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Global fragility and resilience of coral reefs to tropical cyclones waves

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4th International Workshop on Waves, Storm Surges and Coastal Hazards

Incorporating the 18th International Waves Workshop

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Motivation

- **Globally**, coral reefs provide coastal flood risk reduction (Ferrario et al., 2014; Beck et al., 2018)
- **In the US**, coral reefs were declared as **national infrastructure in 2024**, based on their coastal protection service (Storlazzi et al., 2019; 2021; Reguero et al., 2021)
- Coral reefs are threatened by both **natural and anthropogenic stressors**. Some stressor (e.g., ocean acidification) **drive slow, progressive changes**, whereas others such as **storms** and thermal bleaching events produce **sudden changes** with long-lasting effects.
- Interest has grown in determining the **fragility of coral reefs to tropical cyclones (TCs)** to assess effects on ecosystem **services**, **insurance solutions** (e.g., Reguero et al., 2019, 2021, UNDP 2025), **and** future coral **refugia**.
- Increase in the **frequency of 'damaging' TCs** could lead to **fundamental shifts in mortality regimes and natural recovery periods** of reefs (typically of ~10 yr), threatening long-term persistence. This, however, <u>remains to be characterized</u>.

State of the Art – Storm Damage on Reefs

- **Impacts can happen over entire coral reef systems**, but structural damages are also not homogenous across an entire reef due to complexity. Direct mechanical damage can exceed depths of 20 m.
- The **degrees of impact** are influenced by wave height, wave period, water depth, impact duration, reef location and relative exposure, and structural vulnerability of the coral colonies
- **Studies** have attempted to assess risk of breakage (i.e., fragility) of coral reefs based on storm parameters such as surface wind intensity and duration, or significant wave heights (Puotinen, 2007; Puotinen et al., 2016; Dixon et al., 2022).
- However, these models miss
  - (1) **wave-induced forces and processes on the corals themselves at depth,** and
  - (2) **coral species resistance based on historical exposure**.**

coral reef on the Great Barrier Reef is seen before (left) and after (right). Cyclone Ita in 2014. Image AIMS LTMP

** Assumes corals and reefs have developed based on their forcing, in that a *Porites* species on Guam impacted by 7 m waves every 10 years have evolved to handle that, whereas a *Porites* species on Cuba that gets struck by 3 m waves every 10 years have evolved to handle that forcing

