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Climate and human society: adopting sea level fingerprints in next generation projections of airport flood risk

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ABSTRACT: Assessing the impact of sea level changes on airports across the present century is a pressing issue for the rapidly expanding aviation sector and, more generally, for establishing adaptation strategies. To date, these assessments have assumed that future melting of ice sheets and glaciers leads to globally uniform sea level changes. We summarize recent geophysical research that highlights the extreme geographic variability in sea level that will occur in response to such melting — a variability captured in so-called sea level fingerprints. As a case study, we present modeling predictions of sea level change to 2100 CE based on a suite of published projections of polar ice mass flux and consider the implications of these results for airports identified as being at particularly high risk from sea level rise. We conclude that this important source of sea level variability should be incorporated — together with other processes that imprint a geographic pattern on sea level (e.g. storm surges, tides, thermosteric and ocean dynamic changes) — into projections of airport risks in a warming world.

KEY WORDS: Airport flood risk · Sea level geometries · Ice sheets

1. INTRODUCTION

The impacts of climate change on the transportation sector, and the transportation sector on climate, are well established (Douglas et al. 2017). The aviation sector has been a particular focus for studies of the latter given its significant contribution to greenhouse gas emissions and the technical challenges involved in reducing emissions (e.g. Dessens et al. 2014, Andres & Padilla 2018). However, studies of the impact of climate change on aviation have arguably received less attention (Ryley et al. 2020). A recent literature review summarizes a wide range of possible impacts, including direct effects on flights (e.g. increases in the frequency of storms, extreme weather events, clear-air turbulence and ash clouds, changes in fog distribution, and pressure-temperature effects on climb rates), infrastructure stresses (e.g. tarmac conditions, flooding) and airport operations in general (Ryley et al. 2020; see also references therein, including studies with implications for policy and regulation).

An important recent study has provided a comprehensive, global analysis of the risk to airports from sea level rise to 2100 CE, where the metric of 'risk' was defined in terms of the expected disruption of routes (Yesudian & Dawson 2021). They concluded that 10–20% of existing routes will experience an increased risk, and while these routes are globally distributed, the most pronounced increase will occur for routes in Southeast and East Asia. The Yesudian & Dawson (2021) analysis combined the geographic variation in

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extreme water levels at present day, as modeled by the Coastal Dataset for the Evaluation of Climate Impact (Muis et al. 2020), with projections of global mean sea level (GMSL) rise associated with 3 different scenarios for the current century (Jevrejeva et al. 2018): global mean temperature increases of 1.5 and 2.0°C, and the future high emission scenario representative concentration pathway (RCP) 8.5, to the year 2100 CE. These scenarios yield median GMSL increases of 52, 63 and 86 cm, respectively, from a combination of ice sheet melt, glacier melt, and thermal expansion of oceans.

Melting of individual ice sheets and glaciers gives rise to unique geographic variations in sea level that have come to be known as 'sea-level fingerprints' within studies of modern sea level change (e.g. Clark & Primus 1987, Mitrovica et al. 2001, Plag & Jüttner 2001, Tamisiea & Mitrovica 2011, Cederberg et al. 2023). It is common in climate projections, including the Yesudian & Dawson (2021) study, to assume that the sea-level change associated with these processes is uniform; that is, that the variation in sea level at all sites is the same and equal to the GMSL change. The goal of the present study is to highlight the potential importance of incorporating more accurate fingerprints into next generation assessments of the risk to airports of sea level rise. We show predictions of sea level change associated with a set of published, climate model-based scenarios of glacier and polar ice sheet mass loss to the end of the century. The predictions will be in the form of maps and a set of 47 airports identified as being at particularly high risk (Yesudian & Dawson 2021).

2. MATERIALS AND METHODS

2.1. Sea level fingerprints

The technical details of predicting sea level changes following ice mass changes can be found in a number of publications (Farrell & Clark, 1976, Kendall et al. 2005). The physics of such changes is summarized, schematically, in Fig. 1. Sea level is defined as the vertical distance between the ocean surface and the ocean bottom, or crust, and thus a change in either of these bounding surfaces will cause a change in sea level. An airport may be subject to flooding if the sea surface rises or the land subsides, or some combination of both.

