DOUBLE JEOPARDY: The Vulnerability Spiral of Compound Climate Risk Across 5 Islands

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Abstract

Small islands are widely assumed to face a compounding climate risk, made up of high physical exposure to sea level rise stacked on top of degrading natural coastal defenses. That assumption is rarely tested against independent, multi temporal evidence, and rarely broken down by ecosystem type, so I tested it directly, across 5 islands spanning 3 ocean basins (Maldives, Lakshadweep, Seychelles, Fiji, and the Canary Islands). I treated mangrove decline and coral reef degradation as 2 separate pathways, always kept apart, never folded into a single mixed category. Physical exposure came from settlement level elevation data; mangrove extent I tracked across 3 independent time points (1996, 2010, 2020); coral condition came from a 24 year, monthly sampled satellite derived thermal stress record (1996–2020). Coral reef systems show a measurable, rising bleaching stress trend in 4 of 5 islands, most severely in Seychelles. Mangroves, assessed at the same 3 independent time points but without a comparable continuous trend test, show no measurable decline in any of the 3 islands where they're present, so the assumption that ecosystem decline is uniform doesn't hold up. Combine physical exposure with the coral thermal stress trend into a composite vulnerability score, and Seychelles, the highest exposure island on the settlement based measure in this sample, stays the highest overall compound risk once coral thermal stress is factored in too. Population weighted exposure, after fixing an incomplete boundary polygon that had been letting open water leak into the calculation (see Section 6), now shows a different order. Maldives (14.9%) sits marginally ahead of Seychelles (14.2%), close enough that I read it as a near tie between the 2 highest exposure islands and not a clean disagreement with the other measures. An earlier version of this analysis, built on a DEM data quality problem later traced and fixed, made Maldives and Lakshadweep look far more exposed than they are, creating an appearance of disagreement between indicators that didn't actually reflect anything real once the underlying data was fixed. I also ran a supplementary test of whether formal protected area coverage aligns with this empirically verified risk, and found a positive relationship whose p value crosses the conventional 0.05 threshold on this small, 4 island sample ($r=0.965$, $p=0.035$). It's a result I still read with caution, since it rests on so few data points. It's a strong signal on its own, but it doesn't confirm that governance actually responds to risk. A descriptive comparison of settlement expansion (2016–2024) adds a 3rd corroborating signal, since Seychelles shows the clearest built up increase in its broader settled area while Fiji shows none. In short, coastal ecosystem degradation doesn't happen the same way across ecosystem types, and that has a direct effect on how adaptation and conservation resources should be prioritized.

Keywords: sea level rise, mangroves, coral bleaching, compound vulnerability, small island states, protected area effectiveness, remote sensing

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1. Introduction

International climate adaptation policy increasingly treats coastal ecosystems (mangroves, coral reefs, seagrass beds) as a single protective category, financed and managed under the umbrella term "nature based solutions." A substantial body of research documents that these ecosystems really do provide measurable coastal protection. Reef structures dissipate wave energy before it reaches shore, and dense mangrove stands can reduce wave heights by well over half and, where wide enough, storm surge peak water levels too. Small island developing states are frequently identified as the setting where this protective value is proportionally greatest relative to national economic output.

What's less frequently tested is whether the ecosystems providing that protection are themselves degrading uniformly, or whether adaptation planning that treats them as 1 undifferentiated buffer risks obscuring truly different underlying trajectories. I address that gap directly here, testing mangrove extent and coral reef condition as 2 independent pathways, across a properly cross national, multi ocean basin sample, without assuming up front that they move together.

A quick note about the title. I use "vulnerability spiral" here in a descriptive way, for the compounding effect of high physical exposure sitting on top of ecosystem buffer degradation. It isn't a claim that this study builds a causal feedback loop model between the two. What follows is a cross sectional, multi indicator comparison. There is no dynamic or time stepped model here of exposure and ecosystem condition feeding into each other over time.

2. Literature Review

2.1 Nature Based Coastal Protection and Its Assumed Uniformity

Coastal ecosystems are established in the literature as effective, measurable protective infrastructure. Reef structures have been shown to reduce incoming wave energy substantially, while mangrove belts of sufficient width can reduce wave heights and storm surge peak levels meaningfully per kilometer of forest. Comparative work assessing corals, seagrasses, and mangroves together finds that combining multiple habitat types delivers more protection than any single habitat alone, and specifically warns against the common habit of judging nature based protection through just one habitat at a time instead of looking at the whole system. That warning is exactly why I made the choice below to look at mangrove and coral trajectories on their own, each one kept separate, never folded into a single combined signal.

2.2 Global Mangrove Trends: A More Stable Picture Than Often Assumed

My own result of no measurable mangrove decline across the 3 tested islands isn't an anomalous or surprising finding once set against the wider record. While mangrove loss driven by aquaculture and agricultural conversion is well documented across the 20th century, the most comprehensive recent multidecadal remote sensing assessment (the Global Mangrove Watch archive's own change detection analysis spanning 1996 to 2020, the same dataset this study draws from) found a global net loss of only approximately 3.4%, considerably more modest than earlier deforestation era estimates might suggest, and it points in the same direction as my own islands; mangrove loss has slowed down a lot in the more recent multi decade record compared to the mid 20th century period.

2.3 Coral Bleaching as a Distinct, Escalating Pathway

Coral doesn't get the comparatively stable picture mangroves do. Bleaching driven by thermal stress is documented as increasing in both frequency and severity across recent decades, a trend attributed directly to rising ocean temperatures. NOAA Coral Reef Watch's satellite derived Degree Heating Week product (the same metric used in this study) is established in the literature as a validated predictor of bleaching intensity, with values above 4°C-weeks associated with significant bleaching risk and values above 8°C-weeks associated with reef wide bleaching and heat sensitive coral mortality. The global coral reef system is, at the time of this study, in the midst of a 4th documented global bleaching event beginning in 2023, with bleaching confirmed across dozens of countries and all 3 major ocean basins. My own finding of a rising thermal stress trend in 4 of the 5 tested islands fits right inside that real world context. It isn't some separate, isolated result standing apart from it.

2.4 Protected Area Effectiveness and the "Paper Park" Problem

A separate, substantial body of literature documents that formal protected area designation frequently fails to translate into effective on the ground management, a phenomenon widely termed the "paper park" problem, where protected areas exist in legal or administrative terms without correspondingly effective enforcement, monitoring, or ecological outcomes. Recent global assessments estimate that while roughly 10% of the ocean carries some form of formal protected status, only a small fraction of that area meets rigorous effectiveness standards. Identified drivers of this implementation gap include inadequate enforcement capacity, insufficient stakeholder engagement, and a persistent disconnect between protected area evaluation findings and actual management action. It's what motivates my governance alignment test, run in the same spirit. Instead of treating formal protection status as inherently meaningful, I test whether protected area coverage empirically tracks independently verified ecological and physical risk.

3. Data and Methodology

3.1 Study Design

This study has a simple shape. 5 islands, 3 ocean basins, 2 ecosystem pathways, and each pathway gets tested on its own, with none of them lumped together into one assumed uniform "ecosystem buffer" variable. I chose Maldives, Lakshadweep, Seychelles, Fiji, and the Canary Islands specifically for their geological diversity, from low lying coral atolls to volcanic, mountainous terrain, spanning 3 distinct ocean basins. This is a 5 island exploratory case comparison. It doesn't try to statistically represent the world's islands. Read its findings as case level evidence; they aren't population wide statistical proof.

