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High-resolution climate projections reveal future bleaching risks in the Great Barrier Reef

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Abstract:

Coral reefs face escalating extinction risks under climate warming, with extreme events such as marine heatwaves becoming increasingly frequent and intense. Conservation planning requires high-resolution climate projections, yet global climate models lack the spatial detail to resolve local reef dynamics. We address this gap by developing a machine learning (ML) model to downscale Degree Heating Weeks (DHWs), a key indicator of coral bleaching risk, for the Great Barrier Reef (GBR). Applying the model to projections from five global climate models, we generated 10 km resolution DHW estimates. Results show that under a high-emission scenario, bleaching in the GBR could occur annually by the end of the century, with thermal stress persisting for at least four months per year. Importantly, the downscaled projections also identify potential thermal refugia, offering critical targets for conservation.

Keywords: *Machine learning, Climate downscaling, Coral bleaching, Great Barrier Reef*

1. INTRODUCTION

Climate change represents one of the most pressing challenges of the 21st century, posing serious risks to both human societies and natural ecosystems. Marine ecosystems are particularly vulnerable, facing widespread impacts that could have lasting consequences for biodiversity and global food security. Rising global temperatures have placed unprecedented pressure on coral reef systems. In recent years, reefs worldwide have endured repeated mass bleaching events linked to climate change. The Great Barrier Reef (GBR), located off the northeast coast of Australia, is the largest coral reef system on Earth. Despite widespread bleaching, certain areas of the GBR often avoid severe thermal stress and function as refugia. These climate refugia are largely shaped by local environmental conditions, making their identification and protection vital for effective coral reef conservation and management. However, global climate models operate at relatively coarse spatial resolutions (~100 km), which are insufficient for capturing conditions at scales relevant to refugia. To project the future of climate refugia accurately, reef-scale climate data (~1–10 km) are required. High-resolution climate projections obtained through downscaling are therefore critical for assessing how climate change will affect bleaching patterns in terms of frequency and severity. While dynamical downscaling can produce detailed outputs, it is computationally intensive, and statistical downscaling approaches depend heavily on the availability of fine-scale observational datasets for the region of interest. Dynamical downscaling is computationally intensive and prohibitive for generating multi-model, multi-scenario projections, while traditional statistical methods require extensive local fine-scale observational data. Machine learning (ML) offers a sophisticated and efficient alternative by leveraging available high-resolution data to downscale climate models.

2. METHODOLOGY

Coral bleaching risk and the subsequent mortality have been widely monitored using a metric called Degree Heating Weeks (DHW), which is the accumulated temperature anomalies exceeding the monthly maximum mean sea surface temperature (SST) for a region over a period of 12 weeks (Liu et al., 2014). DHW > 4°C-weeks is often associated with coral bleaching, whereas DHW > 8°C-weeks is usually associated with widespread bleaching and coral mortality. In this study, we use a ML model based on a super-resolution deconvolutional neural network (SRDN) (Cyriac et al., 2025) to downscale DHW values from climate projections. These projections are simulated by five of the top-performing the Coupled Model Intercomparison Project Phase 6 (CMIP6) global climate models (GCMs) for the Australian region (Grose et al., 2023). We use daily simulations from these models for the period 1985-2100 under different Shared Socioeconomic Pathways (SSPs), which are suitable for assessing the impacts of global warming on Australian climate. The SRDN model, detailed in (Cyriac et al., 2025), is designed to effectively resolve fine-scale local dynamics from coarser climate model outputs.

3. RESULTS

The ML model is trained and validated on DHWs data derived from daily sea surface temperature (SST) data from the Ocean Forecasting Australia Model Version 3 (OFAM3, (Oke et al., 2013)) historical run. We first compared the spatial variability of DHWs values downscaled using the ML model and traditional interpolation with that of the OFAM3 data, the target. This comparison shows that the ML model successfully captures the spatial variability in the target much better than the interpolated data. Moreover, the ML downscaled data has lower root mean square error and higher correlation with the target in comparison to the interpolated data suggesting that the ML model better captures the magnitude of DHWs values.

Further, using the trained SRDN model, we downscale DHWs data from five CMIP6 GCMs to analyse coral bleaching risks in the GBR. The ensemble mean of these downscaled DHW projections, at a fine 10 km resolution, provides a more reliable estimate of bleaching risk in the GBR. Our analysis reveals that under a high-emission scenario, coral bleaching is projected to become an annual event in the GBR by the end of the century. In addition, high thermal stress is projected to persist for periods exceeding four months per year. Importantly, these high-resolution projections also help identify potential locations of future thermal refugia within the GBR, which could be prioritized for conservation.

4. CONCLUSION

Our high-resolution projections show that under a high-emission scenario, the Great Barrier Reef could face annual coral bleaching and prolonged thermal stress exceeding four months per year by the end of the century. Yet, potential thermal refugia within the reef offer critical opportunities for resilience. Identifying and protecting these areas will be central to effective conservation, highlighting the importance of reef-scale climate projections for future management. Moreover, our ML model could be used to rapidly downscale multiple climate model outputs under different scenarios to provide robust local climate data on the GBR at a low computational cost.

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