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Global analysis of sea level rise risk to airports

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A B S T R A C T

Major airports are already at risk of coastal flooding. Sea level rise associated with a global mean temperature rise of 2 °C would place 100 airports below mean sea level, whilst 1238 airports are in the Low Elevation Coastal Zone. A global analysis has assessed the risk to airports in terms of expected annual disruption to routes. The method integrates globally available data of airport location, flight routes, extreme water levels, standards of flood protection and scenarios of sea level rise. Globally, the risk of disruption could increase by a factor of 17–69 by 2100, depending on the rate of sea level rise. A large number of airports are at risk in Europe, Norther American and Oceania, but risks are highest in Southeast and East Asia. These coastal airports are disproportionately important to the global airline network, by 2100 between 10 and 20% of all routes are at risk of disruption. Sea level rise therefore poses a systemic risk to global passenger and freight movements. Airports already benefit from substantial flood protection that reduces present risk by a factor of 23. To maintain risk in 2100 at current levels could cost up to $57BN. Although the cost of protecting larger airports is higher, busier airports are typically well protected and more likely to have better access to adaptation finance. However, 995 coastal airports operate 5 commercial routes or fewer. More detailed consideration of these airports shows that regions, especially low lying islands, will experience disproportionate impacts because airports can provide important economic, social, and medical lifelines. Route disruption was used as the risk metric due to its global coverage and relationship with direct economic impacts. Further work should collate a wider range of impact metrics that reflect the criticality of an airport in terms of the isolation and socio-economic context of the location it serves.

1. Introduction

Recent weather events have highlighted the exposure of coastal airports to the impacts of climate change. The storm surge from typhoon Jebi in 2018 exceeded 3 m and was the highest recorded water level in Osaka Bay inundating Kansai International Airport (KIX), whilst the surge from Superstorm Sandy in 2012 closed New York City's LaGuardia Airport for three days (NYC, 2013; Mori et al., 2018). Disruption of transport networks has been shown to impact upon wider geographical areas (Dawson, 2015; Pregnolato et al., 2017) and other sectors (Fu et al., 2014; Caparros-Midwood et al., 2015).

Cities are often situated close to the sea, while 10% the world's population live within the Low Elevation Coastal Zone (LECZ), the contiguous area along the coast that is less than 10 m above sea level (McGranahan et al., 2007). Airports are often constructed in low-lying areas for practical reasons: proximity to the cities and population they serve; large areas of flat land; and take-off and landing trajectories that minimise the risks of collision. Coastal wetlands, marshlands, floodplains and reclaimed land, can provide this. With sea levels rising along the majority of the world's shorelines (Oppenheimer, 2019), the risks to low-lying airports will inevitably increase.

Climate change will impact airport operations in a number of ways. Changes in wind speed and direction, temperature, air density, will require alteration of airport and airline operations (Williams, 2016). Increased frequency and magnitude of extreme weather events will increase disruption without appropriate adaptation (Baglin, 2012; Burbidge, 2017). Airports are especially sensitive to

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flooding because of the complexity of their systems and the safety critical nature of their operations (Mosvold Larsen, 2015). Flooding of terminals, power and lighting infrastructure, navigation and communication equipment, inter-terminal transportation, or runways, can led to disruption or halting of airport operations. Critical service infrastructure is often underground meaning that even small volumes of water can infiltrate and damage important equipment (Burbidge, 2018).

A number of airports have undertaken individual climate change impacts assessments (Heathrow Airport, 2016; Massport, 2018; Sydney Airport, 2019), and some agencies have identified that some airports are in low-lying coastal zones (Steffen et al., 2014; Dawson et al., 2018; Jacobs et al., 2018; Christodoulou and Demirel, 2018). These studies focus on the vulnerability, rather than the relative importance, capacity and connectivity of different airports (Poo et al., 2018). To date, there has been no systematic global analysis of sea level rise risk to the world's airports.

Analysis of new data has highlighted that (i) global vulnerability to sea-level rise and coastal flooding has been underestimated (Kulp and Strauss, 2019); (ii) the frequency of coastal flooding is projected to double within decades due to sea-level rise (Vitousek et al., 2017); and, (iii) analysis of 136 coastal urban agglomerations from 68 countries exposed that half did not have any coastal adaptation strategy, and 85% did not factor climate change risks (Olazabal et al., 2019). Given the recent trend in airport expansion, the global connectivity of the airport network, and that the vast majority of the world's shoreline is subject to rising sea levels it is important to understand these risks on a global scale.

The aviation sector makes a significant contribution to global greenhouse gas emissions and other sources of environmental pollution, these issues are outside the scope of this analysis but considered in depth by others (*c.f.* Gössling and Upham, 2009; McManners, 2012; Hales and Caton, 2017; Kantenbacher et al., 2018).

This paper presents the first global analysis of risks to airports from sea level rise. Following this introduction, the methodology for the global risk analysis is described in Section 2. Key results and rankings from the risk analysis are presented in Section 3 (the full dataset, and regional maps, are provided in the Supplementary Material). In Section 4 more detailed consideration is given to the role of airports as passenger and freight hubs, enablers of tourism, and as lifelines to remote communities, before considering the costs of adaptation in Section 5 and discussing the sensitivity of the risk analysis in Section 6.

2. Method for global airport risk analysis

The risk analysis combines information about the location of airports, their exposure to storm surges for current and future sea level, their (pre-COVID-19) connectivity and aircraft traffic, and their current standard of flood protection (Fig. 1). The index only uses data that is readily available, and with global coverage, to ensure the consistency and repeatability of the analysis.

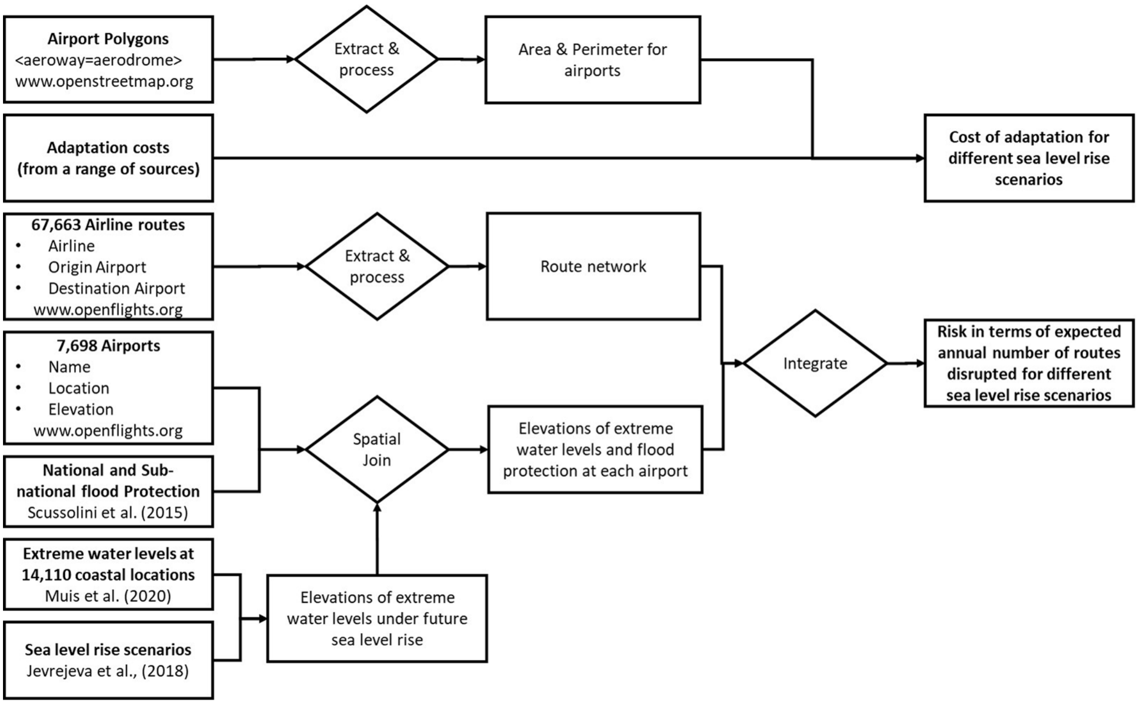

Fig. 1. Overview of global airport risk analysis.