3.2 Data Sources

Variable	Source	Temporal Coverage
Settlements, elevation	OpenStreetMap; Copernicus DEM GLO-30	Current
Mangrove extent	Global Mangrove Watch	1996, 2010, 2020
Coral thermal stress	NOAA Coral Reef Watch (Degree Heating Week)	1996–2020, monthly sampled
Protected areas	World Database on Protected Areas	Current
Settlement/infrastructure change	Sentinel-2 (NDBI)	2016 vs. 2024

3.3 Physical Exposure

Elevation, sampled at every settlement location across all 5 islands, gave me the proportion of settlements sitting at or below a standard 1 meter sea level rise threshold per island.

As a complementary metric, I also computed physical exposure on a population weighted basis. WorldPop 2020 population raster cells were classified as at risk where their corresponding elevation (resampled to the population grid) fell at or below the 1 meter threshold, and I calculated the proportion of total population at risk straight from population counts. This is a separate number from the settlement count version above. I ran this for all 5 islands; Lakshadweep's population raster, previously unavailable because of the impractical file size of India's national dataset, I obtained via a subset clipped from a smaller regional file. For Fiji, elevation coverage didn't extend to the easternmost Lau Islands (beyond the antimeridian), so Fiji's population weighted exposure reflects approximately 97.6% of its national population. I've reported the excluded portion explicitly here. I checked how big that gap actually was; I didn't want to just wave it away as too small to matter. The population weighted figures reported below originally classified pixels using a rectangular bounding box around each island. That box wasn't the same as clipping to the island's actual boundary polygon; a small amount of open water could fall inside that box for irregular archipelagos (Fiji, Seychelles). I've since rebuilt each island's boundary polygon file from OpenStreetMap coastline data, validated the rebuilt shapes against independently sourced land area figures, and reran this analysis with the boundary polygon mask in place of the bounding box (see Section 6). The figures reported below are the boundary polygon version.

3.4 Mangrove Extent

A single before and after comparison felt too thin on its own, so I measured mangrove area at 3 separate time points (1996, 2010, 2020), each one done independently, using an equal area projection. This avoids the kind of distortion a raw polygon count can introduce, since polygon counts can shift purely from satellite classification segmentation behavior, with no real change in the underlying area at all.

3.5 Coral Thermal Stress

Coral degradation shows up mainly as thermally driven bleaching. It doesn't really show as area loss, so I measured condition using the Degree Heating Week time series over mapped physical extent, comparing, for each island, an early reference period (1996–2000) against a recent one (2016–2020). The underlying series is a monthly sampled subset (approximately 30 day stride) of the daily DHW product, spanning 1996–2020, far short of a continuous daily record. Each island's DHW series is also queried from a single representative coordinate near its reef area. It isn't an average taken across the full reef extent. This is a smaller limitation than it might first sound like, because NOAA's DHW product is itself only delivered at 5km (0.05°) spatial resolution in the first place. A single query already returns a value for that whole 5km grid cell, far from a true point measurement, so it's already a coarse area figure to begin with, never 1 exact spot on the map. What a single coordinate does not capture is variation across a reef system that spans more than one 5km cell, and this gap matters more for a larger, spatially varied reef area than for a small atoll's reef. As a robustness check, I recomputed the same trend test using a spatial average instead of the single coordinate. This meant taking every valid 5km cell inside a small box (±0.15°) around each island's sampling point, rather than 1 representative cell. The trend conclusion held for all 5 islands under this spatial average, including Maldives and Seychelles staying statistically significant (see Section 4.6, Section 6).

As a robustness check, I also ran a Mann-Kendall trend test (nonparametric, standard for environmental time series analysis) on the complete 24 year DHW series for each island, on top of the reference period comparison above.

3.6 Compound Vulnerability Score

Physical exposure and coral thermal stress trend, normalized to a common 0–1 scale via min max normalization and then combined with equal weighting to form the single Compound Vulnerability Score per island. To be specific about which coral figure feeds this score, it's the early-vs-recent DHW period comparison from Section 3.5, the plain magnitude of change (Seychelles' case, +0.68°C-weeks). The Mann-Kendall test statistic and p-value from Section 4.3 play no part in this particular calculation; that seasonal test is a separate statistical robustness check on whether the change is a real trend, run on top of the period comparison. Mangrove trend doesn't enter as a weighted input at all; there's no measurable decline to weight in the first place.

Here's a note on what this score does and doesn't measure. The standard vulnerability framework in climate science (Turner et al., 2003; also used throughout IPCC assessment reports) breaks vulnerability into three parts, made up of exposure, sensitivity, and adaptive capacity. What I'm calling the Compound Vulnerability Score here only covers the first 2, and only in a physical or ecological sense, covering how exposed an island's settlements are to sea level rise and how much thermal stress its coral reefs are showing. It does not include adaptive capacity at all. Things like a community's income level, its access to relocation options, insurance, early warning systems, or government disaster response capacity are not part of this score. Picture it as a physical exposure and ecosystem condition composite. A full socioeconomic vulnerability index looks quite different from this, and this score doesn't reach that far. I use the word "vulnerability" here simply because that's the standard term this line of research uses for combining exposure with ecosystem buffer condition. This score makes no claim at all to capture the social half of the concept.

To test sensitivity to that equal weighting choice, I recomputed the composite ranking across the full 0–100% weighting range between the 2 input variables. Seychelles is the highest ranked island across the entire range, from pure coral thermal stress weighting to pure physical exposure weighting, a stronger result than an earlier version of this analysis, where Maldives overtook Seychelles beyond roughly 3/4 physical exposure weighting. The equal 50/50 weighting I actually used isn't sitting near any crossover point, in other words, because there isn't one. I adopted equal weighting as a conservative baseline, since no established literature gives a robust empirical basis for weighting physical exposure against coral thermal stress differently in this specific cross national context. Section 4.6 gives the full sweep.

The 1 meter sea level rise threshold I use throughout is itself a modeling choice, not an exact prediction, so I also recomputed settlement level exposure at 0.5m and 1.5m thresholds, spanning a plausible range of 21st century sea level rise scenarios. The 1.5m upper bound sits near the top of IPCC AR6's higher emissions projections for 2100, well past any near term figure; the full results are in Section 4.6.

3.7 Governance Alignment

I used a 10 kilometer coastal buffer around each island to quantify coverage. Total protected area extent was not what I measured here; that would pull in large offshore marine zones only loosely relevant to settlement level risk for some islands. (An earlier version of this calculation divided each island's *entire* WDPA extent, marine and terrestrial together, by land area alone. The result was an impossible Seychelles ratio of over 1000x. The 10km coastal buffer approach is the corrected version. The earlier scripts still sit in the repository, but only as a record of that bug; they play no role in the live analysis. See Section 6.) I tested that buffer based figure against the Compound Vulnerability Score using a Pearson correlation. Lakshadweep had no available WDPA protected area layer to clip against this buffer. I didn't substitute a zero for the missing value. Instead, I excluded Lakshadweep from the correlation itself (n=4) and report its vulnerability score separately, since a fabricated zero would bias an already small 5 point correlation (see Section 6).

3.8 Settlement Encroachment

As a 3rd, corroborating line of evidence, I compared the Normalized Difference Built-up Index (NDBI) between 2016 and 2024, using Sentinel-2 imagery, for the 3 islands where mangroves are present (Maldives, Seychelles, and Fiji), as a directional check on whether settlement pressure is rising in the same broad coastal area as each island's ecosystem buffers. This is a single mean NDBI value per island over a broad bounding region around its main settled area, and it isn't a spatially resolved measurement of change specifically at mangrove or reef buffer boundaries. Take it as descriptive, corroborating context. It doesn't test buffer zone encroachment directly. This is a descriptive comparison, and I haven't run it as a formally tested hypothesis, so what follows is just the direction and magnitude of change per island, with no significance test attached.