When an ice sheet or glacier melts, the volume of the ocean (and GMSL) is increased by the addition of meltwater. But several other processes also occur to perturb sea level (Fig. 1). First, an ice sheet exerts a gravitational pull on the surrounding ocean, and when the ice sheet loses mass, this gravitational pull is decreased, and water migrates away from the ice sheet, thus lowering the sea surface. Second, an ice sheet acts to load the crust upon which it sits, and thus when the ice sheet melts, the unloaded crust 'rebounds' upward. The combination of these gravitational and deformation processes leads to a remarkably counterintuitive effect; namely, sea level will fall close to a melting ice sheet or glacier. Numerical calculations indicate that this fall will extend ~2000 km away from the location of melting. Beyond this ~2000 km zone, sea level will rise, generally by progressively greater amounts.

We emphasize that the geographic variability is significant. For example, consider the case of ice melt in Greenland sufficient to raise GMSL by 1 m. In this case, sea level will rise in the far field of the ice sheet by up to ~1.3 m, and it will fall in the near vicinity of the ice melt by as much as 10 times the GMSL change, i.e. 10 m. In the results below we consider sea level fingerprints associated with mass flux from the Antarctic Ice Sheet (AIS), the Greenland Ice Sheet (GrIS), and a set of 19 globally distributed glaciers.

2.2. Ice melt scenarios

Goelzer et al. (2020) and Seroussi et al. (2020) compiled a large ensemble of ice sheet-climate model

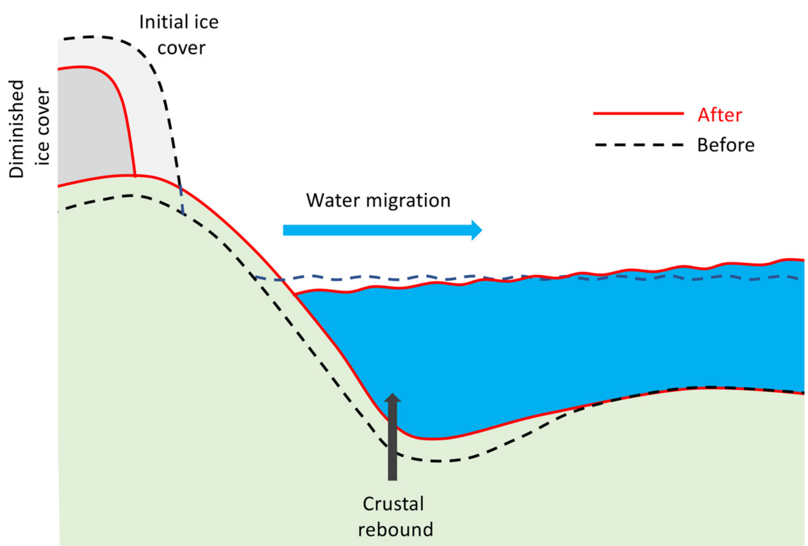

Fig. 1. Schematic illustrating the physics of sea level change driven by modern ice-melt (after Tamisiea & Mitrovica 2011)

projections of the GrIS and AIS, respectively, as part of the Ice Sheet Model Intercomparison Project (ISMIP). We have chosen, as illustrative examples, simulations associated with RCP 8.5 and 2.6. In the case of GrIS projections these are IMAU-IMAUICE2 Expt 09 (GMSL rise 16.6 cm) and GISM-VUB Expt 07 (GMSL rise 5.0 cm), respectively, while the AIS projections are ULB-fETISH Expt A1 (GMSL rise 31.3 cm) and ULB-fETISH Expt 03 (GMSL rise 8.6 cm), respectively. For the global suite of 19 glaciers, we adopted median values of mass loss for each glacier in Edwards et al. (2021) for climate scenarios SSP (shared socioeconomic pathways) 85 and 26. The net ice mass loss from glaciers in each case is equivalent to a GMSL rise of 16 and 8 cm, respectively.