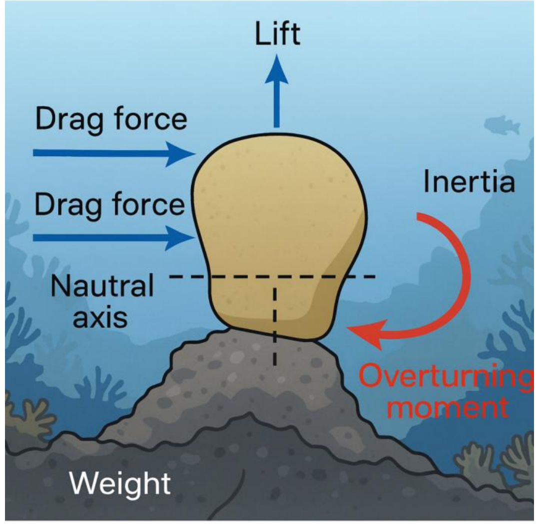
Methods

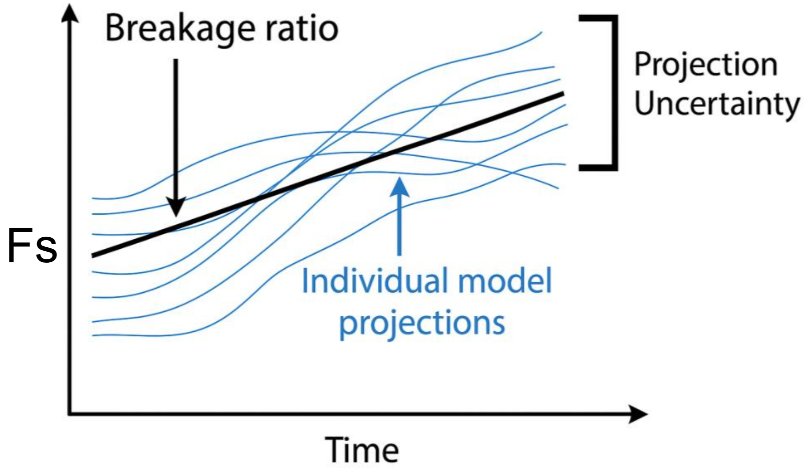
TC waves

Hydrodynamic force-balance model

Statistical characterization at present and future

NASA





Methods

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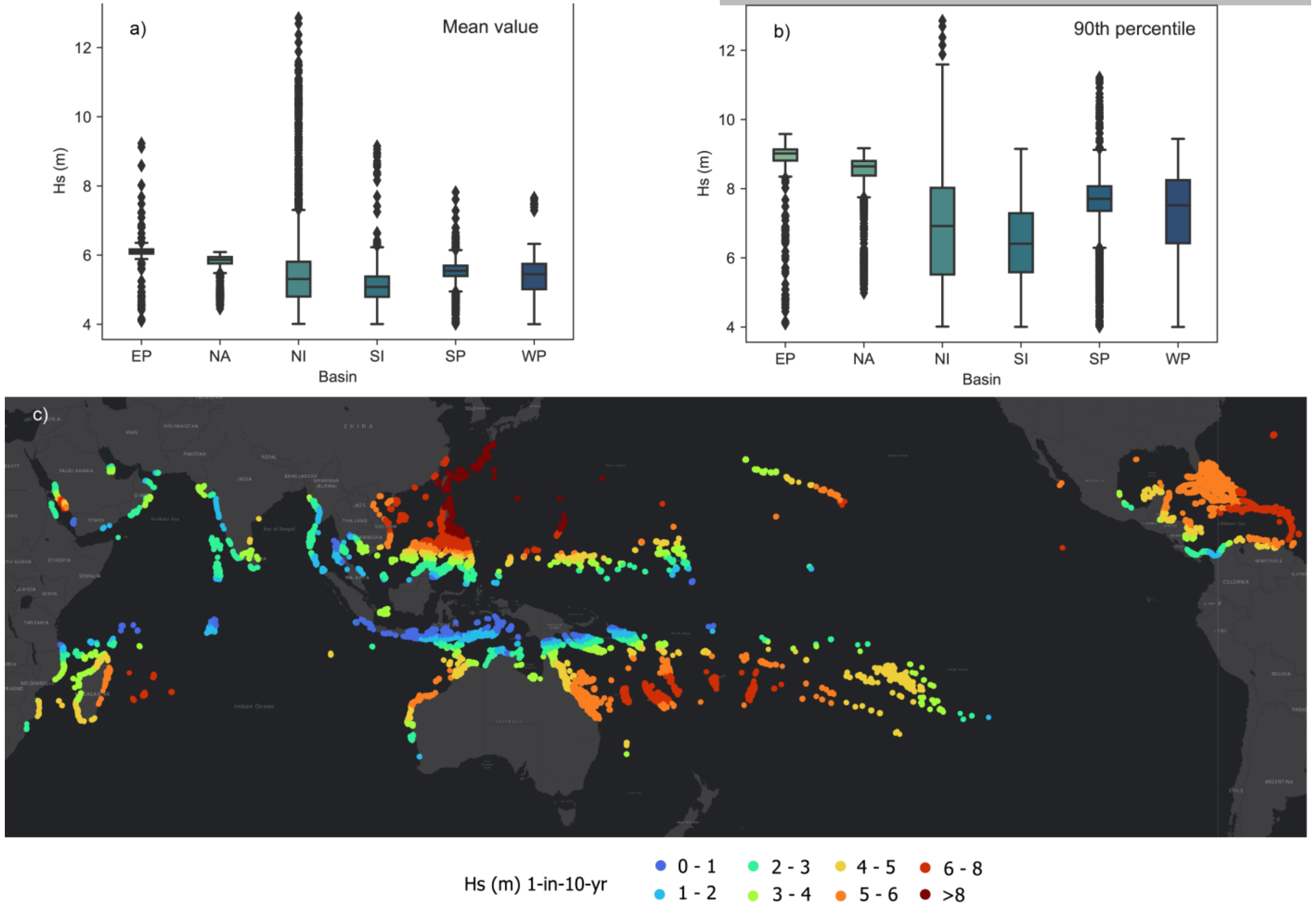


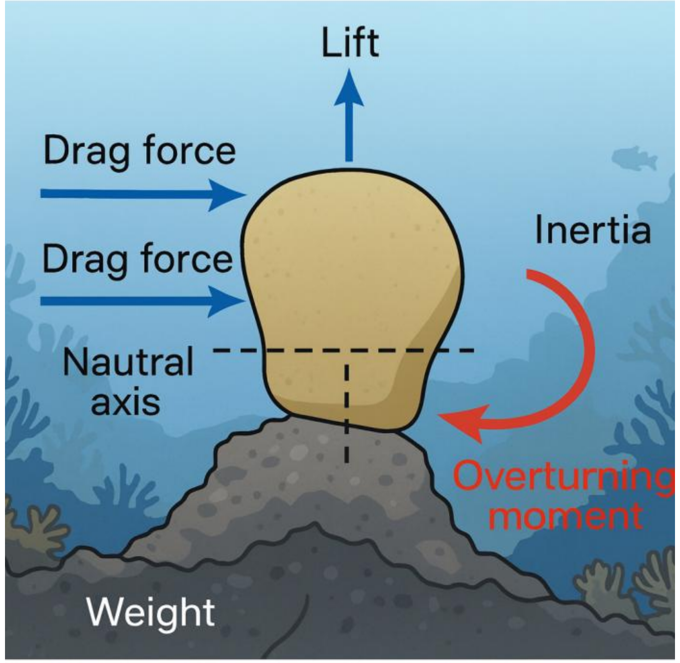
- TC waves from Grossmann-Matheson et al. (2023) synthetic runs
- Similar implementation to Grossmann-Matheson et al. (2024) (presented by I. Young at *WAVES 2025* Thursday 9 am)
- Python implementation and CLIMADA risk model implementation (Bresch et al., 2021)