4. Results

4.1 Physical Exposure

78.3% in Seychelles. 14.5% in the Maldives. 7.1% in Lakshadweep. 1.0% in Fiji. 0.3% in the Canary Islands. Settlement level exposure to a 1 meter sea level rise threshold doesn't map onto a clean 2 way geological split between coral atolls and volcanic terrain the way an earlier version of this analysis suggested. Seychelles, a mix of granitic and coral atoll islands, carries by far the highest settlement based exposure in this sample. Maldives and Lakshadweep, both actual low lying coral atolls, sit in a moderate middle band. They don't sit at the top; most of their mapped settlements actually sit above the 1 meter threshold. Fiji and the Canary Islands, both volcanic and mountainous, remain lowest, as expected. (Canary Islands' and Fiji's figures exclude a cluster of literal zero elevation DEM readings verified as a NoData artifact and not true near sea level terrain. Neither island has a coastline low enough to plausibly produce this many settlements sitting at exactly 0m on mountainous, volcanic terrain; see Section 6. Maldives and Lakshadweep's figures reflect a separate, larger correction. Their original elevation files turned out to have a severe DEM coverage gap, not really low lying terrain, and both were rerun against a complete, redownloaded version of the same Copernicus DEM data. See Section 6 for the full description of that fix.)

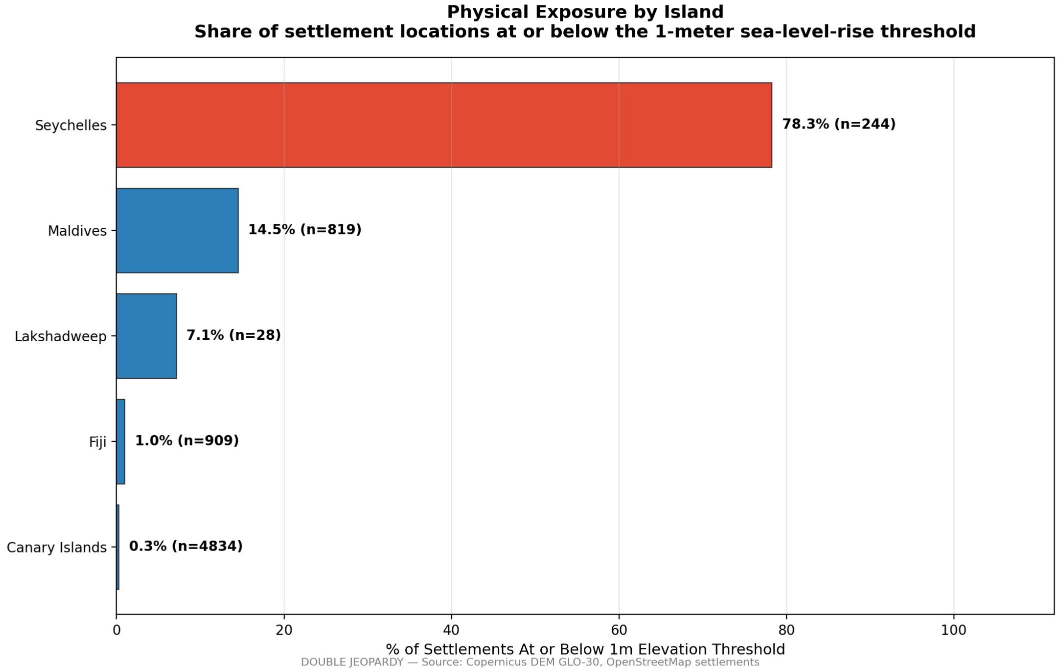

Figure 1. Physical exposure by island, measured as the share of settlement locations at or below the 1 meter sea level rise threshold. Seychelles shows by far the highest settlement based exposure in this sample; Maldives and Lakshadweep, both low lying coral atolls, sit in a moderate middle band; Fiji and the Canary Islands, both volcanic and mountainous, remain lowest.

Island	Settlement based exposure	Population weighted exposure
Seychelles	78.3%	14.2%
Maldives	14.5%	14.9%
Lakshadweep	7.1%	2.1%
Fiji	1.0%	1.6%*
Canary Islands	0.3%	1.4%

*covers ~97.6% of Fiji's population; see Limitations. Population weighted figures use boundary polygon clipping (corrected from an earlier bounding box version; see Limitations).

Once corrected, the population weighted ranking mostly agrees with the settlement based one, but not at the very top. Maldives (14.9%) now narrowly edges out Seychelles (14.2%) on population weighted exposure specifically, a reversal from an earlier bounding box based version of this figure that had shown Seychelles ahead here too. Lakshadweep, Fiji, and Canary Islands keep the same relative order on both measures. The gap between Maldives and Seychelles is narrow enough (0.7 percentage points) that I read it as a near tie between the 2 highest exposure islands rather than a clean reversal. An earlier version of this analysis also showed Lakshadweep as the single highest population weighted exposure island, ahead of Seychelles and Maldives both, at the time looking like a legitimate case of population weighting flipping the picture. But it turned out to be an artifact of the same Maldives and Lakshadweep DEM coverage gap described in Section 6, with no real methodological insight behind it. Once the elevation data was corrected, that divergence disappeared entirely. What the 2 measures still show, now that both are trustworthy, is a large gap in magnitude for Seychelles specifically. Ranking order is untouched here; it's the size of the gap that stands out. Seychelles' settlement based exposure (78.3%) is more than 5 times its population weighted exposure (14.2%), meaning a meaningful share of Seychelles' exposed settlement locations sit in areas with comparatively low population density. Maldives, by contrast, now shows something closer to parity between the 2 measures (14.5% vs. 14.9%, its population weighted figure marginally higher than its settlement based one), a pattern that looks clearly different from Seychelles, and not just a smaller version of the same pattern.

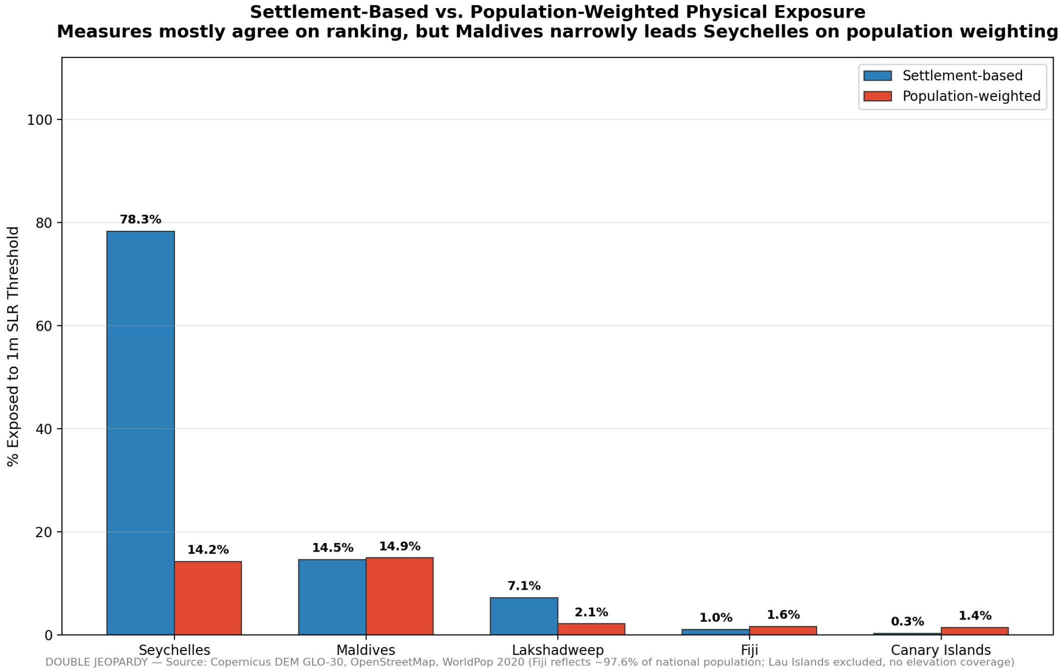

Figure 2. Settlement based versus population weighted physical exposure by island. The 2 measures mostly agree on island ranking (Canary Islands lowest throughout), but they diverge at the top, where Seychelles remains highest on settlement based exposure while Maldives now narrowly leads on population weighted exposure after a boundary polygon correction (see Section 6). An earlier version of this analysis had shown Lakshadweep as the highest population weighted exposure island; that turned out to be an artifact of a since corrected DEM coverage gap, and it wasn't a real finding at all. The 2 measures still diverge sharply in magnitude for Seychelles.