2.1. Airport characterisation

The location of 14,110 airports and helipads from around the world was extracted from the OpenFlights database (Patokallio, 2009) and imported into GIS. Information provided for each airport included the name, city, country, the International Air Transport Association (IATA) code, coordinates (longitude and latitude), activity, elevation, and time zone. Analysis by Verma et al., (2014, 2016) and Yan et al., (2018) has shown this to be a robust and comprehensive source of airport information.

The Low Elevation Coastal Zone (LECZ) is defined as the contiguous area along the coast that is less than 10 m above sea level and is often used as a convenient geography to inform coastal vulnerability studies. This excludes airports near the coast but outside the LECZ such as Mombasa International (MBA) which has an elevation of 61 m. Similarly, inland low elevation airports, such as Bar Yehuda airport (MTZ) in Israel, are also excluded. From the full dataset, 1,238 airports were identified in the LECZ (Fig. 2). The USA has the most airports (199) and routes (3436) in the LECZ, whilst China has the second most routes at risk (2333) from 30 airports. However, Australia (72), Indonesia (43), French Polynesia (39), Bahamas (34) and other countries have more airports at risk than China although they operate fewer flights.

Airports within the LECZ are often of strategic importance. Just 20 LECZ airports (Table SM.1) handle 802 million passengers, 18% of all passengers in 2018 (Statista, 2020a). Although air freight is a small amount of global freight by weight, the amount carried grew by 35% between 2008 and 2018, and by value is 7.4% of the world's GDP (IATA, 2019). The same 20 airports handled 15.8 million tonnes, 25% of all air freight, in 2018 (Statista, 2020b).

Airports were classified according to the nature and volume of activity. Commercial Air Transport (CAT) airports are defined by the Federal Aviation Authority (FAA) as having at least 2,500 passenger boardings per year. We distinguish between Tertiary (defined here as airports with 10 or less routes), Secondary (airports with 11 to 20 routes) and Primary (airports with 21 or more routes). Other Airports (OA) do not have scheduled passenger services but serve small aircraft charter carriers, private and military aircraft for which flight data is not universally available. A total of 34,793 routes (where a return flight by one carrier, LHR → JFK and JFK → LHR, is counted as a single route) between 19,236 airport-pairs (i.e. all flights by all carriers between LHR ↔ JFK are counted as a single airport-pair) have been extracted from the data.

Airport area and perimeter have been calculated using OpenStreetMap (OSM). All features with the < aeroway = aerodrome > tag were extracted from the OSM database which provided polygons for 725 of the 1,238 airports. For each airport, the area and perimeter was calculated (Table SM.1). The remaining airports (365 of which are tertiary) were allocated mean values based on their airport type. These are used to provide estimates of the cost of some adaptation options in Section 5.

2.2. Sea level rise scenarios

Global mean sea level rise comprises two main components (i) thermostatic expansion of ocean waters and (ii) the melting of land-based ice. These processes will continue for many centuries, even after stabilization of surface air temperature, due to the long response timescales of ice sheets and deep ocean temperature (Brown et al., 2018). Additional changes in global mean sea level, not considered here, are caused by other processes, such as surface water storage behind dams (Frederikse et al., 2020). To explore the range of projections of sea level rise on airport disruption, three scenarios consistent with Jevrejeva et al., (2018) are analysed:

1) Stabilization of global mean temperature at 1.5 °C warming this century: 52 cm (median), 87 cm (95th percentile) by 2100;
2) Stabilization of global mean temperature at 2.0 °C warming this century: 63 cm (median), 112 cm (95th percentile) by 2100; and
3) Representative Concentration Pathway 8.5 (RCP8.5), provides a high baseline emission scenarios in which emissions continue to rise through the 21st Century, here contributions of Greenland and Antarctic ice melt are included: 86 cm (median), 1.8 m (95th percentile) by 2100.

Some analyses project more rapid ice melt, for example Bamber et al. (2019) show possible sea level rise exceeding 3 m by 2100.

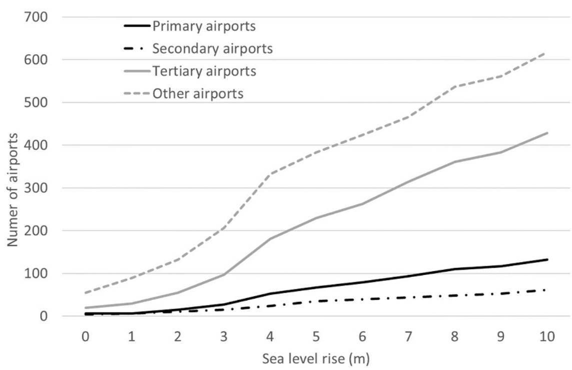

Fig. 2. Cumulative plot of the number of airports, of different activity categories, at different elevations within the LECZ. Other airports includes general aviation and military airports. Elevations for 20 major airports in the LECZ are included in Table SM.1.

Local subsidence and isostatic adjustment can alter relative sea level rise at specific locations, whilst local bathymetry and coastal landform also influence local water levels during storms. These local conditions are not simulated here so to understand the sensitivity of impacts to sea level rise, airport risk is also calculated for sea level rise between 0 and 5 m.

2.3. Risk analysis

After Dawson and Hall (2006) the coastal flood risk, r, calculation can be generalised as:

$$r = \int \rho(x)c(x)\mathrm{d}x \tag{1}$$

where $c(\boldsymbol{x})$ and $\rho(\boldsymbol{x})$ are functions respectively describing the impact and the probability of loading.

Due to the safety critical nature of airport operations, flooding of the runway or other systems will typically cease all aircraft movements (Burbidge, 2018). Impact is therefore measured in terms of aircraft routes that are disrupted. Routes are extracted from the OpenFlights dataset. Other measures of impact such as passenger numbers or cargo volume by route, would provide a more nuanced measure of disruption but are not openly available for all individual airports. Sensitivity of the risk analysis is considered in Section 6.

Airport risk, expressed in terms of expected annual disruptions of aircraft routes, for a given sea level rise scenario, is therefore calculated as:

$$r = \int_{\max(E_{FP},E_A)} \rho(l)D_R\mathrm{d}l \tag{2}$$

where E_A is the airport elevation, E_{FP} is the elevation of flood protection, D_R, is the impact in terms of the number of airport routes that are disconnected if the airport is closed, and $\rho(l)$ is the probability density function of extreme water levels. The number of routes is correlated to the passengers and cargo movements of the airport, and therefore the economic cost of disruption. Other factors are relevant to determining impacts and vulnerability (Tapia et al., 2017; Andrijevic et al., 2020) but the number of routes was the only publicly dataset available that is reported for all individual airports.

Airport elevation, E_A, could be extracted from global digital elevation maps, however there are significant differences between available coastal DEM products (Kulp and Strauss, 2016). Airport elevation data is therefore taken from the OpenFlights database which is based on ground surveys and used by pilots and in navigation.

Extreme water levels are taken from the Coastal Dataset for the Evaluation of Climate Impact (CoDEC) which has been developed to assess present-day flood risk and the impacts of climate change on global infrastructure (Muis et al., 2020). Gumbel parameters and return periods which describe $\rho(l)$ for present and RCP8.5 scenarios have been calculated for 14,110 point locations. The analysis has a global mean bias 50% lower than previous global datasets (ibid). The extreme water levels account for regional SLR variations along the global coastline, consistent with other global coastal studies (e.g. Brown et al., 2018; Nicholls et al., 2018). Each airport uses water

