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Inevitable global coral reef decline under climate change-induced thermal stresses

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Coral reefs, among the most biodiverse ecosystems on Earth, face an existential threat from the increasing frequency and intensity of coral bleaching events driven by global warming. While much of the existing research examines bleaching as an isolated phenomenon, the critical threshold linking bleaching rates to long-term reef degradation remains poorly understood. Here we identified pivotal factors influencing coral bleaching rates at a global scale, leveraging a data-driven model integrating historical field observations with climate simulations across multiple emission scenarios. Our findings reveal a critical bleaching threshold of 7.9% annually, beyond which coral reef ecosystems would undergo significant degradation. Alarmingly, even under the most optimistic mitigation pathways, substantial degradation is projected across all major tropical marine regions by the end of the century. This study highlights the urgent need for bold and effective global policies to safeguard coral reef ecosystems and ensure their sustainability under an increasingly warming climate.

Coral reefs, among the most biologically diverse and economically significant ecosystems on earth, are vital for the livelihood of millions of people worldwide[1]. These ecosystems, however, are extremely sensitive to elevated seawater temperature, which can disrupt the symbiotic relationship between corals and their symbiotic microalgae (Symbiodiniaceae) leading to coral bleaching[2]. Since the early 1980s, mass coral bleaching events caused by global-scale climate anomalies have been documented, resulting in a significant reduction in coral cover[3]. Notably, the bleaching events of 1997–1998 and 2015–2016 had particularly severe impacts[4,5], resulting in an estimated loss of over 15% of reef-building corals worldwide[6]. Currently, the National Oceanic and Atmospheric Administration (NOAA) has confirmed that we are experiencing the fourth global coral bleaching event on record. Coral bleaching is closely associated with high-intensity and high-frequency thermal stress anomalies[7,8]. Marine heatwaves, exacerbated by climate change, pose a significant threat to coral reefs[9]. These extreme temperature events, coupled with the cumulative effects of repeated bleaching episodes, can lead to long-term damage and a reduction in coral cover[10].

While corals have the capacity to recover from bleaching events, this recovery is contingent on the environment returning to normal conditions in a timely manner[11]. Unfortunately, many coral reefs have already experienced mortality and degradation, which can hinder the recovery of entire reef communities, a process that may take decades[10]. The increasing frequency and severity of these bleaching events may overwhelm coral recovery capacities[10], potentially resulting in ecosystem degradation and a potential shift toward algae-dominated or other alternative systems[12]. Given these concerns, it is essential to consider the average annual bleaching extent over extended periods as a reliable metric for assessing the long-term trends of coral reefs. This metric provides a deeper understanding of the compounding effects of thermal stress over time, which is critical for identifying thresholds beyond which coral reef ecosystems transition to states of irreversible decline.

In response to the pressing issue of coral bleaching and its link to climate change, researchers are investigating the frequency of bleaching events that can lead to total coral demise and ecosystem degradation[13]. Predictive models have been developed to enhance our understanding of these events[14–16]. Notably, the Global Coral-Bleaching Database (GCBD) has been utilized to create multivariate models that incorporate geographic and temperature-related metrics[16–19], aiming to improve predictive accuracy for bleaching events and assess future impacts of climate change. However, the diversity of environmental factors influencing coral survival necessitates a comprehensive approach that goes beyond single-variable assessments[20–22]. For instance, NOAA's degree-heating week (DHW) metric[23], which is a temperature threshold model for coral bleaching, can vary dynamically by region and over time[24].

In this study, we leveraged the Global Coral-Bleaching Database alongside Coupled Model Intercomparison Project Phase 6 (CMIP6) climate projections to develop a comprehensive, data-driven multivariate

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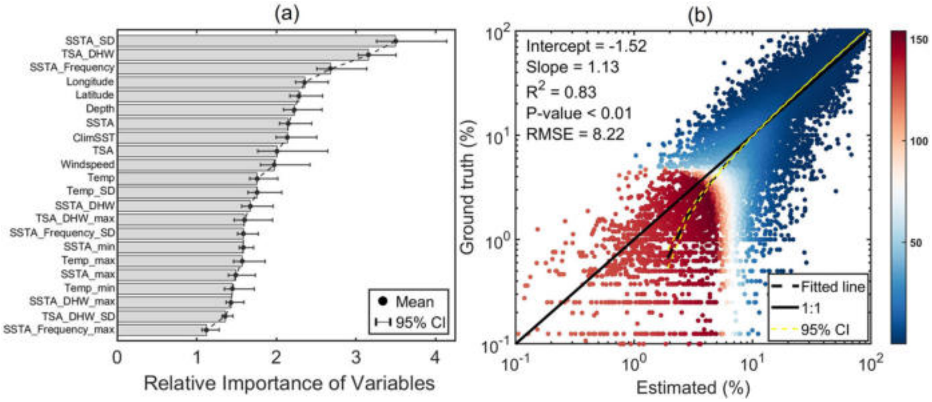