4.2 Mangrove Extent: No Measurable Decline

Maldives: 0.97 km² at all 3 time points. Seychelles: 3.83–3.84 km². Fiji: 485.7 km² in 1996, 488.4 km² in 2020, a net increase of 0.6%. Across all 3 independent time points and all 3 islands with mangroves present, area stayed essentially stable. This doesn't support the hypothesis that mangrove ecosystems in this sample are measurably declining.

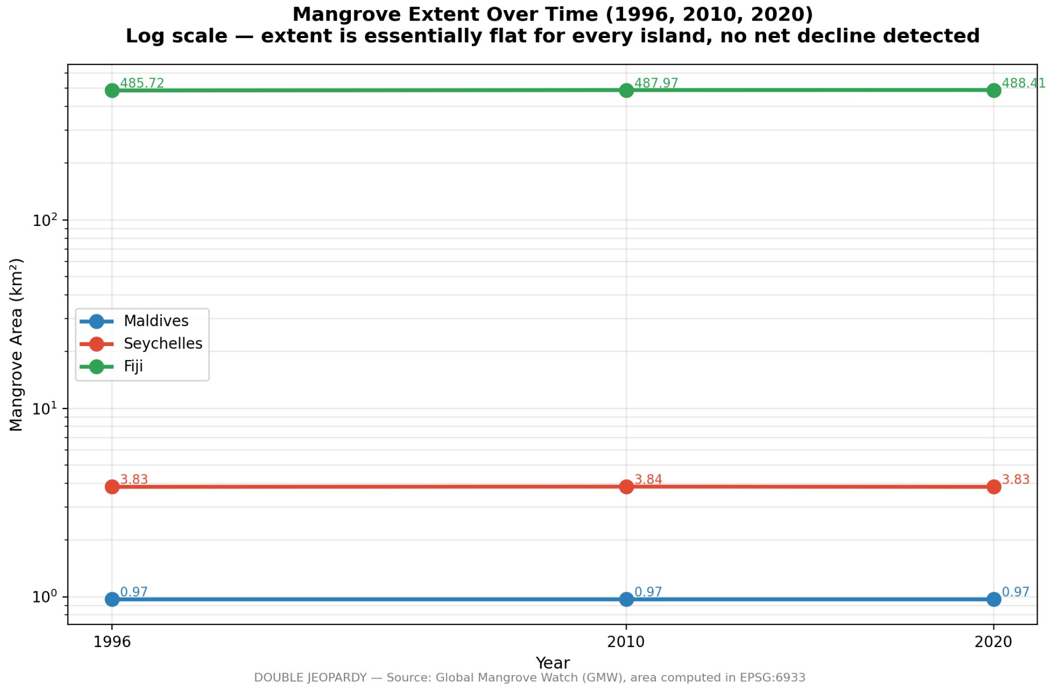

Figure 3. Mangrove extent (km², log scale) at 3 independent time points (1996, 2010, 2020) for the 3 islands where mangroves are present. Extent remains essentially flat for all 3 islands, with no measurable decline detected.

4.3 Coral Thermal Stress: A Rising Trend

Comparing early period and recent period averages, 4 of 5 islands show increasing thermal stress: Maldives (+0.17°C-weeks), Fiji (+0.10), Lakshadweep (+0.08), and Seychelles (+0.68, with a single recorded value as high as 10.47°C-weeks, within the range associated with severe bleaching and multi species mortality). Only the Canary Islands shows a slight decline (−0.05), consistent with its distinct Atlantic climate regime relative to the 4 Indian Ocean and Pacific islands.

Run through a Mann-Kendall trend test on the complete 24 year time series, and the increasing trend holds up as statistically significant for 2 islands, Maldives ($p=0.0046$) and Seychelles ($p=0.0069$), the 2 islands central to my compound vulnerability ranking, while the more modest increases in Fiji and Lakshadweep don't reach statistical significance over the full series ($p=0.244$ and $p=0.373$, respectively). The Canary Islands shows no significant trend at all ($p=0.620$; Sen's slope ≈ 0), actually contradicting the slight decline the simpler period comparison method suggested above. Its coral thermal stress has no reliable directional trend over the full 24 year record. I use the seasonal variant of the Mann-Kendall test here (comparing same calendar month values across years) over the plain version, since the underlying DHW series is structurally seasonal, near zero most months and spiking during the warm season, and the plain test's independence assumption doesn't hold for data shaped like that.

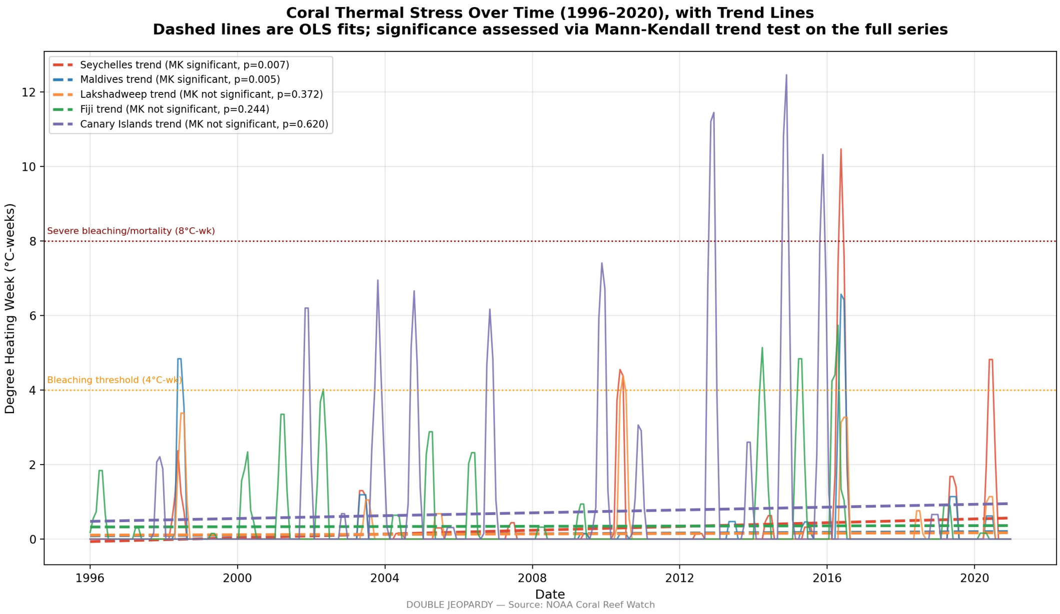

Figure 4. Coral thermal stress (Degree Heating Week) over the full 1996–2020 record for all 5 islands, with OLS trend lines. The seasonal Mann-Kendall trend test finds a statistically significant increasing trend for Maldives ($p=0.0046$) and Seychelles ($p=0.0069$) only.