(1) We used non-linear relationship derived from satellite-based wind analyses between TC size and intensity (Wu et al. 2015) to reconstruct the radius of the wind field (R34) from the other STORM parameters

Methods

TC waves → **Hydrodynamic force-balance model** → Statistical characterization at present and future

- Mechanical damage from wave-induced forces acting on the coral and the corals' strengths and morphologies at depth, rather than empirical relationships *(wind, wave height)*
- Based on measurements from Storlazzi et al. (2004) for corals reefs in Hawai'i
- Spatially discrete for all global coral reef locations



1. Drag $$F_d = \frac{1}{2}\rho_f C_d \bar{u}^2 2 r_c h_c \beta$$

2. Lift $$F_l = \frac{1}{2}\rho_f C_l \bar{u}^2 2 r_c h_c \beta$$

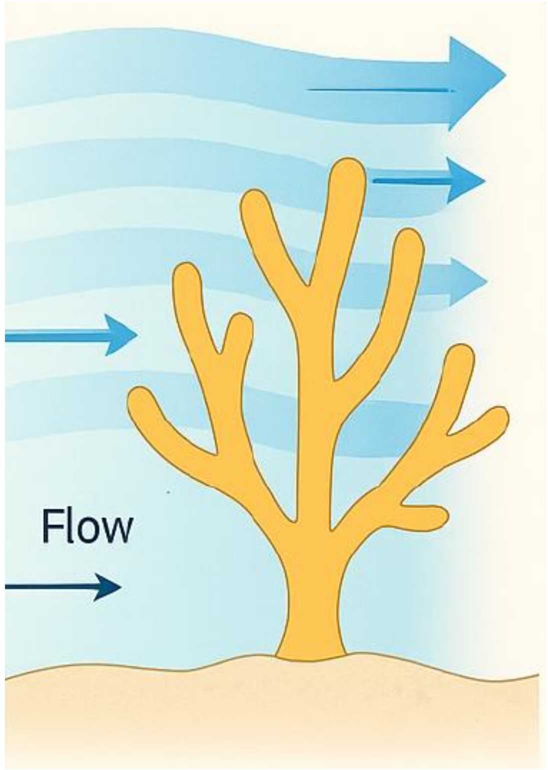
3. Inertia $$F_i = \frac{51}{24}\rho_f \pi r_c^2 h_c a$$

4. Weight $$F_g = (\rho_c - \rho_f) g \pi r_c^2 h_c$$

Massel (1996) adapted for a cylindrical coral shape

Methods

TC waves → **Hydrodynamic force-balance model** → Statistical characterization at present and future



Breakage threshold

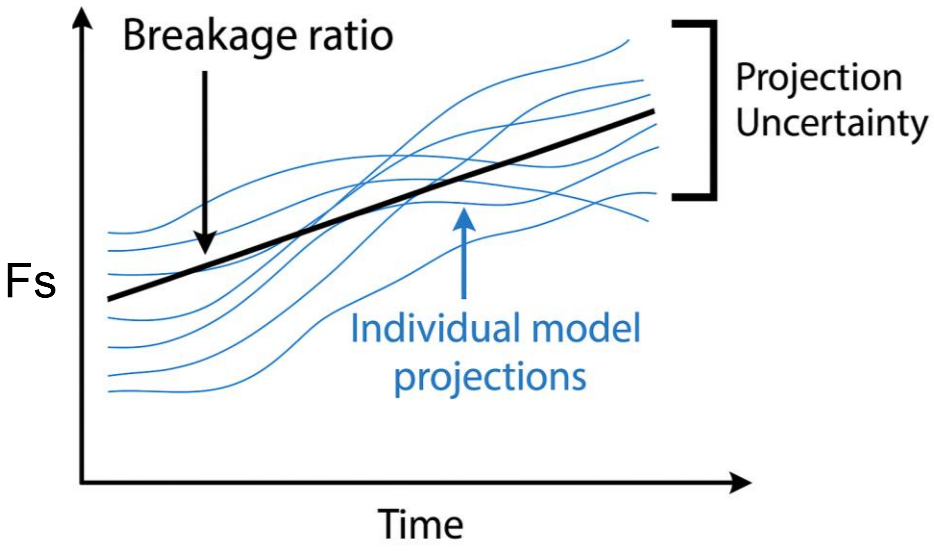
Fs is the ratio of the resistive forces per unit area (mechanical strength) to the applied stresses: i.e., a Factor of safety

$$F_s = \frac{\sigma_{resistive}}{\sum \sigma_{applied}} > 1.5$$

Observations and modeling by Storlazzi et al. (2004) indicated that the **transition occurs when the ratio of the coral colony's mechanical strengths to the applied (wave-induced) forces is on the order of** ***1.5 : 1.0*** (not at ***1.0 : 1.0*** when one would presume)