3. RESULTS AND DISCUSSION

Our fingerprint results are computed following Cederberg et al. (2023), and they are normalized by the GMSL change associated with each scenario, as listed above. In this way, for a given scenario, values >1 correspond to locations which will experience a higher than global average sea level rise, values between 0 and 1 correspond to locations which will experience less than global average sea level rise, and, finally, negative values represent locations which will experience a sea level fall.

The top 2 rows of Fig. 2 show normalized sea level fingerprints associated with the RCP 8.5 (top) and RCP 2.6 (middle) scenarios of GrIS melt between 2015 and 2100 CE. The similarity of these fingerprints is consistent with the results of Cederberg et al. (2023), who showed that the ~160 GrIS projections in the Goelzer et al. (2020) database yielded nearly identical normalized fingerprints, reflecting a strong consistency in the melt geometry amongst the simulations. As discussed in the context of Fig. 1, the region encircling Greenland (red) is predicted to be a zone of sea level fall; beyond this region sea level rise increases progressively toward the southern hemisphere, where it peaks at 1.26 (i.e. 26% above the global average). As examples, melting of the GrIS will lead to a sea level fall in Scotland, Norway and Newfoundland, while moving south along the US East Coast, the predicted sea level rise will increase from 0.2 to 0.8 times the global average.

The final row of Fig. 2 shows the specific values of the normalized fingerprints at 47 sites listed by Yesudian & Dawson (2021) that are included within the 20 airports at highest risk from sea level rise in any of the 3 climate simulations (and uniform sea level scenarios) they considered (see Table A1 in the Appendix, which also provides a list of site names). The predictions vary between 0.1 and 1.2, and as expected from the maps on Fig. 2, there are only minor differences in the normalized values for the RCP 8.5 and RCP 2.6 scenarios (open and solid circles). The 9 airport sites that will experience <50% of the GMSL change associated with any future GrIS mass loss are: Corvo Portugal (Site 11), Bremen (Site 21), La Guardia (Site 27), Amsterdam Schiphol (Site 30), Venice Marco Polo (Site 34), Newark Liberty International (Site 35), London City (Site 36), Rotterdam (Site 37) and Pisa International (Site 47). These sites are, relatively speaking, the closest to the location of GrIS mass flux, and thus water migrates away from these locations due to the gravitational effect highlighted in Fig. 1. Consider, for example, Amsterdam Schiphol Airport. In the case of the RCP 8.5 scenario, and a GMSL rise of 16.6 cm, this airport would actually experience a sea level rise of only 2.5 cm (0.15 × 16.6 cm). In contrast, sites at great distance from Greenland, including airports in Asia and the Solomon Islands, would experience a sea level rise of up to ~20 cm (1.2 × 16.6 cm).

Next, consider the AIS (Fig. 3). In this case, there are somewhat larger differences between the sea level changes computed from the RCP 8.5 and 2.6 scenarios. Cederberg et al. (2023) have shown that this increased sensitivity arises because of the greater variability in the geometry of the mass changes across the ISMIP scenarios, although this variability drops considerably for scenarios with a GMSL rise across the 21st century >~10 cm. Of the 47 airports considered in the bottom frame of Fig. 3, only one, Dunedin New Zealand, is predicted to have a sea level rise significantly lower than the GMSL change. The remaining airports are located at great distance from the Antarctic and are subject to a migration of meltwater toward them (Fig. 1). As a result, they experience a sea level rise up to 25% higher than the GMSL change associated with AIS evolution across the present century.