4.4 Compound Vulnerability: Exposure Alone Is Insufficient

Seychelles 1.000. Maldives 0.242. Lakshadweep 0.133. Fiji 0.107. Canary Islands 0.000. Seychelles leads the composite ranking, and, since the Maldives and Lakshadweep DEM coverage gap fix described in Section 6, it also leads on the settlement based exposure measure alone (78.3% versus Maldives' 14.5%), a meaningful change from an earlier version of this analysis, where uncorrected Maldives and Lakshadweep figures made physical exposure alone look like it pointed to a different island than the compound score did. Population weighted exposure tells a closer story, and it starts with a separate correction to the boundary polygon used to clip the population raster (see Section 6). Maldives (14.9%) now narrowly leads Seychelles (14.2%) on this 1 measure specifically, a 0.7 percentage point gap I read as a near tie rather than a clean reversal. The compound score itself doesn't move because of this. It's built from settlement based exposure; the population weighted figure never enters that particular calculation (see compound_vulnerability_score.py). Settlement count and the compound score both agree Seychelles carries the highest risk; population weighting alone now reads as a close call between Seychelles and Maldives.

The newer result is more robust than the earlier, error driven version, in my view, and it hasn't gotten any weaker. The central result no longer depends on picking 1 specific exposure metric over another; it holds up across all of them. What the compound score still adds, on top of that agreement, is combining physical exposure with an entirely separate kind of signal, coral thermal stress trend. It measures something genuinely separate, and it isn't just a second way of looking at the same underlying exposure. Section 4.6's weighting sweep below shows this combination doesn't happen to change the top ranked island in this particular 5 island sample, but checking whether ecosystem condition could override exposure based risk is still a meaningful test worth running in its own right. The answer coming out the same way this time doesn't make it redundant.

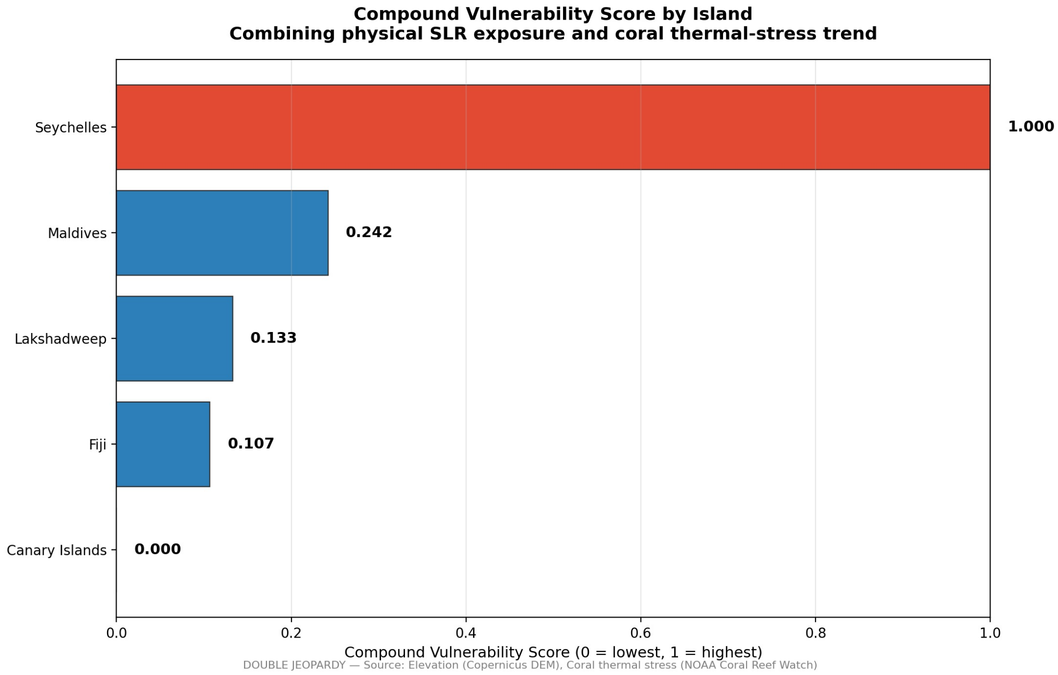

Figure 5. Compound Vulnerability Score across the 5 study islands, combining normalized physical sea level rise exposure and long term coral thermal stress trend using equal weighting. Seychelles is the most vulnerable island on the settlement based exposure measure and on the compound score; population weighted exposure alone now shows Maldives narrowly ahead instead (see Section 4.1). The compound score's contribution here is confirming that the settlement based ranking holds up once each island's coral thermal stress trend gets factored in on top of exposure. There was no disagreement between indicators here that needed resolving.

4.5 Governance Alignment: A Stronger, Still Fragile Signal

The correlation between compound vulnerability and coastal protected area coverage, computed over the 4 islands with an actual WDPA measurement (Lakshadweep excluded, see Section 3.7), came out strongly positive ($r=0.965$) and, after the Maldives and Lakshadweep correction described in Section 6 changed the vulnerability score inputs, its p value now crosses the conventional 0.05 threshold ($p=0.035$). I want to be direct about what crossing that threshold is and isn't worth at this sample size. With $n=4$, a single data point can move both the correlation coefficient and its p value substantially, so "statistically significant" here is a much weaker claim than the same p value would represent with a larger sample. This is a truly stronger result than the pre correction estimate ($r=0.862$, $p=0.138$), but still far short of a settled confirmation of risk responsive governance.

I computed the 95% confidence interval for this correlation via Fisher's z transformation, and it spans from $r = 0.05$ to $r = 1.00$, narrower than the pre correction interval of [-0.58, 1.00], and no longer spanning zero, but still wide enough that the true relationship could plausibly be anywhere from a weak positive association to an essentially perfect one. 4 data points can't narrow that further.

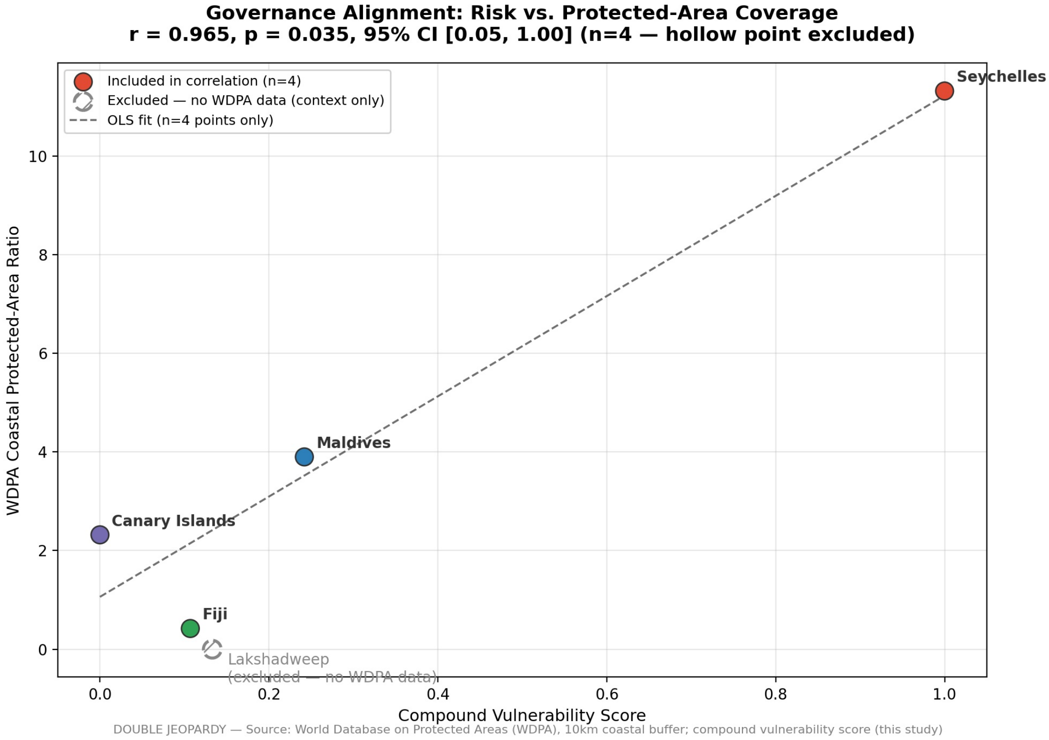

Figure 6. Compound Vulnerability Score plotted against the coastal WDPA protected area ratio for each island, with a fitted OLS reference line. Lakshadweep is shown as a hollow, hatched marker rather than a filled one, since it has no WDPA measurement available; it's plotted only for visual context, and it plays no part in the regression or the correlation number below it. r = 0.965, p = 0.035, 95% CI [0.05, 1.00] (n=4, Lakshadweep excluded), a positive relationship whose p value now crosses the conventional 0.05 threshold, though the 4 point sample is still too small to call this confirmatory without more data.