Methods

TC waves → Hydrodynamic force-balance model → Statistical characterization at present and future



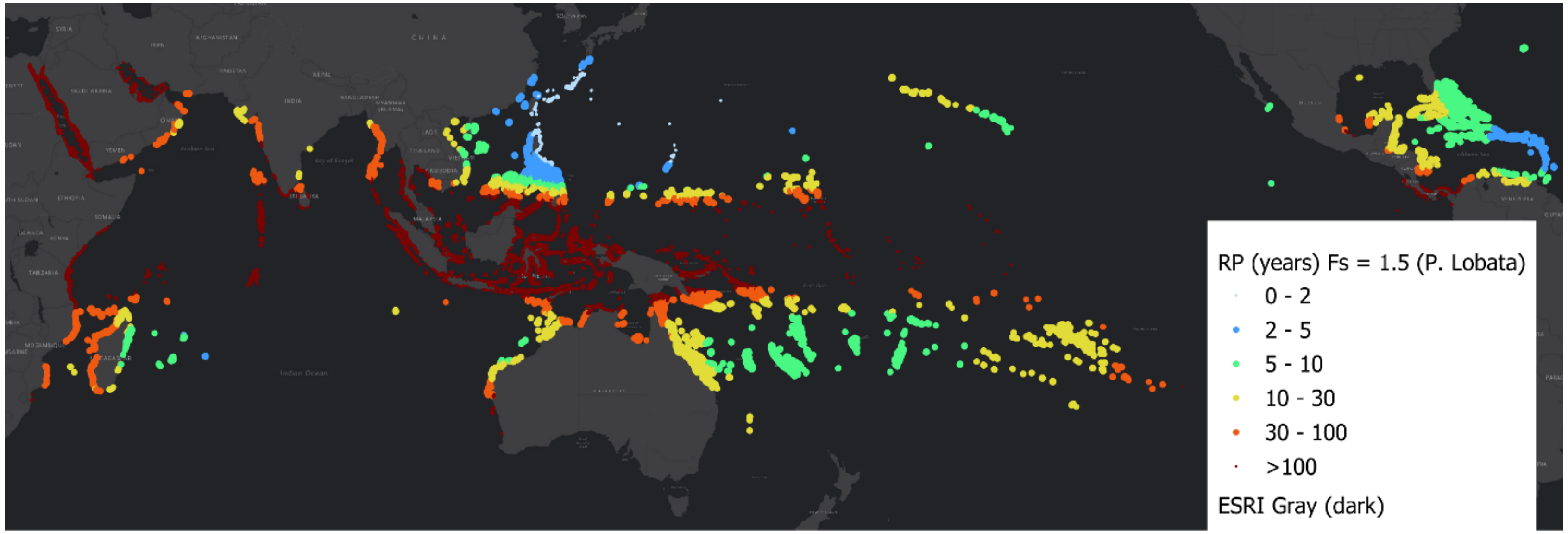
1. Synthetic Tropical cyclOne geneRation Model (STORM; Bloemendaal et al., 2020) & **STORM future TC activity** (Bloemendaal et al., 2023)
2. 10,000 years of TC waves derive F_s and determine if failure occurs.
3. For each location, probability is calculated for exceeding key F_s thresholds: i.e., probability of failure (breakage).
4. Histograms of the return periods for reef breakage threshold of F_s=1.5, for each species in each TC basin**, describe present-day and future changes in breakage frequency
5. Changes in histograms are compared with representative 10-yr recovery cycles of coral reefs in literature, as a proxy of natural resilience regimes.

