise in the
51 continental United States. *Nature Climate Change* 6:691-695. doi:10.1038/nclimate2961
52
53 Hawkins E, Ortega P, Suckling E, Schurer A, Hegerl G, Jones P, Joshi M, Osborn T, Masson-Delmotte V,
54 Mignot J, Thorne P, van Oldenborgh G (2017) Estimating changes in global temperature since the
55 pre-industrial period. *Bulletin of the American Meteorological Society*. doi:10.1175/BAMS-D-16-
56 0007.1
57
58 Hinkel J, Lincke D, Vafeidis AT, Perrette M, Nicholls RJ, Tol RSJ, Marzeion B, Fettweis X, Ionescu C,
59 Levermann A (2014) Coastal flood damage and adaptation costs under 21st century sea-level rise.
60 *Proceedings of the National Academy of Science USA* 111(9):3292–3297.
61 doi:10.1073/pnas.1222469111
62
63 Hodges K, Cobb A, Vidale PL (2017) How well are tropical cyclones represented in reanalysis datasets?
64 *Journal of Climate* 30: 5243-5264. doi:10.1175/JCLI-D-16-0557.1
65
66 Holthuijsen LH (2007) *Waves in Oceanic and Coastal Waters*. Cambridge University Press

- 1
2
3
4 ICF GHK (2012) Climate change adaptation planning in Latin American and Caribbean cities. Final
5 report Castries, Saint Lucia, pp 156
6
7 IDB (2015) Port of Manzanillo: Climate Risk Management (Final Report). Inter-American Development
8 Bank. <https://publications.iadb.org/handle/11319/7649>. Accessed 05 May 2017
9
10 Jagers B, Rego JL, Verlaan M, Lalic A, Genseberger M, Friocourt Y, van der Pijl S (2014) A Global Tide
11 and Storm Surge Model with a Parallel Unstructured-Grid Shallow Water Solver. American
12 Geophysical Union Fall Meeting Abstracts 1:5. doi:2014AGUFMOS21E..05J
13
14 Jevrejeva S, Moore JC, Grinsted A (2012) Sea level projections to AD2500 with a new generation of
15 climate change scenarios. *Global and Planetary Change* 80-81:14-20.
16 <https://doi.org/10.1016/j.gloplacha.2011.09.006>
17
18 Knapp KR, Kruk MC, Levinson DH, Diamond HJ, Neumann CJ (2010) The International Best Track
19 Archive for Climate Stewardship (IBTrACS): Unifying tropical cyclone best track data. *Bulletin of*
20 *the American Meteorological Society* 91:363-376. doi:10.1175/2009BAMS2755.1
21
22 Kreft S, Eckstein D, Melchior I (2016) Global Climate Risk Index 2017. Who suffers most from extreme
23 weather events? Weather-related loss events in 2015 and 1996 to 2015.
24 <https://germanwatch.org/en/download/16411.pdf>. Accessed 02 November 2016
25
26 Klijn F, Kreibich H, de Moel H, Penning-Rowsell EC (2015a) Adaptive flood risk management planning
27 based on a comprehensive flood risk conceptualization. *Mitigation and Adaptation Strategies for*
28 *Global Change* 20:845- 864. <https://doi.org/10.1007/s11027-015-9638-z>
29
30 Klijn F, Merz B, Penning-Rowsell EC, Kundzewicz ZW (2015b) Preface: climate change proof flood risk
31 management. *Mitigation and Adaptation Strategies for Global Change* 20:837–843.
32 <https://doi.org/10.1007/s11027-015-9663-y>
33
34 Lynett PJ, Melby LA, Kim D-H (2010) An application of Boussinesq modeling to hurricane wave
35 overtopping and inundation. *Ocean Engineering* 37(1):135-153.
36 <https://doi.org/10.1016/j.oceaneng.2009.08.021>
37
38 Macdonald R, Hawkesworth CJ, Heath E (2000) The Lesser Antilles volcanic chain: a study in arc
39 magmatism. *Earth Science Reviews* 49:1-76. doi:10.1016/S0012-8252(99)00069-0
40
41 McCall RT, Van Thiel de Vries JSM, Plant NG, Van Dongeren AR, Roelvink JA, Thompson DM, Reniers
42 AJHM (2010) Two-dimensional time dependent hurricane overwash and erosion modeling at
43 Santa Rosa Island. *Coastal Engineering* 57:668-683. doi:10.1016/j.coastaleng.2010.02.006
44
45 Mentaschi L, Vousdoukas MI, Voukouvalas E, Sartini L, Feyen L, Besio G, Alfieri L (2016) Non-
46 stationary Extreme Value Analysis: A simplified approach for Earth science applications. *Hydrol.*
47 *Earth Syst. Sci. Discuss.* 1–38. doi:10.5194/hess-2016-65
48
49 Mentaschi L, Vousdoukas MI, Voukouvalas E, Dosio A, Feyen L (2017) Global changes of extreme
50 coastal wave energy fluxes triggered by intensified teleconnection patterns. *Geophysical Research*
51 *Letters* 44(5):2416–2426. doi:10.1002/2016GL072488
52
53 Mentaschi L, Kakoulaki G, Vousdoukas MI, Voukouvalas E, Feyen L, Besio G (2018) Parameterizing
54 unresolved obstacles with source terms in wave modeling: a real-world application. *Ocean*
55 *Modelling* 126:77–84. <https://doi.org/10.1016/j.ocemod.2018.04.003>
56
57 Monioudi IA, Velegrakis AF, Chatzipavlis AE, Rigos A, Karambas T, Vousdoukas MI, Hasiotis T,
58 Koukouroufli N, Peduzzi P, Manoutsoglou E, Poulos SE, Collins MB (2017) Assessment of island
59 beach erosion due to sea level rise: The case of the Aegean Archipelago (Eastern Mediterranean).
60 *Natural Hazards and Earth System Science* 17:449–466. doi:10.5194/nhess-17-449-2017
61
62 Muis S, Verlaan M, Winsemius HC, Aerts JCH, Ward PJ (2016) A global reanalysis of storm surges and
63 extreme sea levels. *Nature Communications* 7:1-11. doi:10.1038/ncomms11969
64
65 Narayan S, Beck MW, Reguero BG, Losada IJ, van Wesenbeeck B, Pontee N, Sanchirico JN, Ingram JC,
Lange G-M, Burks-Copes KA (2016) The Effectiveness, Costs and Coastal Protection Benefits of