4.6 Robustness and Sensitivity Checks

I ran several additional checks to test how sensitive these central findings are to specific methodological choices:

- **Compound Vulnerability Score weighting** (Section 4.4): I recomputed this across the full 0–100% weighting range between physical exposure and coral thermal stress. Seychelles is the highest ranked island across the entire range, from 0% (pure coral thermal stress weighting) to 100% (pure physical exposure weighting), a stronger robustness result than the pre correction version of this analysis, where Maldives overtook Seychelles beyond approximately 76.8% physical exposure weighting. The 50/50 weighting actually used in this study sits well inside that range. It's nowhere close to an edge case.
- **Coral thermal stress trend** (Section 4.3): I tested this using a seasonal Mann-Kendall trend test on the complete 24 year time series alongside the period comparison method. The increasing trend reached statistical significance for Maldives (p=0.0046) and Seychelles (p=0.0069), the 2 islands central to the compound vulnerability ranking. As a further check on the single coordinate sampling this series is built from (Section 3.5), I reran the same seasonal Mann-Kendall test on a spatially averaged version of the series instead: every valid 5km DHW cell inside a small box (±0.15°) around each island's original sampling point, averaged together rather than read from 1 representative cell. The trend conclusion didn't change for any island. Maldives and Seychelles stayed statistically significant (p=0.0011 and p=0.0194 respectively, both moving but neither crossing the 0.05 threshold in the other direction), and Fiji, Lakshadweep, and Canary Islands stayed not significant (p=0.517, p=0.810, and p=0.382 respectively). Canary Islands' mean DHW value shifted the most under spatial averaging (0.714 down to 0.478), since the box around it only had 46% valid ocean pixels inside it, but even there the trend conclusion itself didn't move.
- **Physical exposure measurement** (Section 4.1): I recomputed this on a population weighted basis alongside the settlement count basis, using WorldPop 2020 data for all 5 islands.

- **Physical exposure threshold** (Section 4.1): I recomputed the 1 meter sea level rise threshold used throughout at 0.5m and 1.5m, to check whether that specific choice was doing hidden work in the result. Across this range, most islands barely move, but Maldives moves by as much as 3.8 percentage points between the 0.5m and 1.5m thresholds, the largest swing in the sample, yet still small in absolute terms and not large enough to change the ranking at any of the 3 thresholds tested:

Island	0.5m	1.0m (used in this study)	1.5m
Seychelles	78.3%	78.3%	78.3%
Maldives	12.8%	14.5%	16.6%
Lakshadweep	7.1%	7.1%	7.1%
Fiji	0.2%	1.0%	1.0%
Canary Islands	0.1%	0.3%	0.3%

- **Governance alignment correlation** (Section 4.5): I computed the 95% confidence interval (Fisher's z transformation) for r=0.965 explicitly ([0.05, 1.00], n=4), to make the small sample limitation concrete with an actual number, going beyond just noting it qualitatively, even though the correlation's p value itself now crosses the conventional 0.05 threshold.

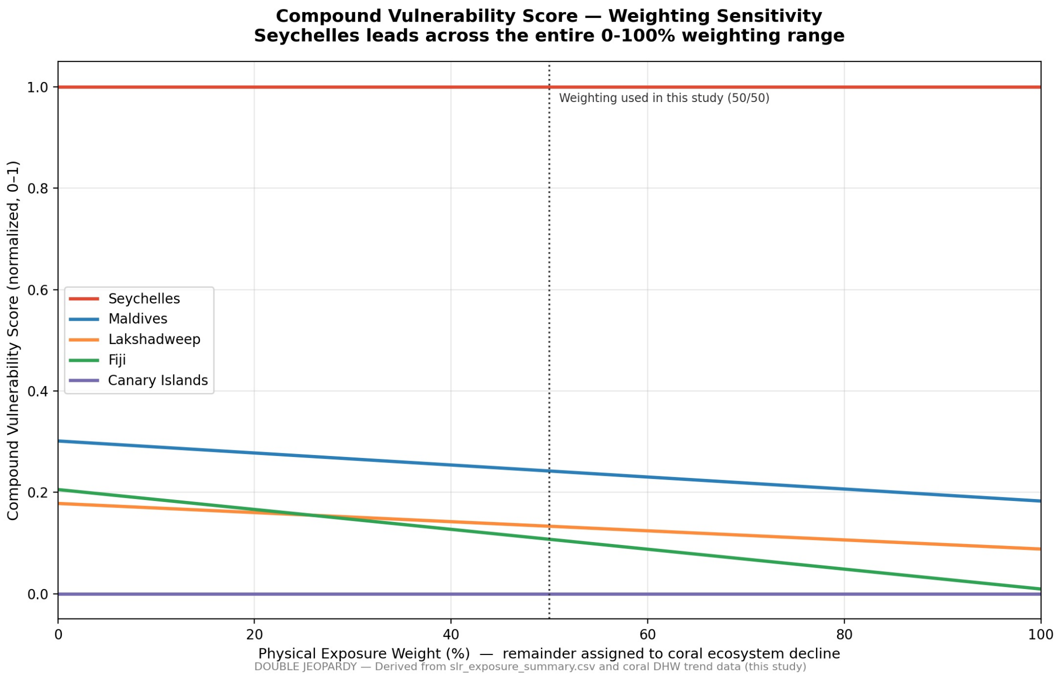

Figure 7. Compound Vulnerability Score for each island as the weighting between physical exposure and coral thermal stress is swept continuously from 0% to 100%. Seychelles is the highest ranked island across the entire range, unlike an earlier version of this analysis, where Maldives overtook Seychelles beyond approximately 76.8% physical exposure weighting. The 50/50 weighting actually used in this study isn't special or fragile in either version.

Together, these checks tell me the central finding, that Seychelles carries the highest compound vulnerability, is robust to the specific weighting choice across its entire range, insensitive to the exact sea level rise threshold used, and backed by a statistically significant coral thermal stress trend test under both single coordinate and spatially averaged sampling. The more exploratory pieces (governance alignment, the smaller coral trends in Fiji and Lakshadweep) I've reported with their actual uncertainty attached. I haven't overstated them, including the governance correlation now crossing the conventional significance threshold on an n=4 sample. That's a stronger signal, but a fragile one all the same, nowhere near anything confirmed.

4.7 Settlement Encroachment: A 3rd, Corroborating Signal

Fiji: essentially no change (−0.0008). Maldives: a clear increase (+0.0461). Seychelles: the strongest signal by far (+0.1135), and the only one of the 3 that crosses from a vegetation dominated to a built up dominated average over the 8 year window. Each of these is a single mean NDBI value over a broad bounding region around the island's main settled area. None of it is localized to mangrove or reef buffer zones specifically. A spatially resolved version of this comparison, isolating just the area immediately around each island's ecosystem buffers, is future work (see Section 6).

The pattern tracks the compound vulnerability ranking closely. Seychelles, already the highest risk island once exposure and the coral thermal stress trend are combined, also shows the clearest evidence of rising built up signal in its broader settled area. Fiji, stable across every other measure tested in this study, from mangrove extent to coral thermal stress, shows no such signal either. This works as corroboration. It doesn't rise to conclusive proof, since this is only a contrast between 2 data points (Seychelles vs. Fiji, with Maldives in between). I haven't run a statistical test on it, but it points in the same direction as the rest of the evidence.