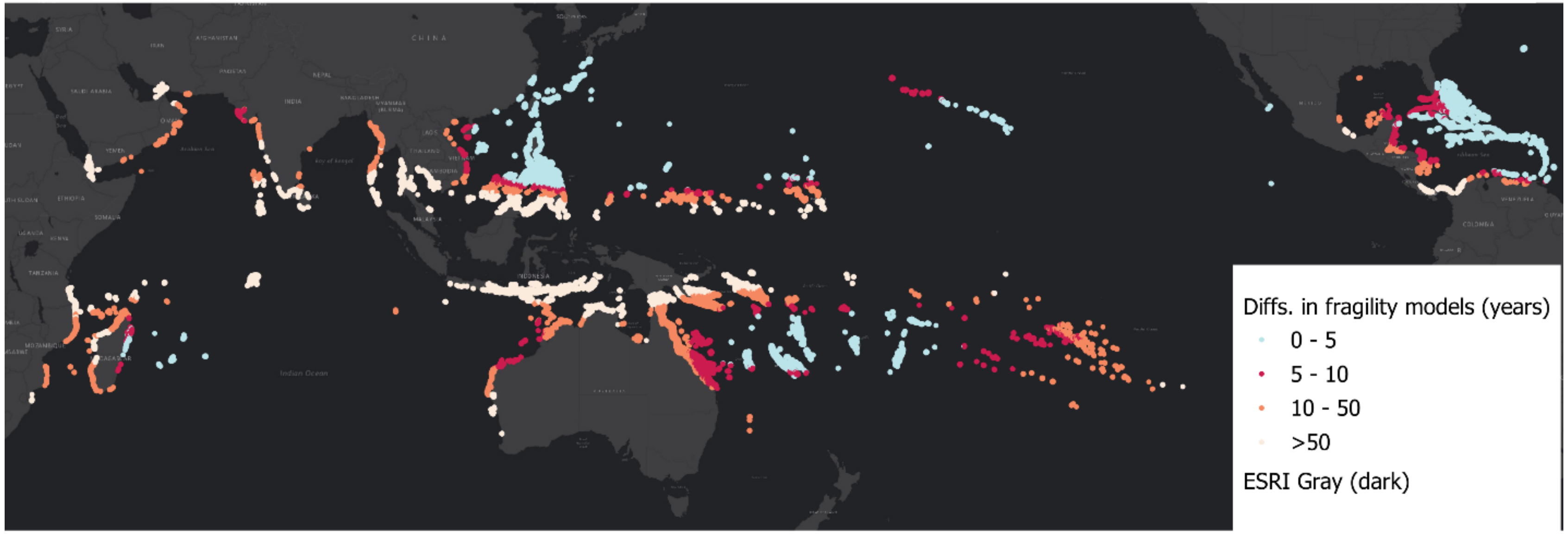
** Assumes corals and reefs have developed based on their forcing, in that a *Porites* species on Guam impacted by 7 m waves every 10 years have evolved to handle that, whereas a *Porites* species on Cuba that gets struck by 3 m waves every 10 years have evolved to handle that forcing

Fragility at present

Strongest end-member

Global distribution of TC-induced, wave-driven breakage risk (F_s = 1.5) for the **robust** coral species, ***Porites lobata***





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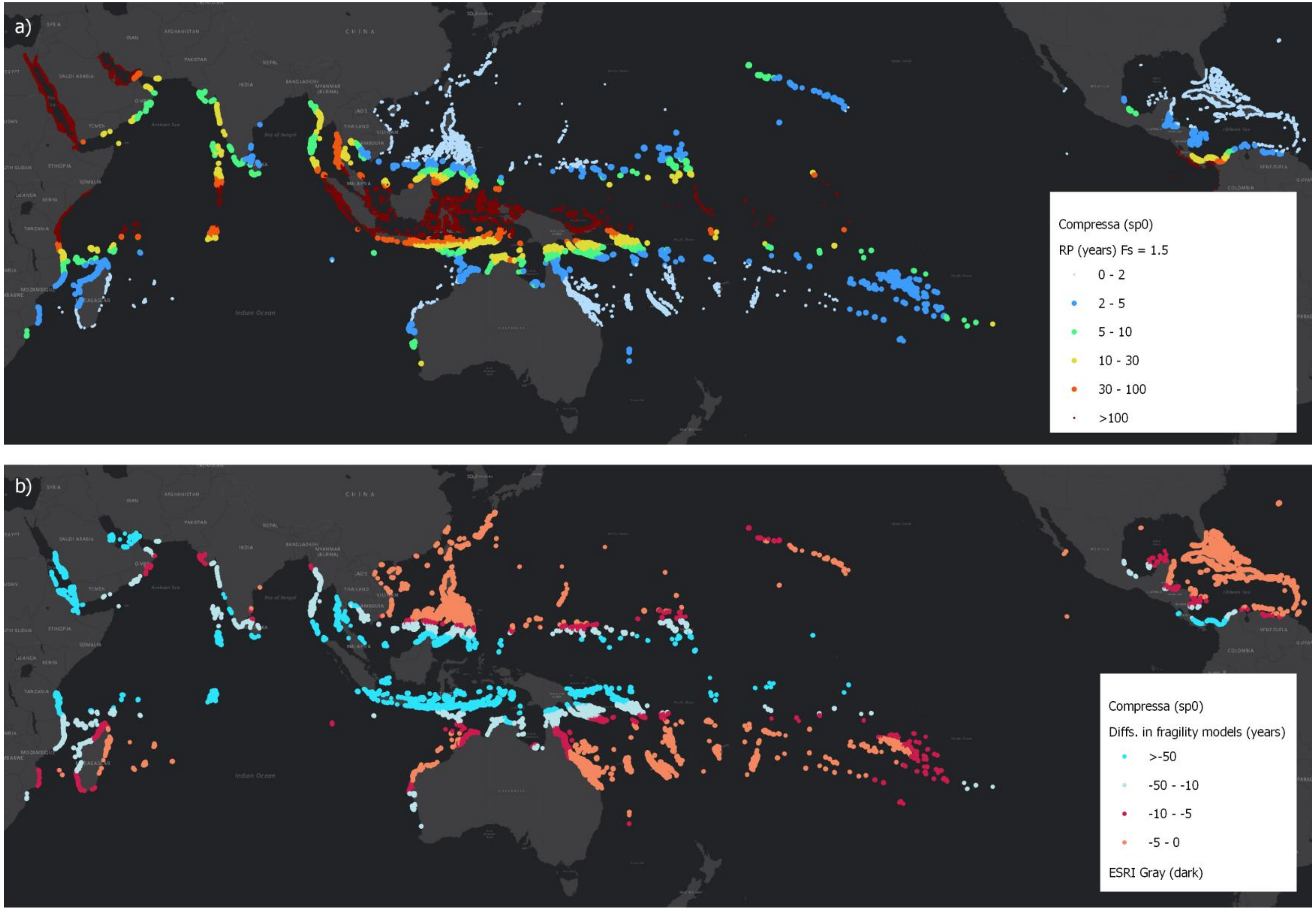
Fragility at present