Fig. 1 | Data-driven model performance and variable importance. **a** The relative importance of the 22 variables used in training the random forest model was assessed. The points represent the average importance of each variable across 10 random training iterations, while the lines indicate the corresponding 95% confidence intervals (CIs). **b** Scatterplot of the kernel density of estimated versus ground truth for the multivariate data-driven model. The color gradient shows the density of data points within a 5-unit radius on the plane, with denser areas represented by warmer colors. Most data points from global coral bleaching surveys are concentrated at bleaching rates below 10%. The 95% CIs for the fitted line are shown as a yellow dashed line.

model using random forest algorithms. By incorporating 32 environmental indicators, our model identifies critical thresholds and projects the spatial and temporal dynamics of coral bleaching under different emission scenarios. Given that corals possess a degree of resilience[14], assessing the mean annual bleaching extent over specific periods and determining significant bleaching thresholds can provide valuable insights into coral status and help identify potential climate refuges for future coral reefs. This approach enables us to quantify the vulnerability of coral reefs globally, thereby informing conservation strategies and policy decisions aimed at preserving these vital ecosystems for generations to come.

Results

Construction of a multivariate data-driven model

To project coral bleaching with enhanced precision, we developed and validated a multivariate random forest model using the Global Coral-Bleaching Database (Supplementary Fig. 1)[19]. The optimal combination of hyperparameter settings was selected by a grid search method based on the lowest Root Mean Square Error (RMSE), with ties broken by selecting the model with the fewest variables. The final model, incorporating 22 environmental variables, achieved the smallest RMSE of 10.6% and the highest R-squared value, as confirmed by the validation dataset (Fig. 1a and Supplementary Fig. 2). Prediction variance across test samples was used to assess epistemic uncertainty in the Random Forest ensemble. Results indicate that 75% of the test samples have bleaching prediction variances concentrated within the range of −0.03% to 26.3% (Supplementary Fig. 3), reflecting reasonable variability across most predictions.

We explored the contributions of different environmental factors to coral bleaching globally. Temperature-related variables, such as the variance of sea surface temperature anomalies (SSTA_SD), heating weeks of thermal stress anomalies (TSA_DHW), and the frequency of sea surface temperature anomalies (SSTA_Frequency), proved to be critical in predicting the extent of coral bleaching (Fig. 1a). Our results highlight the significant role that the variance of temperature anomalies and the accumulation of thermal stress play in coral bleaching patterns. Notably, geographic locations and water depth, also exhibited considerable significance (Fig. 1a). This suggests that coral bleaching responses can vary dramatically across regions, even under similar climatic conditions.

To improve the robustness of the model and reduce potential variability from random data splits, we averaged the results of 10 random training iterations to produce the final output (Fig. 1b, Supplementary Fig. 4). The performance of the integrated random forest model was assessed and demonstrated strong predictive capability ($R^2 = 0.83$, $P\text{-}value < 0.01$), confirming that our model effectively captures the relationship between coral bleaching and environmental variables.

Global coral bleaching assessment 1980–2020

Our model's application to historical data (1980–2020) revealed distinct spatial patterns in annual coral bleaching severity. Reefs in the central Pacific and northwestern Australia experienced consistent bleaching stress, while regions such as the Caribbean, Coral Triangle, and South Pacific showed relative resilience (Fig. 2). This spatial distribution highlights the varying impacts of environmental stressors on coral reefs globally, with some regions showing higher resilience or lower exposure to bleaching-inducing conditions. Our multivariate data-driven model has created projections of expected bleaching that cover the spatial and temporal gaps left by the field survey dataset.

Based on these global bleaching estimates and the coral cover data from the sixth GCRMN Status of Coral Reefs of the World: 2020 Report[6], we further examined the relationship between the average coral bleaching rate and the average decline rate of coral reefs across 10 global regions (Fig. 3a, b, and Supplementary Table 1). Notably, corals in South Asia exhibited a particularly high decline rate (~23%) over the 40-year period from 1979 to 2019. This suggests that, in addition to climate-related stressors, other anthropogenic factors—such as overfishing[25] and tourism[26]—may significantly exacerbate coral reef degradation in this region.