Finally, consider results for projected mass balance of glacier systems (Fig. 4). The normalized fingerprints for the 2 scenarios are consistent and both vary across a wide range at the 47 airport sites. The lowest predicted sea level change is seen at Nightmute Airport, Alaska (Site 32), close to the Alaskan glacier system which is expected to be a major contributor to GMSL changes from 2015–2100 CE. Other airports with sea level changes less than 60% of GMSL are in Northern Europe (Bremen, Site 21; Amsterdam Schiphol, Site 30; London City, Site 36; and Rotterdam, Site 37) and thus proximal to Arctic glaciers and glaciers on the perimeter of the GrIS.

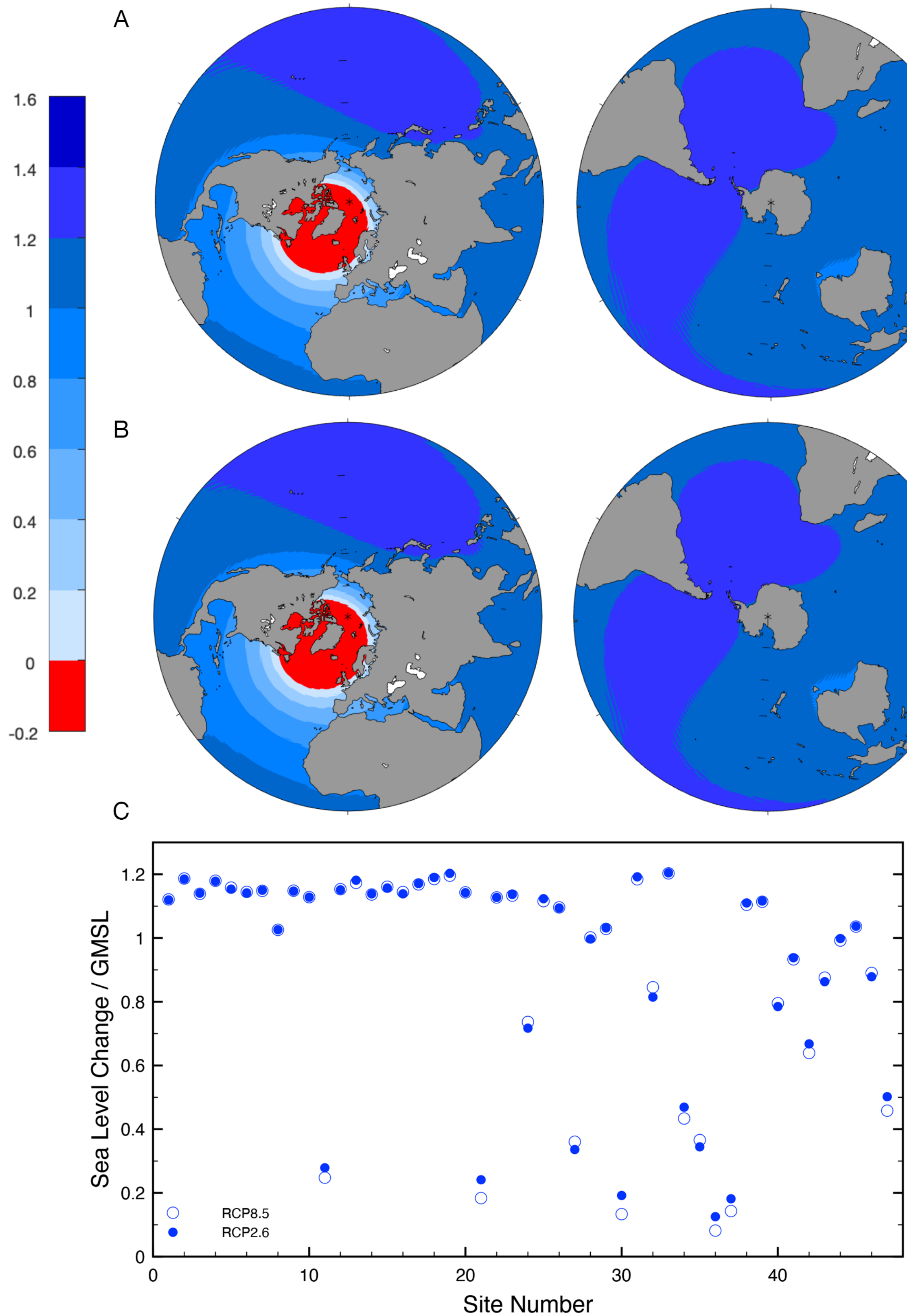

Fig. 2. Normalized fingerprints of sea level change from 2015–2100 CE for 2 Ice Sheet Model Intercomparison Project (ISMIP) simulations of Greenland Ice Sheet mass flux: (A) GISM-VUB Expt 07; (B) IMAU-IMAUICE2 Expt 09. In each case, the fingerprint is normalized (divided) by the global mean sea level (GMSL) rise associated with the simulation, 5.0 cm and 16.6 cm, respectively. (C) Values of the normalized fingerprints at 47 airport locations identified by Yesudian & Dawson (2021) as being at particularly high risk of flooding (see Table A1 in the Appendix for locations). RCP: representative concentration pathway