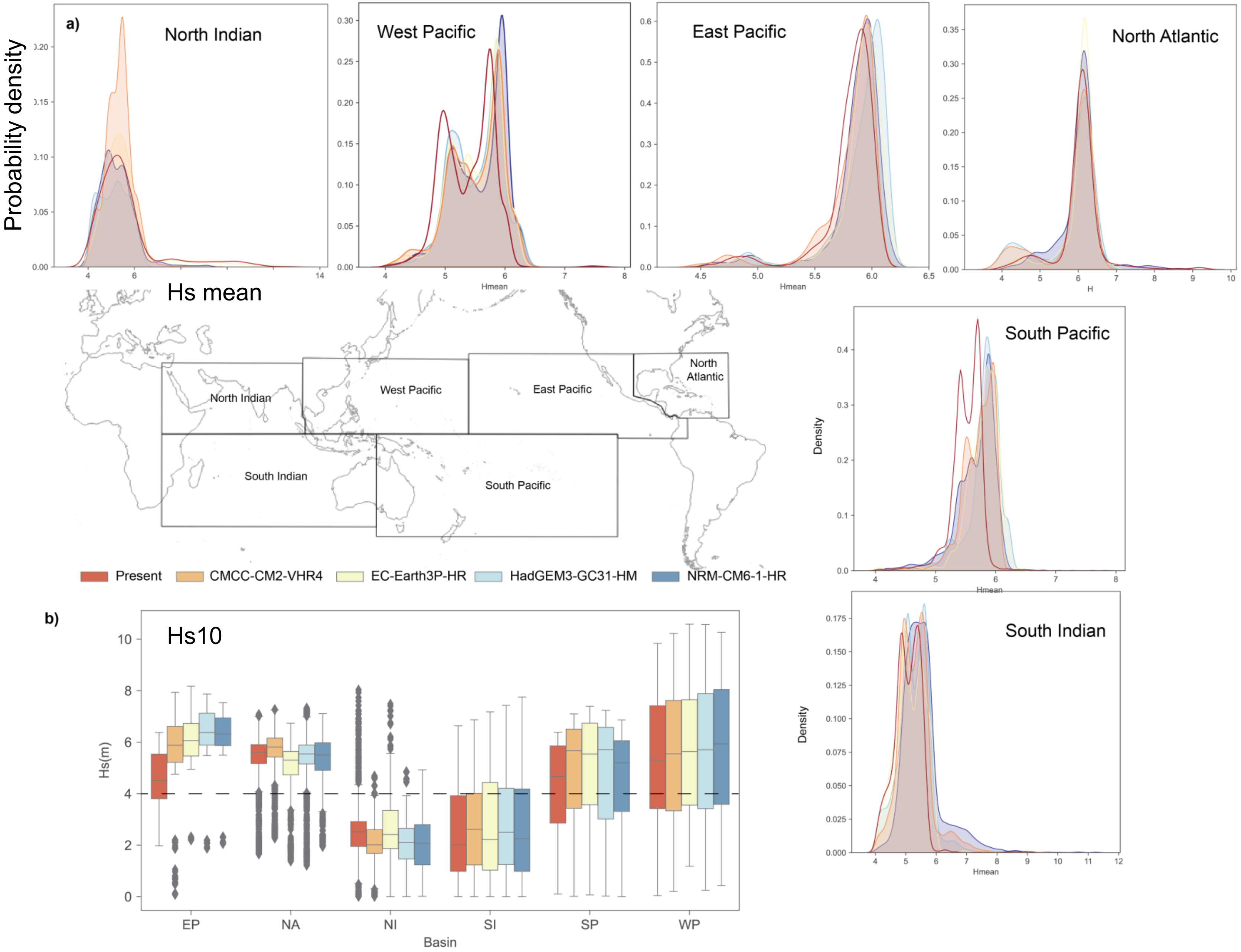
Weakest end-member

Global distribution of TC-induced, wave-driven breakage risk (F_s = 1.5) for the **weak** coral species, ***Porites compressa***