- 1
2
3
4 Natural and Nature-Based Defences. PLoS ONE 11(5):e0154735.
5 doi:10.1371/journal.pone.0154735
6
7 Neal J, Schumann G, Fewtrell T, Budimir M, Bates P, Mason D (2011) Evaluating a new LISFLOOD-FP
8 formulation with data from the summer 2007 floods in Tewkesbury, UK. *Journal of Flood Risk*
9 *Management* 4(2):88-95. doi:10.1111/j.1753-318X.2011.01093.x
10
11 Nurse L (2013) *Climate Change Impacts and Risks: The Challenge for Caribbean Ports*, STC-13, April
12 15-18 Georgetown, Guyana
13
14 Nurse LA, McLean RF, Agard J, Briguglio LP, Duvat-Magnan V, Pelesikoti N, Tompkins E, Webb A
15 (2014) Small islands. In: Barros VR, Field CB, Dokken DJ, Mastrandrea MD, Mach KJ, Bilir TE,
16 Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S,
17 Mastrandrea PR, White LL (eds) *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part*
18 *B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the*
19 *Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, pp 1613-
20 1654
21
22 Oumeraci H (1994) Review and analysis of vertical breakwater failures — lessons learned. *Coastal*
23 *Engineering* 22:3-29. doi:10.1016/0378-3839(94)90046-9
24
25 Perini L, Calabrese L, Salerno G, Ciavola P, Armaroli C (2016) Evaluation of coastal vulnerability to
26 flooding: comparison of two different methodologies adopted by the Emilia-Romagna region
27 (Italy). *Natural Hazards Earth System Science* 16:181-194. doi:10.5194/nhess-16-181-2016
28
29 Phillips MR, Jones AL (2006) Erosion and tourism infrastructure in the coastal zone: Problems,
30 consequences and management. *Tourism Management* 27(3):517–524.
31 <https://doi.org/10.1016/j.tourman.2005.10.019>
32
33 PIOJ (2012) *A Growth-Inducement Strategy for Jamaica in the Short and Medium Term*. Planning
34 Institute of Jamaica Publications, Oxford Rd. Kingston, Jamaica.
35 <https://webstore.pioj.gov.jm/images/PreviewDocument/196.pdf>. Accessed 17 July 2017
36
37 Queffeuilou P, Croizé-Fillon D (2014) Global altimeter SWH data set. Rep., Laboratoire
38 d'Océanographie Spatiale, IFREMER
39
40 Rhiney K (2015) Geographies of Caribbean vulnerability in a changing climate: Issues and trends.
41 *Geography Compass* 9(3):97-114. <https://doi.org/10.1111/gec3.12199>
42
43 Roelvink D, Reniers A, Dongeren Av, Vries JvTd, McCall R, Lescinski J (2009) Modelling storm impacts
44 on beaches, dunes and barrier islands. *Coastal Engineering* 56:1133-1152.
45 <https://doi.org/10.1016/j.coastaleng.2009.08.006>
46
47 Scott D, Simpson MC, Sim R (2012) The vulnerability of Caribbean coastal tourism to scenarios of
48 climate change related sea level rise. *Journal of Sustainable Tourism* 20(6):883-898.
49 <https://doi.org/10.1080/09669582.2012.699063>
50
51 Simpson MC, Scott D, Harrison M, Silver N, O'Keeffe E, Harrison S, Taylor M, Sim R, Lizcano G, Wilson
52 M, Ruddy M, Stager H, Oldham J, New M, Clarke J, Day OJ, Fields N, Georges J, Waithe R, McSharry
53 P (2010) *Quantification and Magnitude of Losses and Damages Resulting from the Impacts of*
54 *Climate Change: Modelling the Transformational Impacts and Costs of Sea Level Rise in the*
55 *Caribbean (Full Document)*. United Nations Development Programme (UNDP), Barbados, West
56 Indies
57
58 Stephenson TS, Jones JJ (2017) *Impacts of Climate Change on Extreme Events in the Coastal and*
59 *Marine Environments of Caribbean Small Island Developing States (SIDS)*. Caribbean Marine
60 *Climate Change Report Card: Science Review 2017*, pp 10-22
61
62 Stockdon HF, Holman RA, Howd PA, Sallenger JAH (2006) Empirical parameterization of setup, swash,
63 and runup. *Coastal Engineering* 53:573-588. <https://doi.org/10.1016/j.coastaleng.2005.12.005>
64
65 Takagi H, Kashihara H, Esteban M, Shibayama T (2011) Assessment of future stability of breakwaters
under climate change. *Coastal Engineering* 53:21-39. doi:10.1142/S0578563411002264

- 1
2
3
4 Taylor KE, Stouffer RJ, Meehl GA (2012) An overview of CMIP5 and the experiment design. *Bulletin of*
5 *the American Meteorological Society* 93:485-499. doi:10.1175/BAMS-D-11-00094.1
6
7 Taylor M (2017) The Caribbean 1.5 Project, A brief overview of a regional climate change impacts
8 project, The Physical Basis. International Conference on Climate Change for the Caribbean,
9 October 9-12, Port of Spain
10
11 Torres RR, Tsimplis MN (2013) Sea-level trends and interannual variability in the Caribbean Sea.
12 *Journal of Geophysical Research* 118:2934–2947. doi:10.1002/jgrc.20229
13
14 UNCTAD (2014) Small Island Developing States: Challenges in transport and trade logistics. Multi-Year
15 Expert Meeting on Transport, Trade Logistics and Trade Facilitation, Third Session, 24-26/11/2014,
16 Trade and Development Commission
17 http://unctad.org/meetings/en/SessionalDocuments/cimem7d8_en.pdf. Accessed 9 May 2017
18
19 UNCTAD (2017a) Climate Change Impacts on Coastal Transportation Infrastructure in the Caribbean:
20 Enhancing the Adaptive Capacity of Small Island Developing States (SIDS), JAMAICA: A Case study.
21 UNDA Project 14150
22
23 UNCTAD (2017b) Climate Change Impacts on Coastal Transportation Infrastructure in the Caribbean:
24 Enhancing the Adaptive Capacity of Small Island Developing States (SIDS), SAINT LUCIA: A Case
25 study. UNDA Project 14150
26
27 UNECE (2013) Climate Change Impacts and Adaptation for International Transport Networks. Expert
28 Group Report, ITC, UN Economic Commission for Europe ECE/TRANS/238, pp 223.
29 http://www.unece.org/fileadmin/DAM/trans/main/wp5/publications/climate_change_2014.pdf.
30 Accessed 23 May 2017
31
32 UNECLAC (2011) An assessment of the economic impact of climate change on the transportation
33 sector in Barbados. UN Economic Commission for Latin America and the Caribbean ECLAC
34 Technical Report LC/CAR/L309. pp 44
35
36 van Vuuren DP, Carter TR (2014) Climate and socio-economic scenarios for climate change research
37 and assessment: reconciling the new with the old. *Climatic Change* 122:415-429.
38 <https://doi.org/10.1007/s10584-013-0974-2>
39
40 Vitousek S, Barnard PL, Fletcher CH, Frazer N, Erikson L, Storlazzi CD (2017) Doubling of coastal
41 flooding frequency within decades due to sea-level rise. *Scientific Reports* 7:1399.
42 doi:10.1038/s41598-017-01362-7
43
44 Vousdoukas MI, Wziatek D, Almeida LP (2012a) Coastal vulnerability assessment based on video wave
45 run-up observations at a mesotidal, steep-sloped beach. *Ocean Dynamics* 62:123-137.
46 <https://doi.org/10.1007/s10236-011-0480-x>
47
48 Vousdoukas MI, Almeida LP, Ferreira Ó (2012b) Beach erosion and recovery during consecutive
49 storms at a steep-sloping, meso-tidal beach. *Earth Surf Processes Landforms* 37:583-691.
50 doi:10.1002/esp.2264
51
52 Vousdoukas MI, Voukouvalas E, Mentaschi L, Feyen L (2016) Developments in large-scale coastal
53 flood hazard mapping. *Natural Hazards Earth System Science* 16(8):1841–1853.
54 doi:10.5194/nhess-16-1841-2016
55
56 Vousdoukas MI, Mentaschi L, Voukouvalas E, Verlaan M, Feyen L (2017) Extreme sea levels on the
57 rise along Europe’s coasts. *Earth’s Future* 5(3):304–323. doi:10.1002/2016EF000505
58
59 Vousdoukas MI, Mentaschi L, Voukouvalas E, Verlaan M, Jevrejeva S, Jackson L, Feyen L (2018) Global
60 probabilistic projections of extreme sea levels. *Nature Communications* (accepted)
61
62 Zijlema M, Stelling G, Smit P (2011) SWASH: An operational public domain code for simulating wave
63 fields and rapidly varied flows in coastal waters. *Coastal Engineering* 58:992-1012.
64 <https://doi.org/10.1016/j.coastaleng.2011.05.015>
65