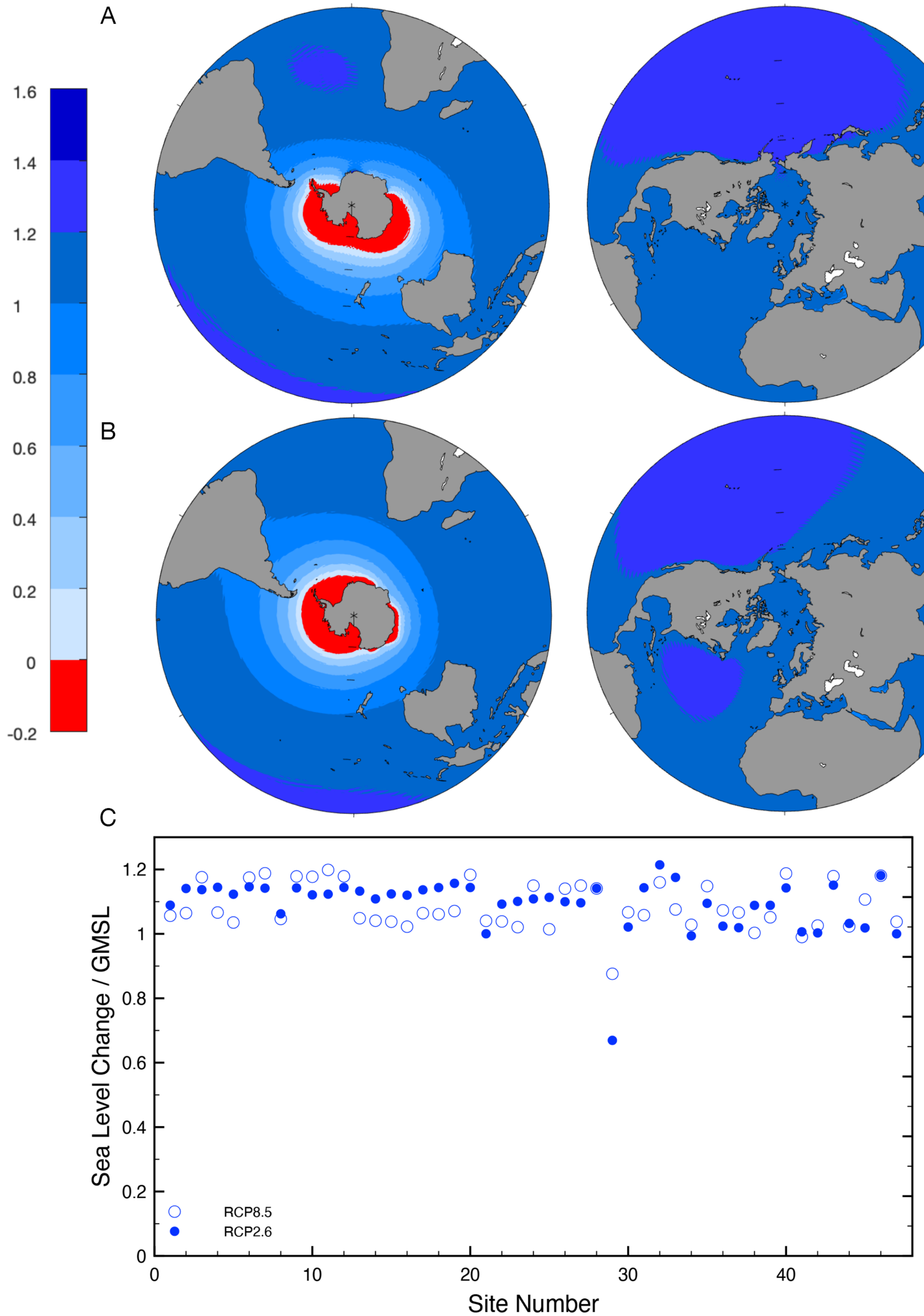

Fig. 3. As in Fig. 2, except for Antarctic Ice Sheet projections: (A) ULB-fETISH Expt 03 (global mean sea level [GMSL] rise = 8.6 cm) and (B) ULB-fETISH Expt A1 (GMSL rise = 31.3 cm)