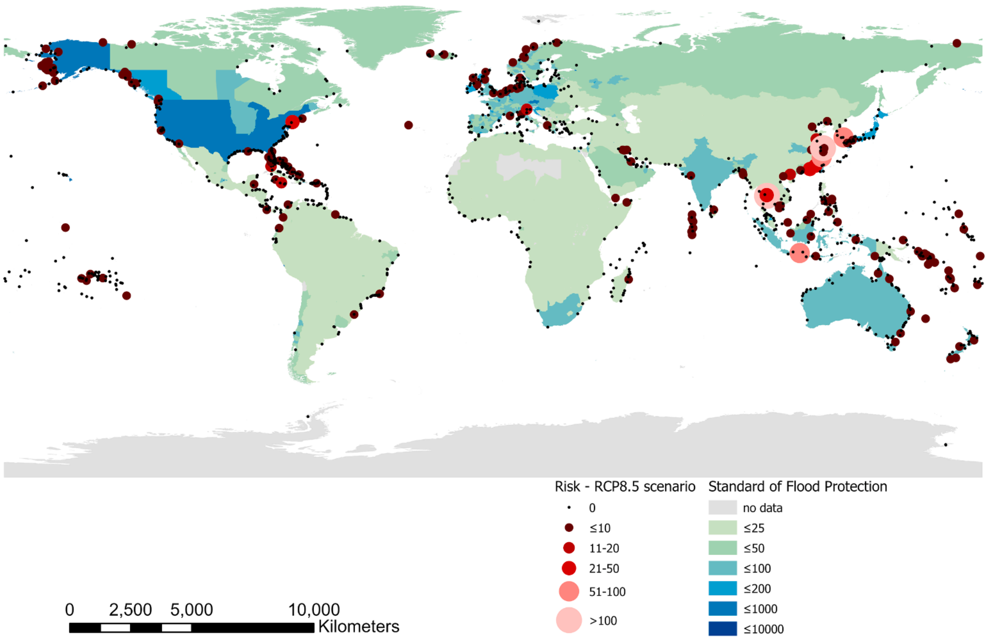

Fig. 3. The expected annual route disruptions by 2100 for the RCP8.5 sea level rise scenario. Land is shaded according to the return period of the flood protection in the FLOPROS database from Scussolini et al. (2016).

levels from the nearest CoDEC location. These are combined with global sea level rise projections from Section 2.2 to calculate extreme water levels in 2100.

Information on the elevation and condition of storm surge protection measures is not publicly available for airports. Protection standards, defined in terms of return periods, are taken from the FLOod PROtection Standards (FLOPROS) database (Scussolini et al., 2016). The most recent version of FLOPROS is currently the only publicly available dataset with global coverage that provides estimated or actual levels of protection at sub-national (e.g. state) and national levels (Tiggeloven et al., 2020). All airports within each national or sub-national unit are assigned the level of protection from FLOPROS.

The elevation of the flood protection height, E_{FP}, is calculated by interpolating from the distribution of extreme water levels from the CoDEC database from Muis et al. (2020). Defences are assumed to protect against any inundation at or below their elevation. Any additional safety margins, or additional local protection for airport sites are unreported. Although a conservative assumption, it is consistent with other broad scale coastal risk analyses (e.g. Hinkel et al., 2014; Brown et al., 2018), inundation is assumed to occur when the storm surge level exceeds the airport and flood defence elevation.

3. Global ranking of airports at risk from sea level rise

Risk is calculated using Equation (2) and reported for: (i) Base (current sea level); (ii) 0FP (Sea level as for Base scenario with flood protection removed); (iii) 1.5 °C (median sea level rise value); (iv) 2 °C (median sea level rise value); (v) RCP8.5 (median sea level rise value); and, (vi) RCP8.5+ (95th percentile sea level rise value). From Fig. 2 it can be seen that one hundred airports will be at an elevation below mean sea level following 0.62 m of SLR in the 2 °C scenario. Coastal airports and their respective risk in the RCP8.5 scenario are shown in Fig. 3, with regional maps in the Supplementary Material (Figures SM.2 to SM.20). The global increase in risk for the different amounts of sea level rise is shown in Fig. 5. A summary of the number of airports in the coastal floodplain, and their risk, within different regions is shown in Table 1.

The relative rank of the 20 airports with the highest risk changes according to the sea level rise scenario considered (Table 2). The risk scores for all airports are listed in the Supplementary Material (Table SM.1). Despite a number of airports at risk in Europe, North America and Oceania, the airports in East and Southeast Asia and the Pacific dominate the top 20 for present day and lower sea level rise scenarios. Suvarnabhumi Airport in Bangkok (BKK) has the highest risk except for the RCP8.5 + scenario where Shanghai Pudong (PVG) has the highest risk. These are consistent with other global analyses that show both Bangkok and Shanghai are at high risk of coastal flooding (Hanson et al., 2011; Kulp and Strauss, 2019).

Overall, China has the most airports ranked in the top 20 for all but RCP8.5+, these include other primary airports such as Shanghai Hongqiao (SHA) and Wenzhou Longwan (WNZ). However, a number of tertiary airports such as Sege (EGM) and Ramata (RBV) in the Solomon Islands have only a few routes each but are at low elevation with limited flood protection. Under higher sea level rise scenarios, airports in Europe and North America, including Newark (EWR) and La Guardia (LGA) that both serve New York become more prominent.

If all flood protection were removed the rank order changes considerably. Amsterdam Schipol (AMS) would have the highest risk, but it currently benefits from protection against the 1 in 10,000 year flood. Globally, flood protection provides significant benefits for airport disruption, currently only 52 routes are expected to be disrupted each year due to coastal flooding. This would be 1220 (i.e. equivalent to 3.5% of global routes) without flood protection.

4. Wider implications of sea level rise for airports

The results in Section 3 provide an initial global assessment. Implicit in the calculation is that all aircraft movements are of

Table 1
Summary of the airports at risk, and the expected annual route disruptions by region for different sea level rise scenarios.

Region		Base	0FP	1.5 °C	2 °C	RCP8.5	RCP8.5+
Africa	No. Airports	4	4	7	7	9	24
	Risk	1.44	4.00	4.00	4.00	4.00	9.35
Caribbean	No. Airports	6	6	14	15	18	36
	Risk	0.63	1.00	2.21	4.00	17.28	100.52
Central and South America	No. Airports	14	14	19	24	26	39
	Risk	0.07	0.07	5.00	5.00	6.59	34.97
East Asia, Southeast Asia and Russia	No. Airports	47	47	61	63	70	95
	Risk	34.53	620.60	780.15	803.44	912.77	1755.18
Europe	No. Airports	82	82	88	90	94	110
	Risk	1.98	526.73	9.20	15.69	35.96	644.86
North America (USA, Canada, Mexico)	No. Airports	51	51	64	71	85	114
	Risk	0.51	35.34	27.86	38.65	68.85	636.28
Oceania	No. Airports	58	58	72	76	91	131
	Risk	12.32	25.70	34.69	42.74	50.06	194.35
West Asia and South Asia	No. Airports	7	7	13	18	20	23
	Risk	0.39	0.39	2.28	4.10	18.47	208.00
Total	No. Airports	269	269	338	364	413	572
	Risk	51.87	1213.83	865.39	917.64	1113.98	3583.51

Table 2
Airports ranked in the top 20 by risk in 2100 for sea level rise scenarios. The list is ordered according to present day risk. Risk values for all airports are listed in Table SM.2.

Airport	Country	IATA	Risk rank					
			Base	OFD	1.5 °C	2 °C	RCP8.5	RCP8.5C
Suvarnabhumi	Thailand	BKK	1	2	1	1	1	2
Wenzhou Longwan Intl.	China	WNZ	2	3	2	2	3	11
Sege	Solomon Islands	EGM	3	17	17	18	24	53
Quanzhou Jinjiang Intl.	China	JJN	4	4	5	5	6	22
Changzhou Benniu	China	CZX	5	5	6	7	7	26
Ramata	Solomon Islands	RBV	6	22	25	28	36	72
Suavanao	Solomon Islands	VAO	7	23	26	29	37	73
Bosaso	Somalia	BSA	8	19	18	19	27	58
Fera/Maringe	Solomon Islands	FRE	9	28	31	36	44	98
Rennell/Tingoa	Solomon Islands	RNL	10	31	34	39	47	101
Corvo	Portugal	CVU	11	26	32	37	45	99
Choiseul Bay	Solomon Islands	CHY	12	25	33	38	46	100
Shanghai Hongqiao Intl.	China	SHA	13	33	7	6	2	4
Beihai	China	BHY	14	8	8	8	11	32
Yancheng	China	YNZ	15	9	9	9	12	33
Lianyungang	China	LYG	16	10	11	12	14	38
Jieyang Chaoshan Intl.	China	SWA	17	6	14	10	8	27
Huangyan Luqiao	China	HYN	18	12	12	13	15	40
Zhoushan	China	HSN	19	13	13	14	17	42
Uru Harbour	Solomon Islands	ATD	20	34	43	54	67	134
Bremen	Germany	BRE	23	14	29	24	20	20
Cat Bi Intl.	Vietnam	HPH	24	45	19	20	28	59
Anqing Tianzhushan	China	AQG	26	15	15	15	21	49
Louis Armstrong New Orleans Intl.	United States	MSY	27	11	41	35	23	10
Anshan Air Base	China	AOG	29	20	22	25	33	69
Juanda Intl.	Indonesia	SUB	32	52	4	4	5	14
La Guardia	United States	LGA	33	629	30	17	9	6
Puerto Jimenez	Costa Rica	PJM	34	53	20	21	29	60
Dunedin	New Zealand	DUD	35	16	16	16	22	51
Amsterdam Schiphol	Netherlands	AMS	38	1	57	64	32	5
Shanghai Pudong Intl.	China	PVG	43	57	65	71	43	1
Nightmute	United States	NME	48	18	56	51	26	55
Gimhae Intl.	South Korea	PUS	50	58	3	3	4	12
Venice Marco Polo	Italy	VCE	51	59	59	52	18	8
Newark Liberty Intl.	United States	EWR	56	405	75	79	88	3
London City	United Kingdom	LCY	58	62	72	75	82	16
Rotterdam The Hague	Netherlands	RTM	63	7	77	82	95	37
Tianjin Binhai Intl.	China	TSN	65	65	80	81	89	7
Don Mueang Intl.	Thailand	DMK	71	69	74	69	10	15
Key West Intl.	United States	EYW	73	71	10	11	13	35
Bahrain Intl.	Bahrain	BAH	167	156	91	95	65	9
Ioannis Kapodistrias Intl.	Greece	CFU	370	253	445	113	124	19
Sangster Intl.	Jamaica	MBJ	574	671	95	98	16	21
Aden Intl.	Yemen	ADE	600	113	94	89	19	29
Cairns Intl.	Australia	CNS	639	266	97	99	109	18
Metropolitan Oakland Intl.	United States	OAK	733	807	100	104	115	17
Pisa Intl.	Italy	PSA	837	899	102	107	117	13