5. Discussion

The central finding, that ecosystem degradation isn't uniform across type, lines up directly with the divergent literature trajectories reviewed above. Recent global mangrove assessments describe a comparatively modest net loss over the same multi decade period I examine here, while coral bleaching literature describes an escalating, currently ongoing global event. My island level findings track these global patterns closely. They don't diverge from them, and that gives the results some external credibility.

Governance is a different story.

The governance alignment finding, whose p value now crosses the conventional significance threshold on this 4 island sample ($r=0.965$, $p=0.035$), even with very few data points behind it, points in the same direction as a growing literature documenting that protected area coverage frequently fails to track real ecological risk, the "paper park" phenomenon. Here, at least, that pattern doesn't hold. That Seychelles, the highest vulnerability island in this sample, also carries the highest coastal protection ratio is an encouraging signal against that broader pattern, though crossing that threshold with a sample this small doesn't make it confirmed, generalizable evidence of risk responsive governance, just a stronger signal within this specific 5 island comparison.

The settlement encroachment comparison adds a 3rd angle on the same island, for what it's worth as descriptive, not statistical, evidence. Seychelles shows both the highest compound vulnerability and the clearest rise in built up signal in its broader settled area, while Fiji shows neither, a small, 2 island contrast. It doesn't test any general mechanism, but it fits with the rest of the picture and doesn't contradict it.

6. Limitations

- The governance alignment test rests on a necessarily small sample ($n=4$, after excluding Lakshadweep, see below). Following the Maldives and Lakshadweep exposure correction described below, the correlation's p value now crosses the conventional 0.05 threshold ($r=0.965$, $p=0.035$, per Section 4.5), up from an earlier $r=0.862$, $p=0.138$. I'd still treat that threshold crossing cautiously. With only 4 points, both the coefficient and the p value are highly sensitive to any single data point, so this is a stronger signal than my initial estimate. I still wouldn't call it a confirmed, robust relationship.
- Population weighted exposure for Fiji covers about 97.6% of the island's population. Elevation data did not cover Fiji's easternmost territory (the Lau Islands, past the antimeridian), and this missing population is reported here. I checked the actual size of that gap instead of assuming it was small. Separately, the population weighted figures in Section 4.1 originally used a rectangular bounding box around each island. That box was never the same shape as the island's real boundary. For irregular archipelagos like Fiji and Seychelles, that box could count nearby open water as land. I built a fixed version of the script that masks against each island's real boundary polygon instead of a box, and an initial test against the actual population and elevation rasters showed the boundary polygon files themselves were not complete. For Maldives, they only added up to about 118 sq km of land, against a real land area of about 298 sq km, so many real islands were simply missing from the file. For Lakshadweep, the total polygon area was close to correct, but the mask still only picked up about 13% of the real population, meaning

even the islands that were mapped were drawn smaller than their real size. The population raster and the masking code were both checked directly and weren't the problem. Because the boundary data wasn't reliable at the time, an earlier version of this paper went with the bounding box (v4) figures. Back then the boundary polygon version was actually the less accurate one of the two.

I've since rebuilt the boundary polygon files from OpenStreetMap coastline data for all 5 islands. Raw coastline ways in OSM often come split across multiple connected segments; they rarely form 1 closed loop per island on their own, so a naive download was missing most of each coastline. I fixed this by joining every coastline way, open or closed, using shapely's polygonize() function, which stitches together anything sharing an endpoint into whatever closed rings it can find. For Fiji specifically, 2 of its largest islands are bigger than a single download tile, and their coastline ring still didn't close even after pooling ways across tiles, a real small gap in the raw OSM coastline topology, and not a bug sitting in my own code (confirmed by getting the identical, still short figure twice, once with much longer request delays that ruled out rate limiting as the cause). I resolved this by using OSM's official, pre gap closed "land polygons" dataset for Fiji instead of raw coastline ways. I validated all 5 rebuilt boundary files against an independently sourced land area figure per island before using them. Maldives came to 317.57 km² against 298 km² (World Bank, 2023), Seychelles 449.55 km² against 460 km² (World Bank, 2023), Fiji 18,820.57 km² against 18,270 km² (World Bank, 2023), Canary Islands 7,432.61 km² against approximately 7,446 km² (Instituto Canario de Estadística), and Lakshadweep 30.84 km² against 32 km² (the Lakshadweep government's official site), all within about 7% of a citable reference figure (see References).