1
2
3
4
5
6 **Figure captions**
7

8 **Fig. 1** Location of the critical transportation assets of Jamaica and Saint Lucia. Key: SIA, Sangster
9 International Airport; HFCP, Historic Falmouth Cruise Port; NMIA, Norman Manley International
10 Airport; KCT, Kingston Freeport and Container Terminal; HIA, Hewanorra International Airport; VFSP,
11 Vieux Fort Seaport; GCIA, George Charles International Airport; and CSP, Port Castries (“see also
12 Online Resource 1”). The location of the tide gauges in Cuba and Martinique is also shown. Digital
13 Elevation Model data from SRTM DTM were used for the 2 islands; Caribbean bathymetric data from
14 GEBCO_2014 Grid, <http://www.gebco.net/>
15
16

17
18 **Fig. 2** Time evolution of Extreme Sea Levels (ESLs; defined as the sum of the mean sea level, the
19 maximum astronomical tide and the episodic water level rise due to storm surge and wave set up) in
20 relation to their baseline return periods for the 20- 50- and 100-year event, under RCP4.5 and
21 RCP8.5, and for Jamaica (a, c) and Saint Lucia (b, d). The stippled line represents the projected year
22 the 1.5 °C temperature increase since the pre-industrial period is reached
23
24

25 **Fig. 3** Inundation of Sangster International Airport (SIA) (a, c, e) and Norman Manley International
26 Airport (NMIA) (b, d, f) under the 100-year event and 1.5 °C SWL (a, b), the 50-year event in 2050
27 under RCP4.5 (c, d) and the ESL_{100} in 2100, under RCP8.5 (e, f). Inundation simulations followed
28 Vousdoukas et al. (2016), using the Lisflood-ACC (LFP) model. DEM resolution is of about 5 m. DEM
29 was corrected for vertical biases; elevation is expressed relative to MSL=0
30
31

32 **Fig. 4** Inundation of Kingston Freeport and Container Terminal (KCT) (a, c, e) and Historic Falmouth
33 Cruise Port (HFCP) (b, d, f) under the 100-year event and 1.5 °C SWL (a, b), the 50-year event in 2050
34 under RCP4.5 (c, d), and the ESL_{100} in 2100 under RCP8.5 (e, f)
35
36

37 **Fig. 5** Inundation of (a, c, e) George Charles International Airport (GCIA) and Castries Seaport (CSP)
38 and (b, d, f) Hewanorra International Airport (HIA) and Vieux Fort Seaport (VFSP) under the 100-year
39 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
40 under RCP8.5 (e, f)
41
42
43
44

45 **Table captions**
46

47 **Table 1** Days of disruptions projected for the Jamaica and Saint Lucia airports and seaports. Heat
48 Index is a measure of the human feeling of heat when relative humidity is factored in with the actual
49 air temperature (http://www.nws.noaa.gov/om/heat/heat_index.shtml). Aircraft take-off length
50 requirements according to the manufacturer manuals. Estimations for aircraft lift assume no related
51 design advances. Impacts in energy costs and crane operation were based on generic thresholds from
52 IDB (2015). Note: Temperature related disruptions are assessed for temperature increases in relation
53 to the 1986-2005 (baseline) average that was about 0.7 °C above the pre-industrial level
54
55
56
57
58
59
60
61
62
63
64
65

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,

1
2
3
4 they still have considerable concerns regarding the coastal inundation methodology. Please take
5 great care in addressing these concerns in your resubmission.
6

7
8 Note that I have set the a 12 days deadline for your resubmission in order to allow for a
9 consideration of your resubmitted manuscript before May 15. I understand that this is a very
10 tight timeline. Please let me know if it is not feasible for you to address the comments with the
11 scientific rigour required and we shall extend your deadline accordingly.
12

13 Best Regards,

14 Carl

15
16 *Authors: We would like to thank the editor for his suggestions and we did our best to address the*
17 *reviewers' comments on time.*
18
19
20
21

22 Reviewer #3

23 This contribution explains interesting aspects on the impacts of sea level rise on Low Elevation
24 Coastal Zones (LE CZ) in Caribbean SIDS. Reviewer One points out reservations subject to change
25 with regards to the analysis of inundation modeling. While most of these points have been
26 addressed within the revision, we suggest adding the following improvements which will
27 significantly enhance the quality of this paper.
28

29 In the discussion, a statement should be added explaining how wave heights may vary around
30 islands. Potentially, sheltering effects become important when calculating impacting wave
31 energies.
32
33

34 *Authors: Information on the way waves are considered in the methodology has been extended*
35 *(Section 3.2, 3rd paragraph) according to suggestions from both reviewers.*
36
37
38

39 The calculation of offshore wave heights should be explained in more detail. At the moment, it is
40 unclear how regional model outputs were obtained and validated (Section 3.2).
41