equivalent importance. In this section, a number of other factors not captured by this calculation are considered.

4.1. Global hubs and connectivity

Airports including AMS, PVG and others that are important to the overall global network in terms of their connectivity are shown to be at increasing risk over the 21st century. Furthermore, as sea levels rise the likelihood of multiple locations being simultaneously impacted will also increase. Fig. 4 shows that the airports at risk of flooding by 2100 provide significant connectivity with each other, and inland airports. Even for low sea level rise scenarios the number of airport routes at-risk is a notable proportion of the global network (Table 3), and disproportionately higher than the number of airports at risk (Table 1). Over two-fifths of all routes involve an airport in the LECZ, which are responsible for a significant proportion of global passenger and freight movement (Table SM.1).

4.2. Tourism

Airports are reported to provide economic benefits, for example Amsterdam Schiphol airport (AMS) is estimated to account for over 2% of the GDP of the Netherlands (InterVISTAS, 2015), although such analyses are uncertain (Zhang and Graham, 2020). The tourism

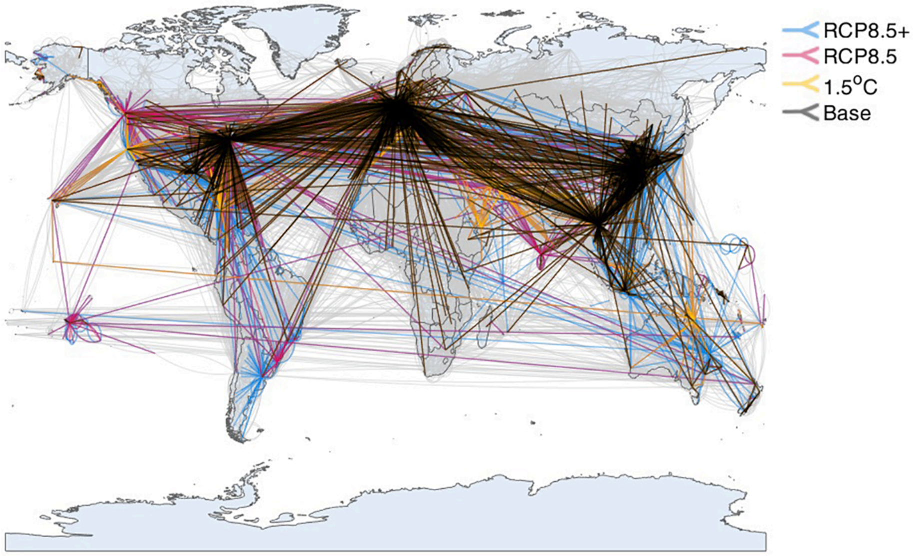

Fig. 4. Map of routes at risk of disruption for different sea level rise scenarios. Grey lines are the routes in the OpenFlights database not at risk of disruption. Black routes are from airports at risk (r > 0) of flooding in the Base scenario. Yellow routes are those at risk for the 1.5 °C sea level rise scenario, pink routes for RCP8.5 and blue for RCP8.5 + . (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

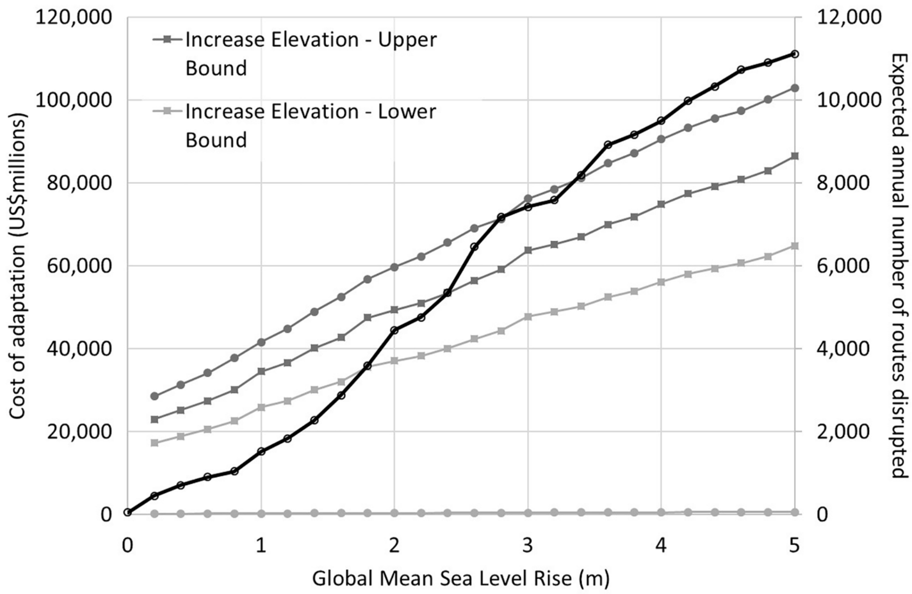

Fig. 5. The expected annual route disruptions, and the lower and upper bounds for the cost of two adaptation options for increases in global mean sea level.

Table 3
Total number of routes at risk (r > 0) of disruption, between other airports at risk of coastal flooding and between all airports, for different sea level rise scenarios.

Routes between at-risk airports and…	Present	1.5 °C	2 °C	RCP8.5	RCP8.5+	LECZ
…other at-risk airports	409	479	521	639	1,102	2,455
…all airports	2,947 (8.5%)	3,507 (10.1%)	3,680 (10.6%)	4,406 (12.7%)	6,931 (19.9%)	14,839 (42.6%)

sector is often a beneficiary of the connectivity airports provide. Globally, tourism direct expenditure is 3.2% of the world's GDP (WTTC, 2019a).

The relative importance of tourism and airports to national economies varies. For example, 7.2% of the GDP of the Caribbean is supported by tourism, the majority accessing islands through airports (IATA, 2016). The only Caribbean airport in the top 20 is Sangster International, Jamaica (MBJ), under RCP8.5. Others, including Jardines Dey Rey, Cuba (CCC) are also ranked in the top 50 for RCP8.5. However, Cuba and Jamaica have tourist sectors that are respectively 11% and 34% of their GDP (WTTC, 2019b). Therefore the vulnerability of these islands, and other tourist spots with limited accessibility, is amplified by the criticality of the airport to support the local economy.

4.3. Lifelines

Many airports do not handle significant volumes of cargo but they can provide crucial lifelines for emergency response during extreme events to ensure fast access to disaster zones or to replace transport modes that are temporarily put out of operation. For example, when container unloading cranes in the seaport of Port-au-Prince were destroyed by an earthquake in 2010 food and medical supplies arrived by air until the port could reopen (Slevin, 2010).