Changes in Waves

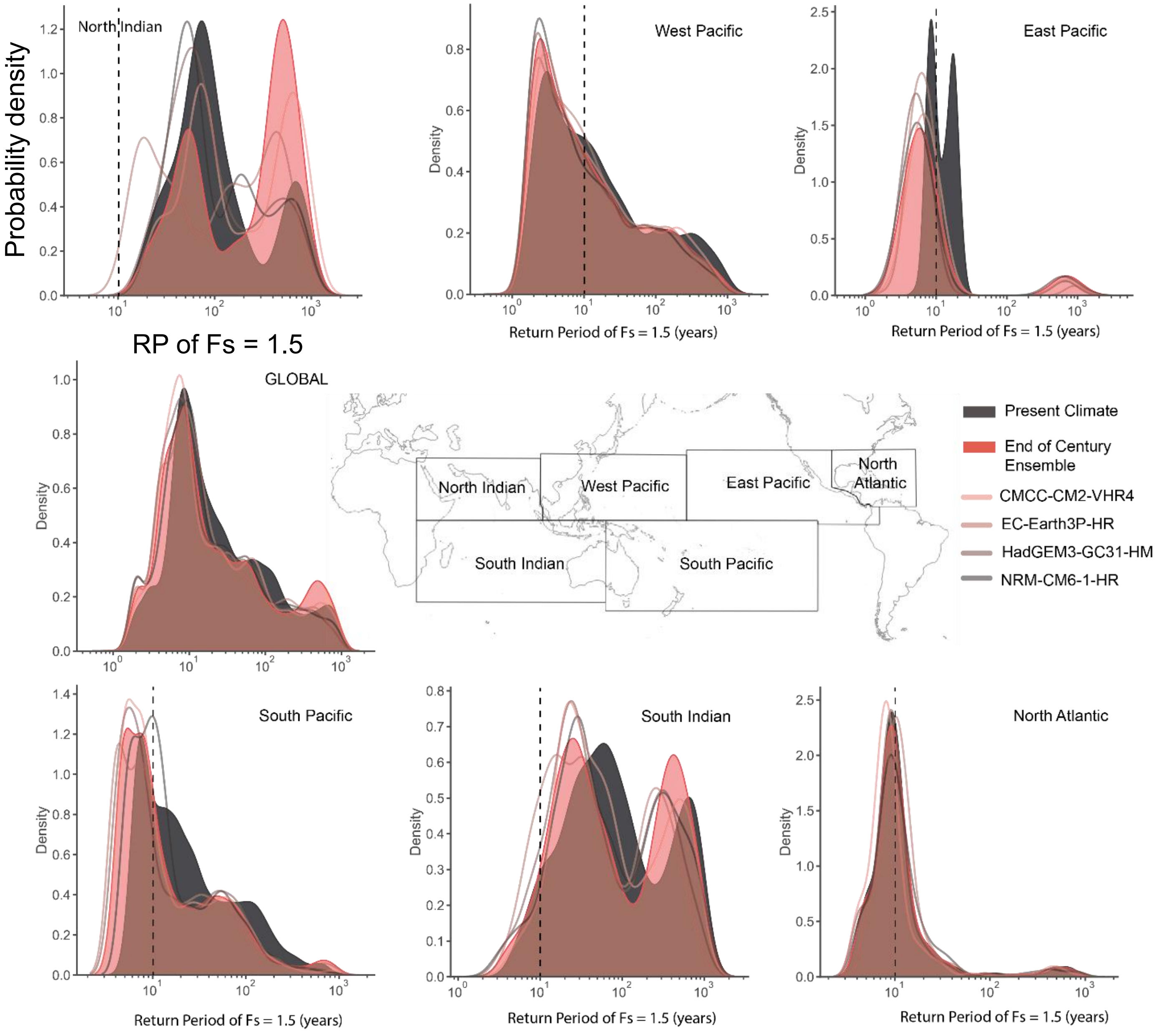
Change in TC waves from climate change *ONLY for coral reef locations* in different ocean basins