42 *Authors: Recently a paper describing in detail the methodology to obtain the projections of SLR,*
43 *tides, waves and storm surges has been accepted in Nature Communications and is in production*
44 *stage and we are citing it in the revision (Vousdoukas et al., 2018). In addition there is a paper*
45 *dedicated to the wave projections (Mentaschi et al., 2017), and another also explaining the*
46 *methodology (Vousdoukas et al., 2017). The number of previous publications is indicative of the*
47 *amount of work involved in generating these projections, combining different models, scenarios,*
48 *etc. Therefore, we think that would be impossible to describe the procedures in detail, taking*
49 *also into account the space limitations. Still, we have added additional clarifications on the*
50 *estimations of the ESL components (e.g. in Section 3.2, 3rd paragraph). We are also confident*
51 *that, following publication of the Nature Communications paper, the reader can have all*
52 *information to follow the methodology in detail.*
53
54
55
56
57

58 Wave directions and power may change during different spatial and temporal scales; we suggest
59 adding statements reflecting on this.
60
61
62
63
64
65

1
2
3
4
5
6 *Authors: We have used WAVEWATCH III that does capture different scales as the reviewer*
7 *mentions. In any case, we now refer to spatio-temporal scaling in the revised discussion on wave*
8 *effects added in this revision (Section 5, 4th paragraph).*
9

10
11
12 Finally, a few sentences explaining field sites will be useful. Section 2 is very broad scale and
13 lacks detail of local environmental specifications - These may become important when
14 considering future shoreline adjustments to external forcing.
15

16 *Authors: In response to this comment, we have added additional relevant information (Section 2,*
17 *2nd and 3rd paragraphs)*
18
19

20
21 Overall, a general rework of the manuscript is recommended for correcting minor orthographic
22 mistakes.
23

24 *Authors: We went through the paper carefully and such mistakes have been eliminated*
25
26

27
28 Once all these points have been addressed to the reviewer satisfaction, I take no issue for
29 publication of this article in 'Regional Environmental Change'.
30
31

32
33
34 **Reviewer #1:**
35 **General**
36

37 The revised paper describes a methodology that disregards the significant effect of waves in
38 hurricane damage in coastal areas.
39

40 The importance of wave action is part of proven flood mapping methodologies by FEMA and
41 others. FEMA uses the concept of Base Flood Elevation, which includes the wave crest and has
42 been shown to be appropriate for evaluation of coastal storm damage. ESL, as defined by the
43 authors, is insufficient to assess vulnerability in coastal areas where waves are expected to
44 impact facilities during extreme events. The authors try to justify this omission, without
45 discussing the limitations of the proposed method, as opposed to recommending that their
46 method be used in cases where wave effects are not expected to be significant. Unfortunately, I
47 disagree with their response.
48
49

50
51
52 *Authors: We agree with the reviewer in all his statements about the importance of waves and*
53 *many of the authors have substantial experience in monitoring and modelling nearshore wave*
54 *processes (including wave run up), erosion and hazard in different environmental settings*
55 *(Broekema et al., 2016; Schimmels et al., 2012; Vousdoukas, 2014; Vousdoukas et al., 2012a;*
56 *Vousdoukas et al., 2014; Vousdoukas et al., 2009a; Vousdoukas et al., 2009b; Vousdoukas et al.,*
57 *2012b; Velegrakis et al 2016). We also acknowledge that waves in flooded areas during an*
58
59
60
61
62
63
64
65

1
2
3
4 extreme event can assault coastal transportation assets in a manner that these assets are not
5 designed for (UNECE 2013).
6

7 However in climate change studies there is: (i) a general lack in nearshore seabed and swash
8 zone bathymetric/topographic and sedimentary information to set up the models as well as
9 inherent uncertainties involving such information in the future and under a changing climate;
10 and (ii) a need to assess several scenarios during multiple time windows that act as bottlenecks
11 to the amount of detail in terms of the methodology applied. We would like also to refer to
12 recent studies on climate change hazards published in high impact journals which for that reason
13 have neglected waves (Garner et al. 2017; Hauer et al. 2016), although they focused on the US
14 coast where data availability is far better than in the Caribbean SIDS.
15
16

17 Still we acknowledge the significance of the point raised and we have tried to include an
18 improved and more extensive discussion of the constraints in the methodology as well as to
19 make clear that wave run up and power can have additional impacts (see Section 5, 4th and 5th
20 paragraphs). We also made it clear in different sections that estimations involve only wave set
21 up contributions and not of wave run up (e.g. Section 3.2, 2nd paragraph). We also acknowledge
22 that the previous Methodology and Discussion sections were not sufficiently clear and missing
23 certain aspects; in the revised manuscript we have addressed these issues.
24
25
26
27

28 Comment 1 29

30 The authors disregard the importance of wave effects in flood maps. The authors have not
31 addressed the request to compare their method and assumptions to the extensive experience of
32 US FEMA and their flood mapping methodologies (R1-2 and R1-4). As such, discussion in section
33 4.3 is considered insufficient.
34

35 *Authors:* We would like to clarify that the applied methodology omits wave run up effects but not
36 wave effects overall. Moreover, although authors have the expertise to conduct an analysis that
37 will involve such effects (see also previous comment), detailed analysis as prescribed by US
38 (FEMA) requires data that are not available, both for present and future conditions. Still as
39 mentioned previously, we have clarified the issue in the Methodology Section (Section 3.2, see
40 e.g. beginning of the 1st and the end of the 2nd paragraphs) and extended the relevant discussion
41 (Section 5, 4th and 5th paragraph) according to the reviewer's comments.
42
43
44
45

46 In section 4.3 of the paper and in response to R1-2, the authors imply that waves are not
47 significant for inundation mapping because they act at a smaller temporal scale. This answer
48 implies that only continuous flooding (still water level) is important, which is not accurate. The
49 answer disregards the fact that coastal hazard analysis in the US and Australia (subject to
50 tropical cyclones) is predicated on the proven fact that wave impacts matter.
51
52

53 *Authors:* We acknowledge that the text was not written clearly, but we never argued that waves
54 are not significant. This is the reason that we include them, while this is not the case for most
55 climate change studies (see also discussion in Vousdoukas et al., 2016). We have now tried to
56 make it clear in different Sections (Sections 3.2, 4 and 5).
57
58
59
60
61
62
63
64
65

1
2
3
4 Further to question their response, simplified models and assumptions based on experience
5 (which are part of the FEMA standard methodology) provide practical solutions to the inclusion
6 of the effects described in the response to R1-2. Disregarding wave effects in the methodology
7 underestimates vulnerability evaluations, so this methodology is not adequate to assess
8 vulnerability in coastal areas where wave effects should be expected.
9