Furthermore, some locations are remote or difficult to access via other transport modes. Of the 1,238 airports in the LECZ, only 80 have over 50 routes, whilst 995 airports have just 5 or fewer routes (Figure SM.21). A small number of commercial routes can be an indicator of reliance on tourism, but in some locations they are crucial community lifelines. For example, Puka-Puka airport (PKP) on the island of Puka-Puka in French Polynesia sits at only 1.5 m elevation and therefore vulnerable to low sea level rise scenarios. Despite this it does not score highly in the risk assessment as Air Tahiti only fly an irregular service to the 163 island inhabitants. However, this service helps provide food, goods and transportation of locals to (boarding) schools, medical and other facilities at larger neighbouring islands such as Makemo (MKP) and Fangatau (FGU). These airports connect to the regional hub of Fa'a'ā International Airport in Tahiti (PPT) which connects to Asia, New Zealand, South and North America. All of these airports are at an elevation between 1 and 3 m above mean sea level. Loss of an individual airport would have substantial impacts for the local community it services, but those settlements at the end of an 'airport chain' are especially vulnerable to wider impacts.

5. Prospects for adaptation

The cost of damage and disruption to an airport can be considerable. Closure of major airports such as London Heathrow (LHR) can cost between $0.76–1.35 M/hour (Faturechi et al., 2014), whilst the annual cost of disruption to European airport operations is estimated to be $390 M/year (Doll et al., 2014). A flood at London Gatwick (LGW) cost $3.4–5.1 M in terms of cancelled flights and diversions, a further $40 M was set aside for recovery and enhancing resilience (Chatterton et al., 2016). The economic costs of airport disruption from flooding, or other climate impacts, will vary considerably according to airport size, connectivity and location. As discussed in Section 3, airport disruption can be disproportionally more significant to the area it serves depending on local socio-economic factors.

Coastal airports have four main adaptation choices: (i) Protect, (ii) Raise, (iii) Relocate, and (iv) Reclaim or Float. The size of an airport, and the nature of their operations, usually means that adaptation requires costly engineering works. Likely costs, where available, are now considered.

Estimates of the capital cost of hard (i.e. seawalls, dikes) coastal protection range from $0.4 M-69.9 M per km length and metre height (Linham et al., 2010; Jonkman et al., 2013; Narayan et al., 2016; Lenk et al., 2017; Nicholls et al., 2019; Tamura et al., 2019; Oppenheimer, 2019). The unit costs estimated from this data varies considerably according to building/fill material used, labour cost, accessibility, hydraulic loads, etc. Using these unit values the cost of defences for PKP, a small airport with a runway of just over 900 m, would be $0.9-$169 M. For larger hub airports the cost could exceed $1BN.

Table 4

Costs of constructing new flood defences or raising airport elevation for an airport of average size, and the total capital cost to adapt all airports to different sea level rise scenarios such that total risk returns to present levels. Maintenance costs for flood defences assume an 80 year design life from 2020 to 2100.

Airport Type	Flood defence around perimeter		Raise entire airport elevation		
	1 m elevation [Lower Bound]	1 m elevation [Upper Bound]	Initial 1 m raise [Lower Bound]	Initial 1 m raise [Upper Bound]	Additional 1 m raise
Costs for an average size airport ($M)					
Primary	5.87	1,025.08	1,011.78	1,349.04	202.36
Secondary	3.64	635.72	309.58	412.77	61.92
Tertiary	2.51	438.01	223.55	298.07	44.71

Total cost of adaptation for all airports at risk ($M)				
	1.5C	2C	RCP8.5	RCP8.5+
Defence construction	188.97–33,022.31	198.49–34,686.97	222.47–38,877.04	325.04–56,800.97
Defence maintenance	1.89–660.45	1.98–693.74	2.22–777.54	3.25–1,136.02
Raise elevation	19,886.12–26,514.82	20,841.32–27,788.43	23,509.79–31,346.38	35,580.86–47,441.15

Hippe et al. (2015) calculate the cost of raising the elevation of a seaport by 1 m as \$150-\$200/m rise/m^2 and an additional \$30/m^2 for each extra metre rise. If these figures are representative for airports the cost to raise the elevation of PKP, by a metre would be \$21-\$29 M. A hub airport, which can have an area of 10–40 km^2 would cost between \$1.5-\$6BN which is similar to new build construction costs. To minimise disruption and costs, adaptation could be undertaken in phases and it will usually be more cost effective to raise by more than one metre because of the high start-up costs. Raising the runway will inevitably be the most disruptive phase, although as they typically need to be re-paved every 8–10 years this provides an opportunity to undertake more substantial works.

The relationships between sea level rise, risk and adaptation costs are shown in Fig. 5. Globally, the rate of growth of risk between 1–3 m sea level rise is double the rate of increase for 0–1 m. The cost of retaining current levels of risk in 2100 under the RCP8.5 median sea level rise scenario by constructing and maintaining flood defences ranges from \$0.2-\$39BN, elevating all the airports would cost \$23–\$38BN (Table 4). This calculation is an upper estimate as it assumes the full airport perimeter requires protection, which is the case for PKP and HKG, but not all airports require protection along all boundaries. In many cases it will be more cost effective to raise some tertiary airports rather than construct flood defences.

Relocation or rebuilding an airport is extremely expensive. Following Hurricane Maria in 2017 San Juan airport (SJU) in Puerto Rico was able to resume military operations within 2 days, however, it took approximately one year and \$80 M to return the airport to full capacity (EFE, 2019). The cost of replacing an airport in Alaska is estimated to be on average \$20 M per airport (Larsen et al., 2008). Runway repair and upgrade of the airport on the pacific island of Atui (AIU), with a population of 571 people, is projected to cost \$4.6 M (Brown, 2016). St Helena Airport (HLE) on an island in the Atlantic 2,000 km from nearest landfall, with a population below 5,000, cost \$372 M to construct (Williams et al., 2020). The cost of major new hub airports are far larger, recent projects include Hong Kong (HKG, \$17.2BN), Doha (DOH, \$9.5BN), Heathrow Terminal 5 (LHR, \$6.1BN) (Statista, 2020c).

HKG, DOH and other airports including PVG, ICN, LGA are all or partly constructed on reclaimed land. A number of coastal airports have expanded into the sea when they reach capacity, providing an opportune moment to implement further adaptation measures in the airport complex. In deeper waters, construction of a floating airport is likely to be more cost effective than reclamation (Lamas-Pardo et al., 2015). A prototype 1 km runway cost \$200 M and proved the technology could be scaled to 4 km runways (Inoe, 1999; Hadžić et al., 2016). However, costs could be as much as \$5-15BN for structures with a 100 year lifespan (Lamas-Pardo et al., 2015).

The overall cost of adaptation is relatively small in the context of the estimated \$1.8tn needed globally by 2050 (GCA, 2019). Many airports, are already well protected, for example AMS benefits from protection against 1 in 10,000 year storm surge. Some cities and countries have the space and finance available to invest in adaptation measures, move airports inland or absorb flights into neighbouring airports. However, many locations and especially those most reliant on airports for tourism, food and medical supplies will struggle to find alternative airport locations or investment to keep pace with the sea level rise.

6. Sensitivity of risk measure

An inherent problem with any global study of risk is the integration of a large number of datasets and assumptions (Hinkel et al., 2014). Here, Suvarnabhumi Airport's high risk is a combination of being one of the busiest airports in SE Asia, and an elevation near sea level. The FLOPROS database indicates the level of flood protection is less than 1 in 50 years, but the airport reportedly benefits from on-site flood protection measures so its risk is likely to be lower. Vousdoukas et al. (2018) suggest that errors in flood protection levels can alter flood risk calculations by up to 60%.

In each stage of the calculation best available global datasets have been used, but each data source has a degree of uncertainty that may alter the expected annual route disruptions, and local factors such as the accuracy of flood protection levels may alter relative ranking. Small errors in airport elevation, or storm surge levels, propagate through the analysis to alter risk. Moreover, airports are expansive with uneven elevation. Whilst a comparison of all airports with ground survey data was not possible, analysis of JFK shows variation of ~ 0.4 m across the airfield, this range is 2.7 m and 4.4 m respectively for EWR and LGA (SkyVector, 2020a; SkyVector, 2020b; SkyVector, 2020c). For all three airports the OpenFlights elevation is within the survey data range, whereas data extracted from the best available DEMs shows far greater variability (Table SM.3).