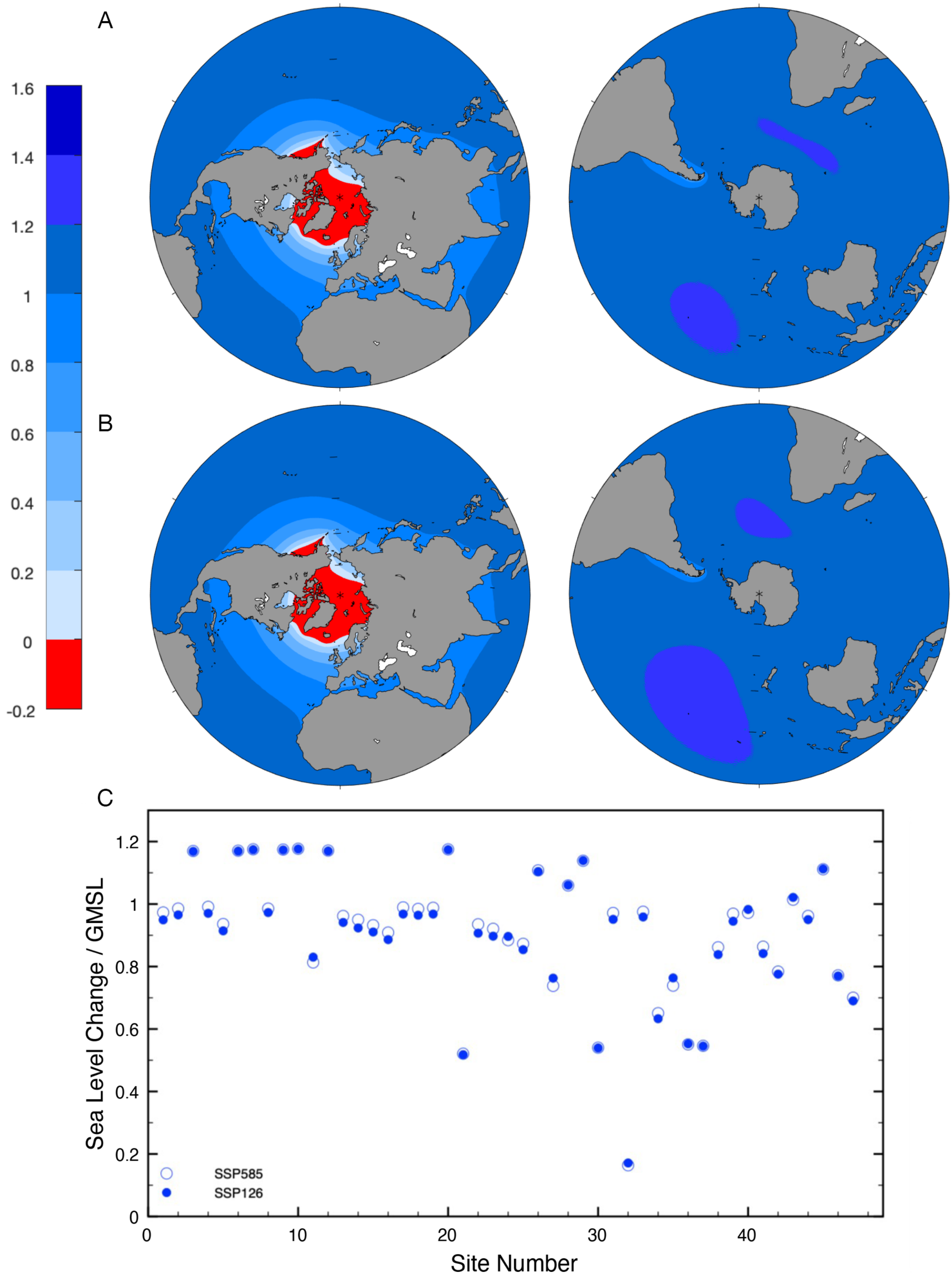

Fig. 4. As in Fig. 3, except for global glacier projections of Edwards et al. (2021): (A) shared socioeconomic pathway (SSP)26 (global mean sea level [GMSL] rise = 8 cm) and (B) SSP85 (GMSL rise = 16 cm)

Note that our normalized maps of sea level change allow one to consider any real-world scenarios of future polar ice mass flux. For example, sea level change associated with melting of the GrIS equivalent to a GMSL rise of 30 cm can be determined by simply scaling the results in Fig. 2 by 30 cm. Furthermore, the sea level change associated with any future combination of GrIS and AIS mass flux can be assessed by taking a sum of the normalized fingerprints weighted by the GMSL value of each ice sheet's mass flux.

4. CONCLUSIONS

Climate change in our warming world will lead to a wide range of disruptions to all sectors of human society, including aviation. Melting of ice sheets and glaciers will increase the frequency and severity of flooding events across many of the world's airports (Yesudian & Dawson 2021). The primary goal of the present paper is to highlight that next generation projections of the risk to airports presented by sea level change should account for the significant geographic variability in sea level changes that will result from expected changes in ice sheet and glacier mass across the 21st century. We also note that the total sea level change will also involve processes we have not considered, including thermosteric effects and variations in ocean dynamics (Hamlington et al. 2020). Public domain platforms are being developed that incorporate all these sources of variability in estimating the costs to coastal communities of sea level rise (Depsky et al. 2023) — the same level of complexity should be included in future assessments of costs incurred by transportation sectors, including aviation, in a warming world.

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Appendix

Table A1. Normalized sea level fingerprints for Antarctic Ice Sheet (AIS), Greenland Ice Sheet (GrIS) and Glacier melt scenarios plotted at 47 sites in Figs. 3, 2 & 4, respectively. In each case, results are shown for both the low and high emission scenarios. RCP: representative concentration pathway; SSP: shared socioeconomic pathway