10
11 *Authors: See previous replies.*
12
13

14 **Comment 2**

15
16 The authors justify omissions of major physical effects in the fact that they cannot obtain data.
17 This does not seem an appropriate explanation in a scientific paper that proposes a
18 methodology to assess vulnerability.
19

20
21 *Authors: The reviewer does not take into account that the aim of our methodology/study has*
22 *been to assess vulnerability under certain scenarios of climate change and well into the future*
23 *and not to conduct a detailed assessment of the present day vulnerability that will be required*
24 *for the planning/design of effective technical adaptation measures. In the latter case, detailed*
25 *data on nearshore bathymetry, swash zone and facility topography would have been required,*
26 *together with the collection/analysis of time series of nearshore directional wave and flow*
27 *information to drive and validate the models; high frequency monitoring of the storm effects*
28 *would also be required to evaluate the actual wave effects on coastal morphodynamics. Such*
29 *studies require very substantial human and financial resources and, ultimately, also rely on*
30 *assumptions involving the stationarity of the coastal bathymetry/topography under a storm*
31 *event.*
32
33

34
35 *As, however, our purpose has been to provide an assessment under different scenarios of climate*
36 *change such an analysis could not be undertaken, not only due to the non-availability of the*
37 *necessary present day information, but also due the uncertainties involving the future nearshore*
38 *topography under a changing climate. Moreover, we think that the computational effort*
39 *involved for such an assessment, as well as inherent uncertainties in the climate change*
40 *projections do not support the undertaking of such projections. Nevertheless, we acknowledge*
41 *that we should have discussed these issues in more detail, which we now do in the revised*
42 *manuscript (Sections 5, 4th and 5th paragraphs).*
43
44
45

46
47 Because the method is proposed to assess infrastructure, and those are a finite number of sites
48 and each one has a limited spatial scale, surveys should be recommended to obtain accurate
49 data. The fact that they may not be readily available to a researcher does not justify omitting
50 significant physical effects in a general recommended methodology. The authors also justify
51 omitting critical physical phenomena in the assumption that future morphology cannot be
52 predicted. Their position may be arguable on a sandy beach, but is not true on hard bottom
53 areas and most overland flooding conditions. In any case, the authors do not demonstrate that
54 the potential errors of considering wave effects in the nearshore with uncertain shoreline
55 morphology are higher than the certain errors of not accounting for wave impacts. The
56 reviewer's opinion is certainly different.
57
58
59
60
61
62
63
64
65

1
2
3
4 *Authors: A recommendation for high resolution coastal bathymetric/topographic surveys is now*
5 *included, as suggested by the reviewer (Section 5, end of the 4th paragraph). We do not fully*
6 *agree with the reviewer that hard seabed morphology is easily predicted. Hard nearshore*
7 *seabeds can be altered by erosion/sedimentation and certainly affect the evolution of the*
8 *coastline (e.g. Velegrakis et al., 2016); in any case, many of the studied assets (e.g. GCIA and HIA*
9 *in St Lucia and SIA in Jamaica) are partially fronted by beaches, the morphology of which the*
10 *reviewer acknowledges may be difficult to predict. Secondly, in the case of defended coastlines*
11 *(as is the case of the western margin of GCIA runway and of the studied seaports), the likelihood*
12 *of change in the next 20 years (not to mention by the end of the century) is rather high due to*
13 *storm damages and improvements/modifications, among others (e.g. Asariotis et al., 2017).*
14 *Finally, collection of the necessary data needed to resolve these issues will require large financial*
15 *and human resources which have not been available for the present study. See also the response*
16 *to previous comment.*
17
18
19
20
21

22 **Comment 3**

23
24 The conclusion that "ESL increases are mostly controlled by MSLR" may be the result of the
25 assumption that "waves do not matter".
26

27 *Authors: We think that the reviewer misread/misinterpreted our statement. Our finding that*
28 *"ESL increases are mostly controlled by mean sea level rise", is logical since future mean sea level*
29 *rise is > 0.5 m in some cases whereas minor changes are projected for tides, waves and storm*
30 *surges in this area (see also Vitousek et al., 2017). We have the feeling that the reviewer misread*
31 *our statement to mean that "ESL is mostly controlled by MSLR", which is obviously not correct.*
32 *Although mean sea level and its rise may control the magnitude and temporal changes of the*
33 *other ESL components, it forms only a fraction of the overall ESL value as shown in Fig. 2; the*
34 *baseline 100-year ESL event has been projected as 1.96 and 1.29 m above the baseline mean sea*
35 *level, for Jamaica and Saint Lucia, respectively.*
36
37

38 *As it appears that our statement could be misread, the manuscript (Section 4.2, 2nd paragraph)*
39 *has been redrafted and Tables S5 and S6 (Online resource 4) redone, so as to make our findings*
40 *clearer.*
41
42
43

44 Had wave impacts been considered, the results would have shown that wave heights will
45 increase with MSLR. It can be shown that the influence of sea level rise on the total flood
46 elevation (including wave crest elevation) is more than the nominal increase in mean sea level,
47 even disregarding storm intensity effects. When calculating the base flood elevation following
48 FEMA guidelines, adding the effect of SLR results in an increase of the BSE of up to 2 times the
49 nominal SLR (this ratio varies, but exceeds 1.5 and a simple and conservative rule of thumb is
50 2). This impact of SLR on waves is not exposed by this methodology, because wave effects are
51 omitted entirely.
52
53

54 *Authors: The comment implies that SLR will increase nearshore water depths, and decrease wave*
55 *attenuation, resulting in higher wave power reaching the coast. While there is no doubt that SLR*
56 *will affect tides and waves/storm surges, predicting that effect at large spatial and temporal*
57 *scales remains a challenge for several reasons. The most sensitive point is that, as previous*
58 *studies highlight, SLR will probably drive shoreline retreat, and previous studies have shown that*
59
60
61
62
63
64
65

1
2
3
4 *the extent of shoreline retreat will modulate changes in astronomical (Idier et al., 2017; Pickering*
5 *et al., 2017) and/or meteorological water level variations (Du et al., 2018). SLR effects can even*
6 *reverse in extreme retreat scenarios; which could lead to higher attenuation. That could be the*
7 *case also for waves (e.g. when flat terrains will become permanently inundated and will result in*
8 *extensive flat submerged areas). All the above are difficult to predict, as natural long-term*
9 *shoreline evolution is a complex process per se, and it becomes even more challenging when*
10 *human interventions are involved.*

11
12
13
14 *As we have stated in our previous replies as well as in the manuscript itself, we have included*
15 *wave effects (e.g. the wave set up) that could be predicted with reasonable accuracy. Potential*
16 *effects from wave run up and wave impacts that are not included are now clearly referred to in*
17 *the manuscript (e.g. Section 5, 4th paragraph).*