As observation datasets grow, understanding of the likelihood of storm surge levels improves. For example, LGA was not expected to flood from Hurricane Sandy, but did (Knowlton and Rotkin-Ellman, 2014). Here, it is identified to be at risk of low probability events, and has the highest risk of New York airports. As sea level rise increases, the risk to EWR and subsequently to JFK begins to increase, consistent with local analysis (Stringer, 2019). However, this study does not identify a high risk to Kansai International Airport (KIX) in Osaka, despite flooding during Typhoon Jebi in 2018. This is because its elevation is reported to be over 5 m, far above extreme water levels used here. However, Typhoon Jebi created the highest surge on record and waves of over 5 m that overtopped on-site flood defences (Lacoin, 2019). Wave heights are affected by local processes and so not included in this analysis, but only make a small contribution to flood risk on a global scale (Kirezci et al., 2020). Despite these uncertainties, modelling these physical processes is important. An index based purely on elevation does not account for variations in sea level or local flood protection, and would place airports like AMS at the top of the risk rankings despite having high levels of coastal protection.

Over the timeframe of interest here routes will not be static and over time change for a range of reasons, inevitably impacting upon the risk. Most recently, COVID-19 has led to a rapid decline in air travel (Suau-Sanchez et al., 2020) which would decrease the overall risk calculated here by 80–90%. Recent industry forecasts are for a recovery to pre-COVID levels of air travel by 2024, but with significant regional variation in the rate of recovery (Pearce, 2020). China already has a number of airports in the highest risk category, and Asia Pacific is forecast to see the greatest growth in air travel and airport expansion in the next two decades (IATA, 2020) so the current spatial distribution of airport risk might be amplified. However, this study shows it is necessary to understand current and future risk from sea level rise to provide the necessary long lead time for adaptation which might include the engineering interventions considered in Section 5, but also changes to flight routes.

Route disruption has been used as the measure of risk as it is strongly related to the direct economic impact and losses associated with airport closure (Faturechi et al., 2014). However, as discussed in Section 4, other factors are also important. Use of other metrics provides a different perspective on risk and alters the ranking of different airports, and can bring to the fore airports especially susceptible to flooding, or those at high risk of flooding but also in locations especially reliant on imports of goods or tourists (Table SM.4). These indicators are reported at the national level, and are incomplete in coverage, so cannot be attributed to a particular airport. Whilst they are therefore not of sufficient granularity for an airport scale risk analysis, they do provide useful insight into reliance on domestic and international connectivity.

7. Conclusions

A number of airports around the world are already at risk of coastal flooding. A modest amount of sea level rise, such as that associated with a global mean temperature rise of 2 °C, would place 100 airports below mean sea level. Despite international agreements to reduce global greenhouse gas emissions, prior to the COVID-19 pandemic, new airports and airport expansion projects continued to be approved (Statista, 2020d), driven predominately by just-in-time supply chains, business, and tourism.

The risk from sea level rise to airports has been calculated in terms of route disruptions, using only globally available datasets. The analysis identifies that 269 airports at risk now and this could grow to 572 by 2100. The expected annual route disruptions could increase respectively by a factor of between 17 and 69 by 2100 under the 1.5 °C and 95th percentile value of the RCP8.5 sea level rise scenario respectively. Current levels of flood protection reduce the risk to airports by a factor of 23. Airports in the coastal zone are disproportionately important in the global airport network, with 10.1% of all routes at risk from a 1.5 °C warming scenario, and up to 19.9% at risk by 2100 from the highest sea level rise scenario considered. This risk is likely to be an underestimate in areas susceptible to typhoons and hurricanes, or compound flooding events (e.g. estuaries). Sea level rise therefore poses a significant, and systemic, risk to the airport sector and global economy as many of these locations will be simultaneously affected.

This risk is not equitably distributed and will be amplified by connectivity, isolation, and local socio-economic conditions. Some regions, especially low lying islands, will experience disproportionate impacts because airports provide crucial economic, social, and medical lifelines. However, data coverage and resolution are currently inadequate to include these in the risk analysis. Future work should develop and collect globally available indicators in order to assess these risks.

Globally the cost of adaptation to maintain risk in 2100 at present levels could cost up to $39BN for the median RCP8.5 sea level rise scenario, and $57BN for the highest scenario considered, which are modest in the context of global infrastructure expenditure. The rate of increase in risk between 1 and 3 m is double that rate of increase for 0–1 m sea level rise providing an opportunity to plan for long term adaptation. The long lead-time for major engineering works, and to minimise disruption by scheduling works into less disruptive windows, requires this to start right away. However, in some locations the rate of sea level rise, limited economic resources or space for alternative locations will make some airports unviable.

More detailed modelling of coastal hazard could be undertaken, including wave setup, subsidence, and collation of airport specific levels of flood protection. However, crucial to improved risk analysis will be a higher resolution, more accurate global DEM as called for by McClean et al. (2020) and Sampson et al. (2016). Development of the risk analysis should develop methods to consider how the airline network may evolve in the future, perhaps based upon spatial socio-economic scenarios of development (e.g. Brown et al., 2018). Furthermore, it is necessary to start collating a wider range of impact metrics related to isolation and local socio-economic conditions. This would allow a composite assessment of risk based on the economic and social importance of airports to the communities they serve, as well as their overall importance in the global network as considered here. Finally, the risk analysis could be further expanded to consider other climate change impacts, in particular the influence of compound risks from multiple sources of flooding, hurricanes and tropical cyclones.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crm.2020.100266.