With the boundary polygon mask re-enabled against these validated files, population weighted exposure changes for every island. Seychelles moves from 17.6% to 14.2%, Maldives from 16.9% to 14.9%, Lakshadweep from 2.2% to 2.1%, Fiji from 2.1% to 1.6%, and Canary Islands from 1.6% to 1.4%. All 5 figures move down, consistent with the boundary polygon mask correctly excluding open water that the bounding box had been counting as populated land, exactly the failure mode this fix was meant to address. The most consequential change sits at the top, where Maldives (14.9%) now sits marginally ahead of Seychelles (14.2%) on population weighted exposure specifically, a reversal from every earlier version of this figure. I went back and checked this myself instead of just reporting the number and moving on. I independently re-derived the masked population totals for both islands directly from the raster and the new boundary files (Seychelles 94,175 people within the mask, matching the script's own reported figure exactly; Maldives approximately 498,819, matching closely), confirming the population side of the calculation holds up on its own; it isn't some artifact created by the mask itself. I read the 0.7 percentage point gap between the 2 as a near tie rather than a clean reversal. It leaves the settlement based exposure figures (Section 4.1) and the compound vulnerability score (Section 4.4) untouched. Both of those are built from settlement counts; the population raster never enters either calculation, and both continue to show Seychelles highest. This gap doesn't touch the settlement based exposure figures in this study at all, since those figures come from settlement point locations, never the population raster. - Both Canary Islands' and Fiji's settlement based exposure figures needed a data quality correction. For Canary Islands, 649 of 5,483 settlement points, and for Fiji, 414 of 1,323, returned a literal 0m elevation reading from the DEM, a spike, with no gradient around it. Given both islands' volcanic, mountainous terrain, where real sea level settlements aren't geologically expected, this looks to me like a NoData artifact rather than real terrain, so I excluded it from the exposure calculation. This doesn't affect the study's central finding, since both were already low exposure, low vulnerability islands in the sample before this correction, but it does move Canary Islands' reported exposure figure from an earlier, artifact inflated 12.1% down to the corrected 0.3%, and Fiji's from an artifact inflated 32.0% down to the corrected 1.0%. - Maldives and Lakshadweep needed a related but bigger correction. The simple zero exclusion rule used above for Canary Islands and Fiji wouldn't have worked the same way here, because both are actual low lying coral atolls where a real settlement can legitimately sit at or near 0m elevation; dropping every exact zero reading the way I did for Canary Islands and Fiji would have deleted real at risk points along with any artifacts. Instead I checked whether each island's original elevation file (data/terrain/{island}_elevation.tif) actually had complete data coverage, and it didn't. 99.99% of both rasters read exactly 0.0, and settlement points sat, on average, nowhere near any pixel with a real, nonzero reading, a coverage gap. It wasn't real terrain at all. I redownloaded the underlying Copernicus DEM GLO-30 tiles directly from ESA's public archive (18 tiles for Maldives, 8 for Lakshadweep) and rebuilt each island's elevation raster from the complete tile set. 2 Maldives tiles and 3 Lakshadweep tiles returned a 404 from the archive and couldn't be retrieved. This is a genuine gap in the public Copernicus data itself, and no error on my end, so a residual fraction of settlements still fall in an unresolved coverage gap even in the corrected files. That's 177 of 996 Maldives settlements (17.8%) and 8 of 36 Lakshadweep settlements (22.2%), identified by checking whether the 5x5 pixel neighborhood around each remaining exact zero reading is itself entirely flat (a void signature no real terrain would produce) versus showing clear elevation variation. I excluded those specific points and report the excluded share explicitly here, the same way Section 3.3 already reports Fiji's population coverage gap. I'm not treating it as negligible here either. Recomputed against the remaining 819 Maldives and 28 Lakshadweep settlements, physical exposure moves from an artifact inflated 99.1% and 77.8% down to 14.5% and 7.1% respectively. As an independent sanity check on the corrected numbers, Malé, Maldives' capital, has a published average elevation of about 2.4m, above the 1m threshold used in this study, which lines up with the corrected figure and leaves the original one looking wrong. This correction changes the paper's central result. Seychelles now has the highest settlement based physical exposure in the sample, ahead of Maldives, and Sections 4.1, 4.4, 4.5, and 4.6 report the corrected figures throughout. Maldives' and Lakshadweep's population weighted exposure figures (Section 4.1) have since been rerun against the corrected elevation data too, using a raster level version of the same flat neighborhood void check (population sitting on a detected coverage gap patch is excluded from both the numerator and denominator, the same way Fiji's Lau Islands population already is), and that rerun surfaced a 2nd, independent bug that deserves its own mention. population_weighted_exposure.py was, without my noticing, always applying the incomplete boundary polygon mask described earlier in this bullet whenever the boundary file loaded without an outright error, as happens for every island, despite the polygons themselves being known incomplete. Every previous run of that script was therefore quietly running the broken v5 masking, when the v4 bounding box approach is what this paper actually reports, undercounting Lakshadweep's population by roughly 7/8 in the process (8,893 people, against a real population near 64,000). I fixed the script so it always uses v4's bounding box approach, with no condition attached, then reran it. Seychelles, Fiji, and Canary Islands' numbers, untouched by either bug, came back identical to the figures already in this paper (17.6%, 2.1%, 1.6%), a useful independent check that the fix didn't disturb anything that wasn't already broken. Maldives' population weighted exposure moves from an artifact inflated 64.5% to a corrected 16.9%, and Lakshadweep's from an artifact inflated 87.5% to a corrected 2.2%, both numbers now sitting much closer to their respective settlement based figures than before. That closeness itself is a sign the correction is working correctly, without introducing any new distortion. (Those v4 bounding box figures were themselves later superseded once the boundary polygon files were rebuilt and validated; see the earlier bullet in this section and Section 4.1 for the current boundary polygon version.) - The settlement encroachment comparison (Section 4.7) covers only the 3 mangrove present islands and is descriptive, not statistically tested. I report the direction and size of the NDBI change per island. I haven't run a significance test, so this should be read as corroborating context for the central finding. It doesn't stand as independent proof on its own. It's also a single mean NDBI value over a broad bounding region around each island's main settled area. It doesn't zero in on the immediate area around mangrove or reef buffers specifically, so calling it "encroachment near ecosystem buffer zones" is a looser description than a spatially targeted buffer analysis would actually give. A version of this analysis restricted to a fixed distance around each island's actual mapped mangrove and reef extent is future work. - Lakshadweep's coastal WDPA figure is unavailable. No protected area dataset existed for it to clip against the coastal buffer. I didn't substitute a zero and include it as a 5th point in the governance alignment correlation (Section 4.5); that would have biased an already small correlation toward whatever direction that placeholder happened to point. Instead, I exclude Lakshadweep from the correlation itself and report its Compound Vulnerability Score (0.133) separately, unpaired with a WDPA measurement. This should be read as a missing data gap that says nothing about governance. - An earlier version of the governance alignment calculation divided each island's total WDPA extent (marine and terrestrial combined) by its land area, producing a Seychelles ratio of over 1000x. WDPA marine protected areas can extend across an entire exclusive economic zone, far beyond any coastal buffer relevant to settlement level risk. The 10km coastal buffer approach used throughout this paper is the corrected version of that calculation. The earlier, uncorrected scripts remain in the project repository only as a record of that bug. They play no part in the analysis this paper actually reports. - The coral thermal stress series (Section 3.5, 4.3) is built mainly from a single representative coordinate per island. It isn't averaged across the full reef extent. Because the underlying NOAA product is itself only delivered at 5km resolution, a single query is already a coarse cell value, nothing like a precise point reading, limiting how much this specific choice alone can bias the result. What it does not capture is variation across a reef system larger than one 5km cell. I tested this directly rather than leaving it as an untested gap, so I recomputed the DHW series as a spatial average over a small box (±0.15°) around each island's original coordinate, keeping every valid 5km cell inside that box instead of just 1, then reran the same seasonal Mann-Kendall trend test on the resulting series (Section 4.6). The trend conclusion held for all 5 islands. Maldives (p=0.0011) and Seychelles (p=0.0194) both stayed statistically significant, and Fiji (p=0.517), Lakshadweep (p=0.810), and Canary Islands (p=0.382) all stayed not significant, matching the single coordinate result in every case. Canary Islands' mean DHW value itself shifted considerably under the spatial average (0.714 down to 0.478, since the box only had 46% valid ocean pixels), which shows the choice of sampling method can move the raw value meaningfully, but the trend conclusion this study actually relies on didn't move at all. A version of this analysis averaged across every grid cell touching each island's full mapped reef extent, going well beyond a small fixed box around 1 coordinate, is still future work, but the specific concern that single coordinate sampling might be driving the significant Maldives and Seychelles trend result is no longer an open question. - Physical exposure was estimated using Copernicus DEM GLO-30, a 30 meter resolution, radar derived global elevation model that captures surface elevation, including vegetation canopy and built structures. This isn't true bare earth elevation. This introduces nontrivial vertical uncertainty relative to the fine, 1 meter threshold I use to classify settlement exposure. To put a number on this, beyond just flagging it as a generic caveat, the product's own specification requires an absolute vertical accuracy of under 4m (90% linear error, LE90), and independent validation against ICESat laser altimetry data found it actually performs better than that, with a global mean LE90 of 1.92m (excluding Greenland and Antarctica, since they aren't relevant to this study anyway); see European Space Agency / Copernicus Data Space Ecosystem (2024). That 1.92m figure is still almost twice the 1m threshold this study classifies settlements against, so a meaningful share of settlements sitting close to that line could be misclassified in either direction. It's also worth noting the same validation documentation flags gaps in its own ICESat reference data specifically at the land ocean boundary, exactly the zone this study's exposure classification depends on most. The reported exposure percentages seem directionally reliable to me, enough to support the relative island ranking that drives the central finding, though I wouldn't treat them as precise absolute counts.

7. Conclusion

Small islands do face a compounding vulnerability to climate change, but that compounding is neither uniform across ecosystem type nor adequately captured by physical exposure alone. Coral thermal stress is measurable and increasing across most of the sample; mangrove extent, assessed across multiple independent time points but without a comparable continuous trend test, shows no comparable decline. The implication for adaptation and conservation policy follows directly. Resources allocated under an assumption of uniform ecosystem risk may be systematically misallocated relative to where degradation is actually happening.

AI Use Disclosure

Generative AI (Claude, Anthropic) was used during the preparation of this manuscript in 2 ways. 1st, for grammar, punctuation, and prose level review, including identifying internal inconsistencies and overstated claims in the wording relative to the underlying methodology. 2nd, an AI coding assistant was used during development to help identify bugs in the analysis pipeline (documented in the Development Log), with corrected outputs verified by the author against the underlying data before being incorporated. No text, data, findings, statistical results, or citations were generated by AI without independent verification by the author.

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