21 References

- 22 Asariotis R, Benamara H, Mohos-Naray V (2017) Port Industry Survey on Climate Change Impacts and
23 Adaptation. UNCTAD/SER.RP/2017/18
- 24 Broekema, Y.B., Giardino, A., van der Werf, J.J., van Rooijen, A.A., Vousdoukas, M.I., van Prooijen, B.C.,
25 2016. Observations and modelling of nearshore sediment sorting processes along a barred beach
26 profile. Coastal Eng. 118, 50-62.
- 27 Du, J., Shen, J., Zhang, Y.J., Ye, F., Liu, Z., Wang, Z., Wang, Y.P., Yu, X., Sisson, M., Wang, H.V., 2018. Tidal
28 Response to Sea-Level Rise in Different Types of Estuaries: The Importance of Length, Bathymetry, and
29 Geometry. Geophys. Res. Lett. 45, 227-235.
- 30 Garner, A.J., Mann, M.E., Emanuel, K.A., Kopp, R.E., Lin, N., Alley, R.B., Horton, B.P., DeConto, R.M.,
31 Donnelly, J.P., Pollard, D., 2017. Impact of climate change on New York City's coastal flood hazard:
32 Increasing flood heights from the preindustrial to 2300 CE. Proceedings of the National Academy of
33 Sciences 114, 11861-11866.
- 34 Hauer, M.E., Evans, J.M., Mishra, D.R., 2016. Millions projected to be at risk from sea-level rise in the
35 continental United States. Nature Clim. Change 6, 691-695.
- 36 Idier, D., Paris, F., Cozannet, G.L., Boulahya, F., Dumas, F., 2017. Sea-level rise impacts on the tides of the
37 European Shelf. Cont. Shelf Res. 137, 56-71.
- 38 Mentaschi, L., Vousdoukas, M.I., Voukouvalas, E., Dosio, A., Feyen, L., 2017. Global changes of extreme
39 coastal wave energy fluxes triggered by intensified teleconnection patterns. Geophys. Res. Lett. 44,
40 2416-2426.
- 41 Pickering, M.D., Horsburgh, K.J., Blundell, J.R., Hirschi, J.J.M., Nicholls, R.J., Verlaan, M., Wells, N.C., 2017.
42 The impact of future sea-level rise on the global tides. Cont. Shelf Res.
- 43 Schimmels, S., Vousdoukas, M.I., Oumeraci, H., Wziatek, D., 2012. Wave run-up observations at
44 revetments with different porosity, 33rd International Conference on Coastal Engineering, Santander,
45 Spain.
- 46 UNECE, 2013. Climate Change Impacts and Adaptation for International Transport Networks. Expert
47 Group Report, Inland Transport Committee, United Nations Economic Commission for Europe
48 ECE/TRANS/238, 223 pp.
49 http://www.unece.org/fileadmin/DAM/trans/main/wp5/publications/climate_change_2014.pdf
- 50 Velegrakis, A.F., Trygonis, V., Chatzipavlis, A.E. et al., 2016. Shoreline variability of an urban beach fronted
51 by a beachrock reef from video imagery. *Natural Hazards*, 83 (S1), 201–222.
- 52 Vitousek, S., Barnard, P.L., Fletcher, C.H., Frazer, N., Erikson, L., Storlazzi, C.D., 2017. Doubling of coastal
53 flooding frequency within decades due to sea-level rise. *Scientific Reports* 7, 1399.
- 54 Vousdoukas, M.I., 2014. Observations of wave run-up and groundwater seepage line motions on a
55 reflective-to-intermediate, meso-tidal beach. *Mar. Geol.* 350, 52-70.
- 56 Vousdoukas, M.I., Almeida, L.P., Ferreira, Ó., 2012a. Beach erosion and recovery during consecutive
57 storms at a steep-sloping, meso-tidal beach. *Earth Surf. Processes Landforms* 37, 583-691.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Vousdoukas, M.I., Kirupakaramoorthy, T., Oumeraci, H., de la Torre, M., Wübbold, F., Wagner, B., Schimmels, S., 2014. The role of combined laser scanning and video techniques in monitoring wave-by-wave swash zone processes. *Coastal Eng.* 83, 150-165.

Vousdoukas, M.I., Mentaschi, L., Voukouvalas, E., Verlaan, M., Feyen, L., 2017. Extreme sea levels on the rise along Europe's coasts. *Earth's Future*.

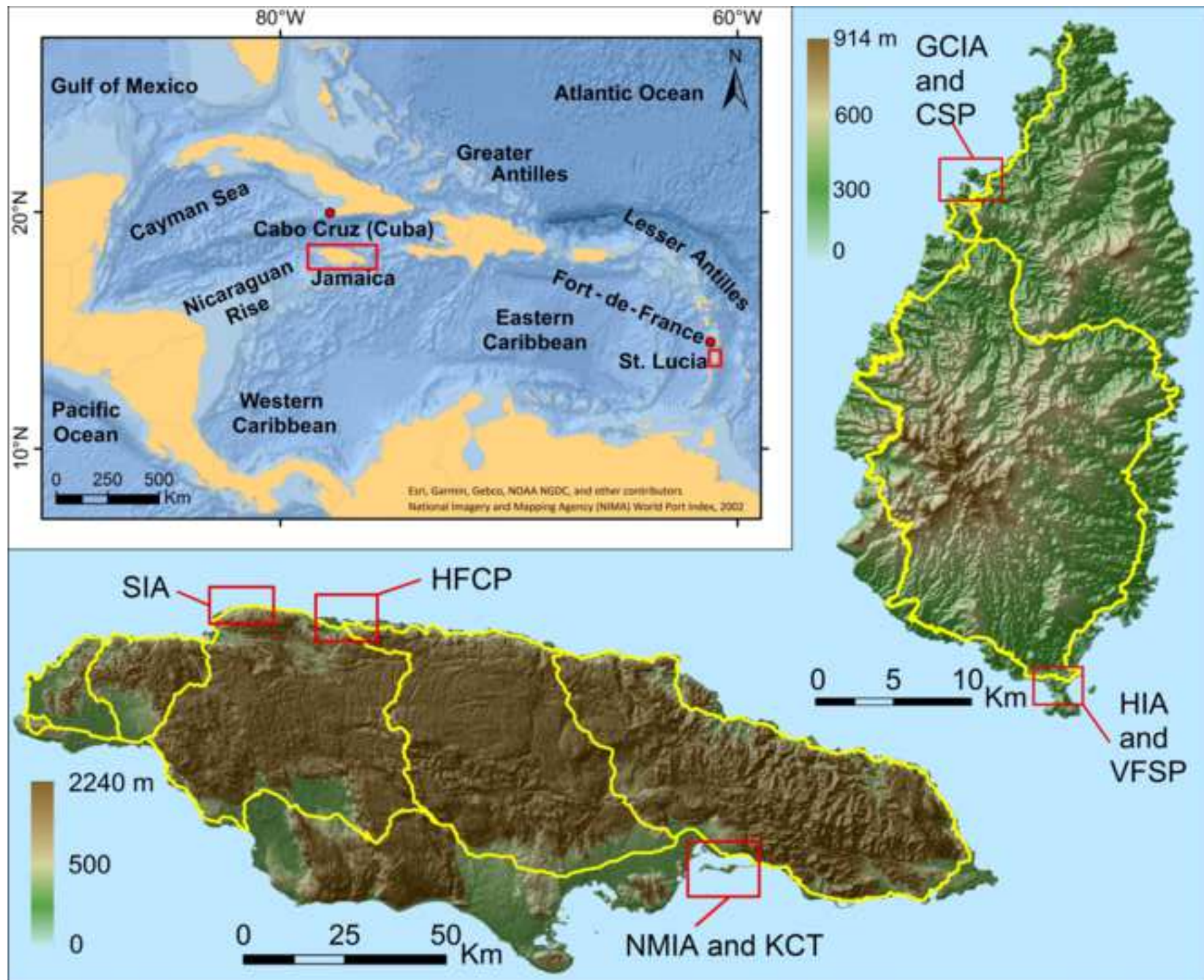
Vousdoukas, M.I., Mentaschi, L., Voukouvalas, E., Verlaan, M., Jevrejeva, S., Jackson, L., Feyen, L., 2018. Global probabilistic projections of extreme sea levels show intensification of coastal flood hazard. *Nature Communications* (accepted).