References

Andrijevic, M., Cuaresma, J.C., Muttarak, R., Schleussner, C.F., 2020. Governance in socioeconomic pathways and its role for future adaptive capacity. Nat. Sustainability 3 (1), 35–41.
Baglin, C., 2012. Airport Climate Adaptation and Resilience. Transportation Research Board of the National Academies Vol. 33.
Bamber, J.L., Oppenheimer, M., Kopp, R.E., Aspinall, W.P., Cooke, R.M., 2019. Ice sheet contributions to future sea-level rise from structured expert judgment. Proc. Natl. Acad. Sci. 116 (23), 11195–11200.
Brown, M., 2016. Cook Islands Government Budget Estimates 2016/2017 Book 3 Capital Plan, http://procurement.gov.ck/wp-content/plugins/ck_procurement/uploads/033817_18-10-2016_2016-17_Cook-Islands_Budget-Book-3_Capital-Plan.pdf (accessed 13/2/2020).
Brown, S., Nicholls, R.J., Goodwin, P., Haigh, I.D., Lincke, D., Vafeidis, A.T., Hinkel, J., 2018. Quantifying land and people exposed to sea-level rise with no mitigation and 1.5 C and 2.0 C rise in global temperatures to year 2300. Earth's Future 6 (3), 583–600.
Burbidge, R., 2017. Climate-proofing the airport of the future. J. Airport Manage. 11 (2), 114–128.
Burbidge, R., 2018. Adapting aviation to a changing climate: key priorities for action. J. Air Transp. Manage. 71, 167–174.
Caparros-Midwood, D., Barr, S., Dawson, R.J., 2015. Optimized Spatial planning to meet urban sustainability objectives. Comput. Environ. Urban Simul. 54, 154–164. https://doi.org/10.1016/j.compenvurbsys.2015.08.003.
Chatterton, J., Clarke, C., Daly, E., Dawks, S., Elding, C., Fenn, T., Hick, E., Miller, J., Morris, J., Ogunyoye, F., Salado, R., 2016. The costs and impacts of the winter 2013 to 2014 floods Report – SC140025/R1. Environment Agency, Bristol, UK.
Christodoulou, A., Demirel, H., 2018. Impacts of climate change on transport - A focus on airports, seaports and inland waterways, EUR 28896 EN. Publications Office of the European Union, Luxembourg.
Dawson, R.J., 2015. Handling interdependencies in climate change risk assessment. Climate 3 (4), 1079–1096. https://doi.org/10.3390/cli3041079.
Dawson, R., Hall, J., 2006. Adaptive importance sampling for risk analysis of complex infrastructure systems. Proc. R. Soc. A 462 (2075), 3343–3362.
Dawson, R.J., Thompson, D., Johns, D., Wood, R., Darch, G., Chapman, L., Hughes, P.N., Watson, G.V., Paulson, K., Bell, S., Gosling, S.N., 2018. A systems framework for national assessment of climate risks to infrastructure. Philos. Trans. R. Soc. A: Math., Phys. Eng. Sci. 376 (2121), 20170298.
Doll, C., Klug, S., Enei, R., 2014. Large and small numbers: options for quantifying the costs of extremes on transport now and in 40 years. Nat. Hazards 72 (1), 211–239.
EFE, 2019. Post-hurricane rebuilding of Puerto Rico's main airport nearly complete, www.efe.com/efe/english/world/post-hurricane-rebuilding-of-puerto-rico-s-main-airport-nearly-complete/50000262-3749059 (accessed 16/2/2020).
Faturechi, R., Levenberg, E., Miller-Hooks, E., 2014. Evaluating and optimizing resilience of airport pavement networks. Comput. Oper. Res. 43, 335–348.
Frederikse, T., Landerer, F., Caron, L., Adhikari, S., Parkes, D., Humphrey, V.W., Dangendorf, S., Hogarth, P., Zanna, L., Cheng, L., Wu, Y.H., 2020 Aug. The causes of sea-level rise since 1900. Nature 584 (7821), 393–397.
Fu, G., Dawson, R.J., Khoury, M., Bullock, S., 2014. Interdependent networks: Vulnerability analysis and strategies to limit cascading failure. Eur. Phys. J. Part B 87 (7), 148. https://doi.org/10.1140/epjb/e2014-40876-y.
GCA, 2019. Adapt now: A global call for Leadership on climate resilience. Global Commission on Adaptation and World Resources Institute.
Gössling, S., Upham, P. (Eds.), 2009. Climate change and aviation: Issues, challenges and solutions. Earthscan.
Hadžić, N., Tomić, M., Vladimir, N., Senjanović, I., 2016. Some aspects of mega-floating airport design and production. Ann. Maritime Stud. 1, 81–99.
Hales, R., Caton, K., 2017. Proximity ethics, climate change and the flyer's dilemma: Ethical negotiations of the hypermobile traveller. Tourist Studies 17 (1), 94–113.
Hanson, S., Nicholls, R., Ranger, N., Hallegatte, S., Corfee-Morlot, J., Herweijer, C., Chateau, J., 2011. A global ranking of port cities with high exposure to climate extremes. Clim. Change 104 (1), 89–111.
Heathrow Airport, 2016. Climate Change Adaptation and Resilience Progress Report, Heathrow Airport, UK. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/566147/climate-adrep-heathrow.pdf (accessed 16/2/2020).
Hinkel, J., Lincke, D., Vafeidis, A.T., Perrette, M., Nicholls, R.J., Tol, R.S., Marzeion, B., Fettweis, X., Ionescu, C., Levermann, A., 2014. Coastal flood damage and adaptation costs under 21st century sea-level rise. Proc. Natl. Acad. Sci. 111 (9), 3292–3297.
Hippe, A., Becker, A., Fischer, M., Schwegler, B., 2015. Estimation of Cost Required to Elevate US Ports in Response to Climate Change: A Thought Exercise for Climate Critical Resources. CIFE Working Paper #WP138, December.
IATA. 2016. A blueprint for maximizing the social and economic value of aviation, IATA. www.iata.org/contentassets/4ede2aabfcc14a55919e468054d714fe/ican_caribbeanreport.pdf (accessed 16/2/2020).
IATA, 2019. The value of air cargo, https://www.iata.org/contentassets/62bae061c05b429ea508cb0c49907c4c/air-cargo-brochure.pdf (accessed 16/2/2020).
IATA, 2020. 20 year passenger forecast, July 2020. https://www.iata.org/en/publications/store/20-year-passenger-forecast/ (accessed 16/8/2020).
Inoe, K., 1999. Mega Float: Achievements to Date and Ongoing Plan of Research, in Proc. 9th Int. Offshore and Polar Engineering Conf., France, 1999.
InterVISTAS, 2015. Economic Impact of European Airports A Critical Catalyst to Economic Growth, Bath, UK. www.intervistas.com/downloads/reports/Economic%20Impact%20of%20European%20Airports%20-%20January%202015.pdf (accessed 16/2/2020).
Jacobs, J.M., M. Culp, L. Cattaneo, P. Chinowsky, A. Choate, S. DesRoches, S. Douglass, and R. Miller (2018) Transportation. in Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 479–511. doi: 10.7930/NCA4.2018.CH12.
Jonkman, S.N., et al., 2013. Costs of adapting coastal defences to sea level rise – new estimates and their implications. J. Coast. Res. 290, 1212–1226.
Jevrejeva, S., Jackson, L.P., Grinsted, A., Lincke, D., Marzeion, B., 2018. Flood damage costs under the sea level rise with warming of 1.5 C and 2 C. Environ. Res. Lett. 13 (7), 074014.
Kantenbacher, J., Hanna, P., Cohen, S., Miller, G., Scarles, C., 2018. Public attitudes about climate policy options for aviation. Environ. Sci. Policy 81, 46–53.
Kirezci, E., Young, I.R., Ranasinghe, R., Muis, S., Nicholls, R.J., Lincke, D., Hinkel, J., 2020. Projections of global-scale extreme sea levels and resulting episodic coastal flooding over the 21st Century. Sci. Rep. 10 (1), 1–12.
Knowlton, K., Rotkin-Ellman, M., 2014. Preparing for Climate Change: Lessons for Coastal Cities from Hurricane Sandy, Natural Resources Defence Council, Report: 14-04-A.
Kulp, S.A., Strauss, B.H., 2019. New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. Nat. Commun. 10 (1), 1–12.
Kulp, S., Strauss, B.H., 2016. Global DEM errors underpredict coastal vulnerability to sea level rise and flooding. Front. Earth Sci. 4 (36).
Lacoin, S., 2019. Climate Change Resilience Strategy – Redefining Flood Protection At Kansai International Airport. In: ICAO 2019 Environmental Report. International Civil Aviation Organization, Montreal, Canada, pp. 263–267.
Lamas-Pardo, M., Iglesias, G., Carral, L., 2015. A review of very large floating structures (VLFS) for coastal and offshore uses. Ocean Eng. 109, 677–690.
Larsen, P.H., Goldsmith, S., Smith, O., Wilson, M.L., Strzepek, K., Chinowsky, P., Saylor, B., 2008. Estimating future costs for Alaska public infrastructure at risk from climate change. Global Environ. Change 18 (3), 442–457.
Lenk, S., Rybski, D., Heidrich, O., Dawson, R.J., Kropp, J.P., 2017. Costs of sea dikes – regressions and uncertainty estimates. Nat. Hazards Earth Syst. Sci. 17, 765–779. https://doi.org/10.5194/nhess-17-765-2017.
Linham, M., Green, C., Nicholls, R., 2010. AVOID Report on the Costs of adaptation to the effects of climate change in the world's large port cities. AV/WS2. Available at: www.avoid.uk.net/2010/07/avoid-1-costs-of-adapta tion-to-the-effects-of-climate-change-in-the-worlds-large-port-cities/.
Massport, 2018. Sustainable Massport: Annual sustainability and resiliency report, Massachusetts Port Authority, Boston. www.massport.com/media/2774/massport-annual-sustainability-and-resiliency-report-2018_lr.pdf (accessed 16/2/2020).
McClean, F., Dawson, R.J., Kilsby, C.G., 2020. Implications of using Global Digital Elevation Models for Flood Risk Analysis in Cities, Water Resources Research, Accepted for publication.
McGranahan, G., Balk, D., Anderson, B., 2007. The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones. Environ. Urbaniz. 19 (1), 17–37.