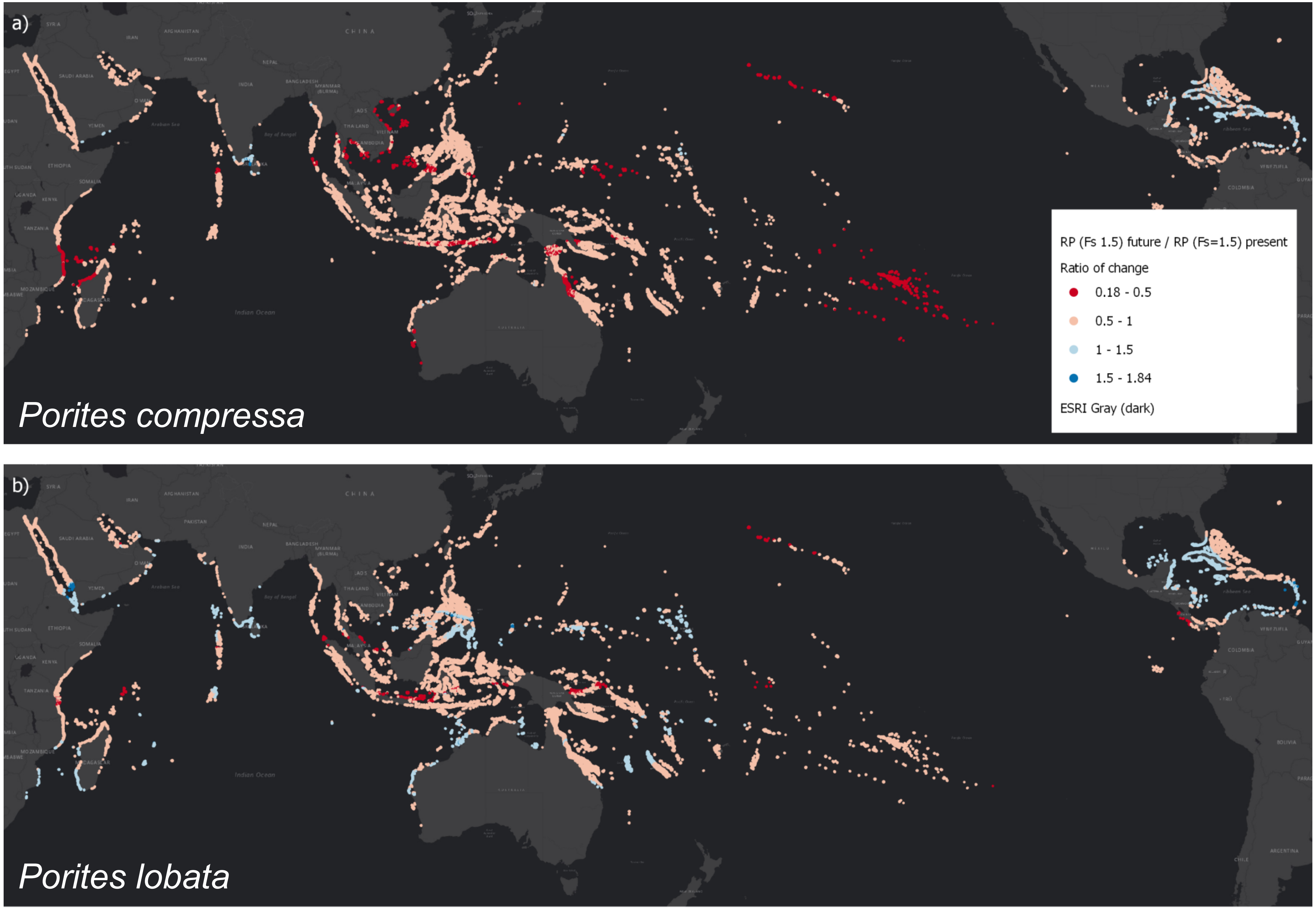
Recurrence levels of TC wave-driven breakage risk

Breakage is defined by the critical transition ratio in the force balance model (F_s = 1.5)

Dashed vertical lines:
10 years is the typical recovery period for coral reefs following TC impacts



Ratio of change in natural resilience regime



Reds = increased susceptibility

Blues = decreased susceptibility

Conclusions

- New model accounts for wave-induced forces on corals at depth and species resistance based on historical frequency of disturbance
- Climate-driven changes to TCs will change risk to corals by changing the frequency of damage on reefs.
- The most significant increases are projected for the **South and West Pacific reefs**, coinciding with areas of widespread degradation.
- However, the geographically-isolated reefs in the **Eastern Pacific Ocean** historically have been the slowest to recover from disturbances and could be the most affected by future changes in the frequency of TC impacts.
- Many thermal refugia will be affected by more frequent storm stresses, but we find areas that will remain as refugia from both stressors.
- **Next steps:** TCs in the future affecting frequency and intensity according to Knutson et al 2020 ensemble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Thank you

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Problem with STORM for climate change projections

- Bloemendaal et al. paper presents a statistical model based on a methodology appropriate for present day climate fluctuations (internal variations)
- However, **not fit for purpose for long-term projections of TC activity** changes under greenhouse gas dominated global warming.
- Background on problems with TC climate change projections based on statistical models that rely on SST alone (Vecchi et al., 2008)
    - Vecchi et al. show that one can build a statistical model that represents present day fluctuations in TC power dissipation fairly well, based on either local SST in a region, or on SST in a region relative to tropical mean SST, and these two approaches seem to perform equally well.
    - However, when used **in a global warming projection context, there is a huge difference between the approaches, with a ~300% increase in power dissipation predicted over the 21st century by the local absolute SST relationship**, but little trend over the 21st century using the statistical model based on relative SST.
    - The relative SST projection (i.e., a relatively small trend) is consistent with projections using dynamical models, with statistical-dynamical models based on Emanuel's MPI theory (see green bar in Figure 1 of Vecchi et al., 2008), and with physical arguments. **The absolute SST approach is inconsistent with all of these.**