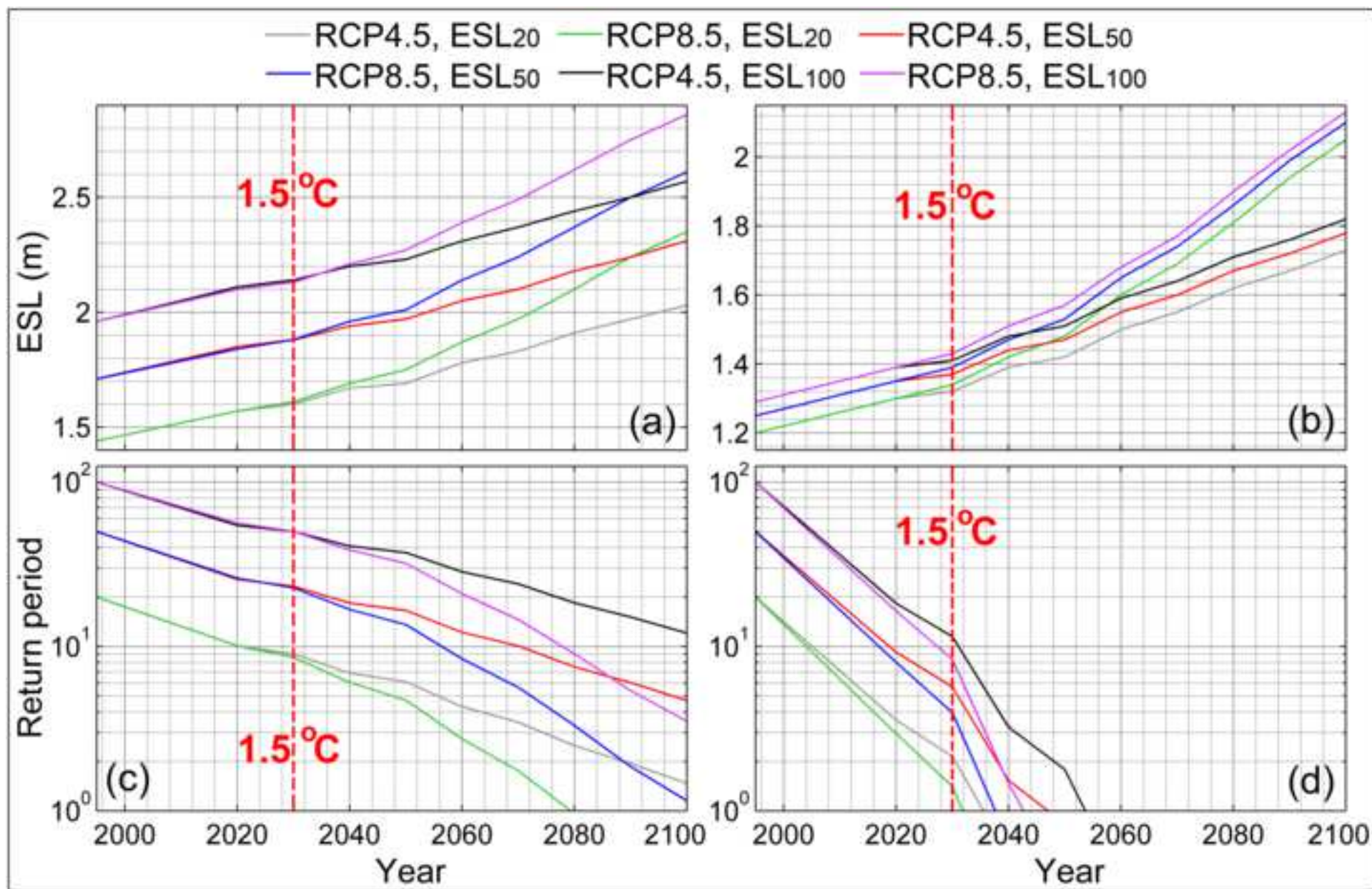
Vousdoukas, M.I., Velegrakis, A.F., Karambas, T.V., 2009a. Morphology and sedimentology of a microtidal beach with beachrocks: Vatera, Lesbos, NE Mediterranean. *Continental Shelf Research* 29, 1937-1947.