McManners, P., 2012. Fly and be damned: what now for aviation and climate change? Zed Books Ltd.
Mori, N., Yasuda, T., Arikawa, T., Kataoka, T., Nakajo, S., Suzuki, K., Yamanaka, Y., Webb, A., 2019 Jul 3. 2018 Typhoon Jebi post-event survey of coastal damage in the Kansai region, Japan. Coast. Eng. J. 61 (3), 278–294.
Mosvold Larsen, O., 2015. Climate change is here to stay: reviewing the impact of climate change on airport infrastructure. J. Airport Manage. 9 (3), 264–269.
Muis, S., Apecechea, M.I., Dullaart, J., de Lima, Rego J., Madsen, K.S., Su, J., Yan, K., Verlaan, M., 2020. A high-resolution global dataset of extreme sea levels, tides, and storm surges, including future projections. Front. Mar. Sci. 7, 263.
Narayan, S., Beck, M.W., Reguero, B.G., Losada, I.J., Van Wesenbeeck, B., Pontee, N., Sanchirico, J.N., Ingram, J.C., Lange, G.M., Burks-Copes, K.A., 2016. The effectiveness, costs and coastal protection benefits of natural and nature-based defences. PLoS ONE 11 (5), e0154735.
Nicholls, R.J., Lincke, D., Hinkel, J., van der Pol, T., 2019. Global Investment Costs for Coastal Defence Through the 21st Century. World Bank, Group, W.B.G.S.D.P. [Available at: http://documents.worldbank.org/curated/en/433981550240622188/pdf/WPS8745.pdf]. Accessed: 2019/09/20.
Nicholls, R.J., Brown, S., Goodwin, P., Wahl, T., Lowe, J., Solan, M., Godbold, J.A., Haigh, I.D., Lincke, D., Hinkel, J., Wolff, C., 2018. Stabilization of global temperature at 1.5 C and 2.0 C: implications for coastal areas. Philos. Trans. R. Soc. A: Math., Phys. Eng. Sci. 376 (2119), 20160448.
NYC, 2013. New York City: A Stronger, More Resilient New York https://www1.nyc.gov/site/sirr/report/report.page (Accessed, 16/2/2020).
Olazabal, M., de Gopegui, M.R., Tompkins, E.L., Venner, K., Smith, R., 2019. A cross-scale worldwide analysis of coastal adaptation planning. Environ. Res. Lett. 14 (12), 124056.
Oppenheimer, M., Glavovic, B.C., Hinkel, J., van de Wal, R., Magnan, A.K., Abd-Elgawad, A., Cai, R., Cifuentes-Jara, M., DeConto, R.M., Ghosh, T., Hay, J., Isla, F., Marzeion, B., Meyssignac, B., Sebesvari, Z., 2019. Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)].
Patokallio, J., 2009. Openflights data. http://openflights.org/ (Date of access:01/08/2019).
Pearce, B., 2020. COVID-19 June data and revised air travel outlook, IATA. (https://www.iata.org/en/iata-repository/publications/economic-reports/june-data-and-revised-air-travel-outlook/).
Poo, M.C.P., Yang, Z., Dimitriu, D., Qu, Z., 2018. Review on seaport and airport adaptation to climate change: a case on sea level rise and flooding. Mar. Technol. Soc. J. 52 (2), 23–33.
Pregnolato, M., Ford, A., Glenis, V., Wilkinson, S., Dawson, R.J., 2017. Impact of climate change on disruption to urban transport networks from pluvial flooding. ASCE J. Infrastruct. Syst. 23 (4), 04017015. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000372.
Sampson, C.C., Smith, A.M., Bates, P.D., Neal, J.C., Trigg, M.A., 2016. Perspectives on open access high resolution digital elevation models to produce global flood hazard layers. Front. Earth Sci. 3, 85.
Scussolini, P., Aerts, J.C., Jongman, B., Bouwer, L.M., Winsemius, H.C., de Moel, H., Ward, P.J., 2016. FLOPROS: an evolving global database of flood protection standards. Nat. Hazards Earth Syst. Sci. 16 (5).
Slevin, P., 2010. Quake-damaged main port in Port-au-Prince, Haiti, worse off than realized. Washington Post, 28 January 2010 (accessed 12 February 2020).
SkyVector, 2020a. LaGuardia Airport https://skyvector.com/files/tpp/2012/pdf/00289AD.PDF (accessed 10th August 2020).
SkyVector, 2020b. Newark Liberty International Airport https://skyvector.com/files/tpp/2012/pdf/00285AD.PDF (accessed 10th August 2020).
SkyVector, 2020c. John F Kennedy International Airport https://skyvector.com/files/tpp/2012/pdf/00610AD.PDF (accessed 10th August 2020).
Statista, 2020a. Number of scheduled passengers boarded, www.statista.com/statistics/564717/airline-industry-passenger-traffic-globally/ (accessed 16/2/2020).
Statista, 2020b. Worldwide air freight traffic, www.statista.com/statistics/564668/worldwide-air-cargo-traffic/ (accessed 16/2/2020).
Statista, 2020c. Airport infrastructure investments, www.statista.com/statistics/653269/airport-infrastructure-investments-by-region/ (accessed 16/2/2020).
Statista, 2020d. Construction costs for selected airports, www.statista.com/statistics/233999/construction-costs-for-selected-airports/ (accessed 16/2/2020).
Steffen W., Hunter J., Hughes L., 2014. Counting the costs: Climate change and coastal flooding, Climate Council of Australia, ISBN 978-0-9941623-1-1 www.climatecouncil.org.au/uploads/56812f1261b168e02032126342619dad.pdf (accessed 16/2/2020).
Stringer, S., 2019. Safeguarding Our Shores. Office of the New York City Comptroller, New York City, USA.
Suau-Sanchez, P., Voltes-Dorta, A., Cugueró-Escofet, N., 2020. An early assessment of the impact of COVID-19 on air transport: Just another crisis or the end of aviation as we know it? J. Transp. Geogr. 86, 102749.
Sydney Airport, 2019. Environment Strategy 2019-2024, Sydney, Australia. https://assets.ctfassets.net/v228i5y5k0x4/cxZTrfYEhY0GQuKBVb1b2/a0caa7b4c46aebad0b69c59793123eff/Sydney_Airport_Environmental_Strategy_2019-2024_F.pdf (accessed 16/2/2020).
Tamura, M., Kumano, N., Yotsukuri, M., Yokoki, H., 2019. Global assessment of the effectiveness of adaptation in coastal areas based on RCP/SSP scenarios. Clim. Change 152 (3–4), 1–15.
Tapia, C., Abajo, B., Feliu, E., Mendizabal, M., Martinez, J.A., Fernández, J.G., Laburu, T., Lejarazu, A., 2017. Profiling urban vulnerabilities to climate change: an indicator-based vulnerability assessment for European cities. Ecol. Ind. 78, 142–155.
Tiggeloven, T., Moel, H.D., Winsemius, H.C., Eilander, D., Erkens, G., Gebremedhin, E., Diaz Loaiza, A., Kuzma, S., Luo, T., Iceland, C., Bouwman, A., 2020. Global-scale benefit–cost analysis of coastal flood adaptation to different flood risk drivers using structural measures. Nat. Hazards Earth Syst. Sci. 20 (4), 1025–1044. https://doi.org/10.5194/nhess-20-1025-2020.
Verma, T., Araújo, N.A.M., Nagler, J., Andrade Jr, J.S., Herrmann, H.J., 2016. Model for the growth of the World Airline Network. Int. J. Mod. Phys. C 27 (12), 1650141.
Verma, T., Araújo, N.A., Herrmann, H.J., 2014. Revealing the structure of the world airline network. Sci. Rep. 4, 5638.
Vitousek, S., Barnard, P.L., Fletcher, C.H., Frazer, N., Erikson, L., Storlazzi, C.D., 2017. Doubling of coastal flooding frequency within decades due to sea-level rise. Sci. Rep. 7 (1), 1–9.
Vousdoukas, M.I., Bouziotas, D., Giardino, A., Bouwer, L.M., Mentaschi, L., Voukouvalas, E., Feyen, L., 2018. Understanding epistemic uncertainty in large-scale coastal flood risk assessment for present and future climates. Nat. Hazards Earth Syst. Sci. 18 (8), 2127–2142.
Williams, C., You, J.J., Joshua, K., 2020. Small-business resilience in a remote tourist destination: exploring close relationship capabilities on the island of St Helena. J. Sustain. Tourism 1–19.
Williams, P.D., 2016. Transatlantic flight times and climate change. Environ. Res. Lett. 11 (2), 024008.
WTTC, 2019a. Economic Impact 2019, World Travel and Tourism Council, London. www.wttc.org/-/media/files/reports/economic-impact-research/regions-2019/world2019.pdf (accessed 16/2/2020).
WTTC, 2019b. 2019 Annual Research: Key Highlights, Reports for Cuba, Jamaica, Puerto Rico, Former Netherlands Antilles. www.wttc.org/economic-impact/country-analysis/country-data/ (accessed 16/2/2020).
Yan, X., Jeub, L.G., Flammini, A., Radicchi, F., Fortunato, S., 2018. Weight thresholding on complex networks. Phys. Rev. E 98 (4), 042304.
Zhang, F., Graham, D.J., 2020. Air transport and economic growth: a review of the impact mechanism and causal relationships. Transport Reviews 1–23.