Site no.	Site name	AIS RCP8.5	AIS RCP2.6	GrIS RCP8.5	GrIS RCP2.6	Glaciers SSP85	Glaciers SSP26
1	Suvarnabhumi, Thailand	1.056	1.089	1.121	1.120	0.973	0.949
2	Wenzhou Longwan Intl., China	1.064	1.141	1.187	1.185	0.986	0.965
3	Seghe, Solomon Islands	1.176	1.137	1.139	1.141	1.170	1.169
4	Quanzhou Jinjiang Intl., China	1.066	1.145	1.180	1.178	0.991	0.970
5	Changzhou Benniu, China	1.035	1.123	1.158	1.153	0.936	0.914
6	Ramata, Solomon Islands	1.175	1.146	1.145	1.142	1.171	1.170
7	Suavanao, Solomon Islands	1.188	1.142	1.148	1.150	1.175	1.174
8	Bosaso, Somalia	1.046	1.062	1.026	1.026	0.985	0.973
9	Fera/Maringe, Solomon Islands	1.178	1.143	1.149	1.147	1.174	1.173
10	Rennell/Tingoa, Solomon Islands	1.177	1.121	1.128	1.128	1.177	1.176
11	Corvo, Portugal	1.199	1.123	0.248	0.279	0.813	0.830
12	Choiseul Bay, Solomon Islands	1.179	1.144	1.153	1.151	1.171	1.170
13	Shanghai Hongqiao Intl., China	1.049	1.133	1.173	1.181	0.962	0.941
14	Beihai, China	1.041	1.109	1.137	1.139	0.950	0.924
15	Yancheng, China	1.038	1.124	1.161	1.157	0.932	0.911
16	Lianyungang, China	1.022	1.120	1.144	1.139	0.909	0.886
17	Jieyang Chaoshan Intl., China	1.064	1.137	1.168	1.171	0.989	0.968
18	Huangyan Luqiao, China	1.061	1.144	1.185	1.190	0.984	0.964
19	Zhoushan, China	1.071	1.157	1.196	1.203	0.988	0.968
20	Uru Harbour, Solomon Islands	1.183	1.144	1.143	1.142	1.175	1.174
21	Bremen, Germany	1.040	1.000	0.184	0.241	0.521	0.518
22	Cat Bi Intl., Vietnam	1.038	1.092	1.127	1.127	0.935	0.907
23	Anqing Tianzhushana, China	1.021	1.101	1.133	1.137	0.921	0.897
24	Louis Armstrong New Orleans Intl., USA	1.150	1.109	0.737	0.717	0.884	0.896
25	Anshan Air Base, China	1.014	1.113	1.116	1.123	0.873	0.854
26	Juanda Intl., Indonesia	1.140	1.100	1.096	1.094	1.108	1.104
27	La Guardia, USA	1.150	1.096	0.361	0.336	0.738	0.763
28	Puerto Jimenez, Costa Rica	1.141	1.141	1.002	0.997	1.059	1.061
29	Dunedin, New Zealand	0.876	0.669	1.029	1.032	1.139	1.139
30	Amsterdam Schiphol, Netherlands	1.067	1.021	0.133	0.192	0.540	0.539
31	Shanghai Pudong Intl., China	1.058	1.143	1.184	1.192	0.971	0.951
32	Nightmute, USA	1.160	1.214	0.845	0.815	0.164	0.171
33	Gimhae Intl., South Korea	1.076	1.175	1.203	1.205	0.975	0.959
34	Venice Marco Polo, Italy	1.028	0.994	0.433	0.469	0.651	0.633
35	Newark Liberty Intl., USA	1.148	1.095	0.366	0.345	0.739	0.764
36	London City, UK	1.073	1.024	0.082	0.125	0.551	0.553
37	Rotterdam The Hague, Netherlands	1.066	1.019	0.143	0.181	0.546	0.545
38	Tianjin Binhai Intl., China	1.003	1.088	1.104	1.110	0.862	0.838
39	Don Mueang Intl., Thailand	1.051	1.089	1.114	1.116	0.969	0.945
40	Key West Intl., USA	1.188	1.143	0.795	0.785	0.972	0.983
41	Bahrain Intl., Bahrain	0.990	1.006	0.933	0.938	0.864	0.842
42	Ioannis Kapodistrias Intl., Greece	1.026	1.003	0.639	0.668	0.784	0.776
43	Sangster Intl., Jamaica	1.179	1.151	0.876	0.863	1.014	1.021
44	Aden Intl., Yemen	1.023	1.032	0.992	0.998	0.962	0.950
45	Cairns Intl., Australia	1.107	1.018	1.036	1.037	1.111	1.112
46	Metropolitan Oakland Intl., USA	1.181	1.181	0.890	0.878	0.772	0.770
47	Pisa Intl., Italy	1.038	1.000	0.458	0.502	0.700	0.690

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