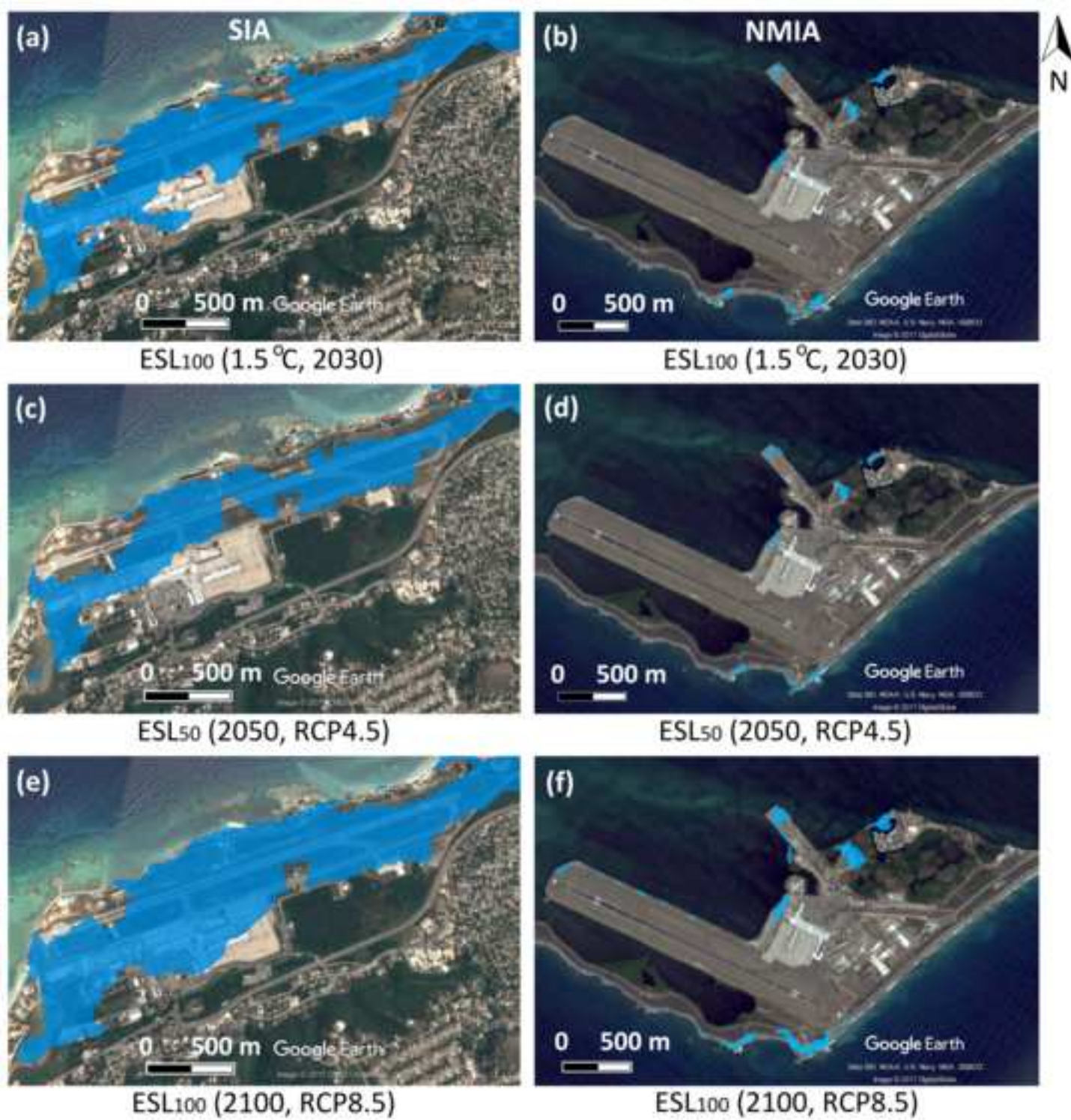
Vousdoukas, M.I., Voukouvalas, E., Mentaschi, L., Dottori, F., Giardino, A., Bouziotas, D., Bianchi, A., Salamon, P., Feyen, L., 2016. Developments in large-scale coastal flood hazard mapping. *Natural Hazards and Earth System Science* 16, 1841-1853.

Vousdoukas, M.L., Velegrakis, A.F., Dimou, K., Zervakis, V., Conley, D.C., 2009b. Wave run-up observations in microtidal, sediment-starved pocket beaches of the Eastern Mediterranean. *Journal of Marine Systems* 78, S37-S47.

Vousdoukas, M.I., Almeida, L.P., Ferreira, Ó., 2012b. Erosion-recovery and nearshore bar processes during consequent storms, 33rd International Conference on Coastal Engineering, Santander, Spain.

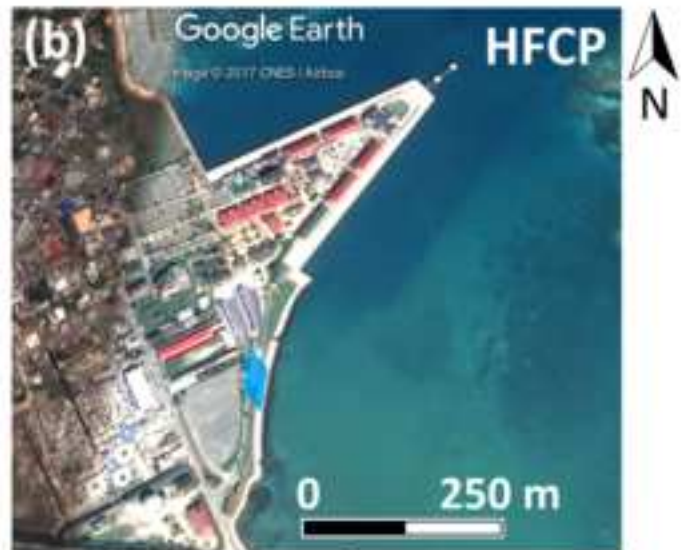








ESL100 (1.5 °C, 2030)



ESL100 (1.5 °C, 2030)



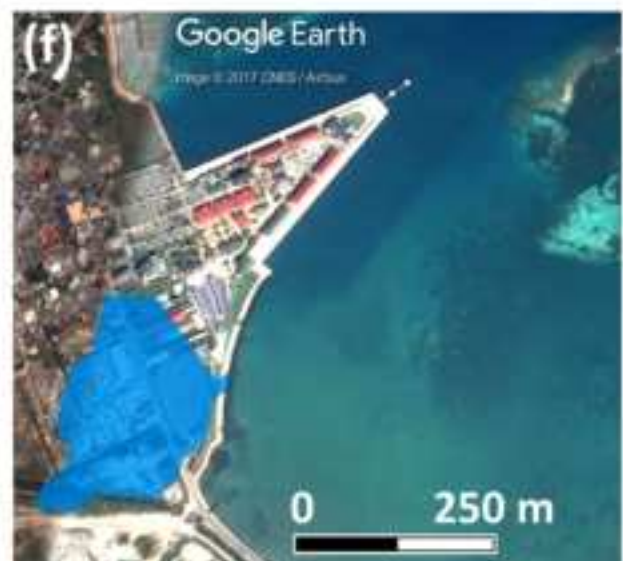
ESL50 (2050, RCP4.5)



ESL50 (2050, RCP4.5)



ESL100 (2100, RCP8.5)



ESL100 (2100, RCP8.5)



ESL100 (1.5°C, 2030)



ESL100 (1.5°C, 2030)



ESL50 (2050, RCP4.5)



ESL50 (2050, RCP4.5)



ESL100 (2100, RCP8.5)



ESL100 (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 |



[Click here to access/download](#)

Electronic Supplementary Material
ESM_1.pdf