Standard regression diagnostics (Supplementary Fig. 5) revealed that South Asia was a statistical outlier, with high leverage and Cook's distance values exceeding conventional thresholds, indicating a disproportionately large influence on the model fit. Therefore, South Asia was excluded from the linear regression to avoid distortion of the global relationship. After excluding this outlier, a significant positive linear correlation emerged between the average annual bleaching rate and the coral decline rate globally (Fig. 3b, $R^2 = 0.6$, p-value = 0.01). This indicates a consistent trend of coral degradation linked to increased bleaching, and further reveals a critical threshold: when the annual bleaching rate exceeds 7.9% (95% CI: 7.6–9.3%), significant coral degradation tends to occur. This threshold corresponds to the estimated bleaching rate at which coral cover remains stable (i.e., the decline rate is zero).

Future bleaching projections under SSP scenarios

To assess the potential impacts of varying levels of global warming on coral bleaching, projections were made under three Shared Socioeconomic Pathway (SSP) emission scenarios: high emission (SSP5-8.5), medium emission (SSP2-4.5), and low emission (SSP1-2.6). These projections, based on CMIP6 data, cover two time periods: 2020–2060 and 2060–2100 (Fig. 4 and Supplementary Fig. 6). Under the low emission scenario (SSP1-2.6), which assumes substantial efforts to reduce greenhouse gas emissions, thermal stress on coral reefs is expected to be limited. As a result, minimal annual bleaching (<5%) is projected for the Caribbean and South Pacific regions in both time periods (Fig. 4a, b). Correspondingly, in these two regions, the projected coral degradation rate over the 40-year periods remains below zero (Supplementary Fig. 7), indicating no significant degradation.

In the medium emission scenario (SSP2-4.5), which reflects moderate emission reductions and moderate levels of global warming, regions such as southern Japan, in addition to the Caribbean and South Pacific, are

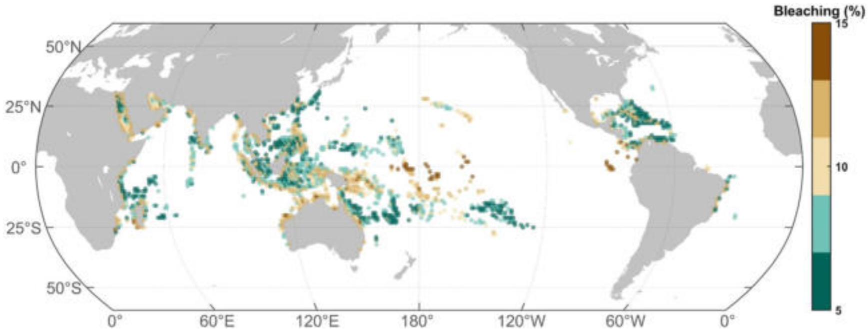

Fig. 2 | Historical coral bleaching Projections. Annual average coral bleaching estimates from 1980 to 2020 for all coral reef regions worldwide, derived from the multivariate data-driven model and historical environmental data.

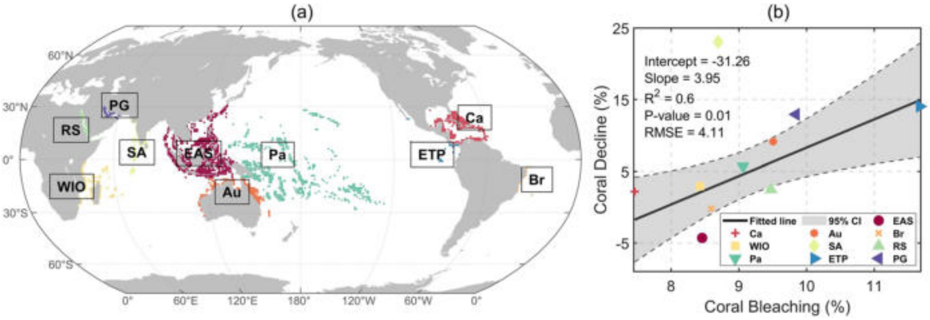

Fig. 3 | Global coral reef regions and bleaching–decline relationships. a Delineation of the 10 global coral reef regions: East Asian Seas (EAS), Caribbean (Ca), Australia (Au), Brazil (Br), West Indian Ocean (WIO), South Asia (SA), Red Sea (RS), Pacific (Pa), East Tropical Pacific (ETP), and Persian Gulf (PG). **b** Scatterplot showing the linear relationship between the average coral bleaching rate and decline rate, using data from the 10 global coral reef regions. Each data point represents statistical data from one of these regions, distinguished by different markers and colors. The 95% confidence interval (CI) for the fitted line is shaded in gray.

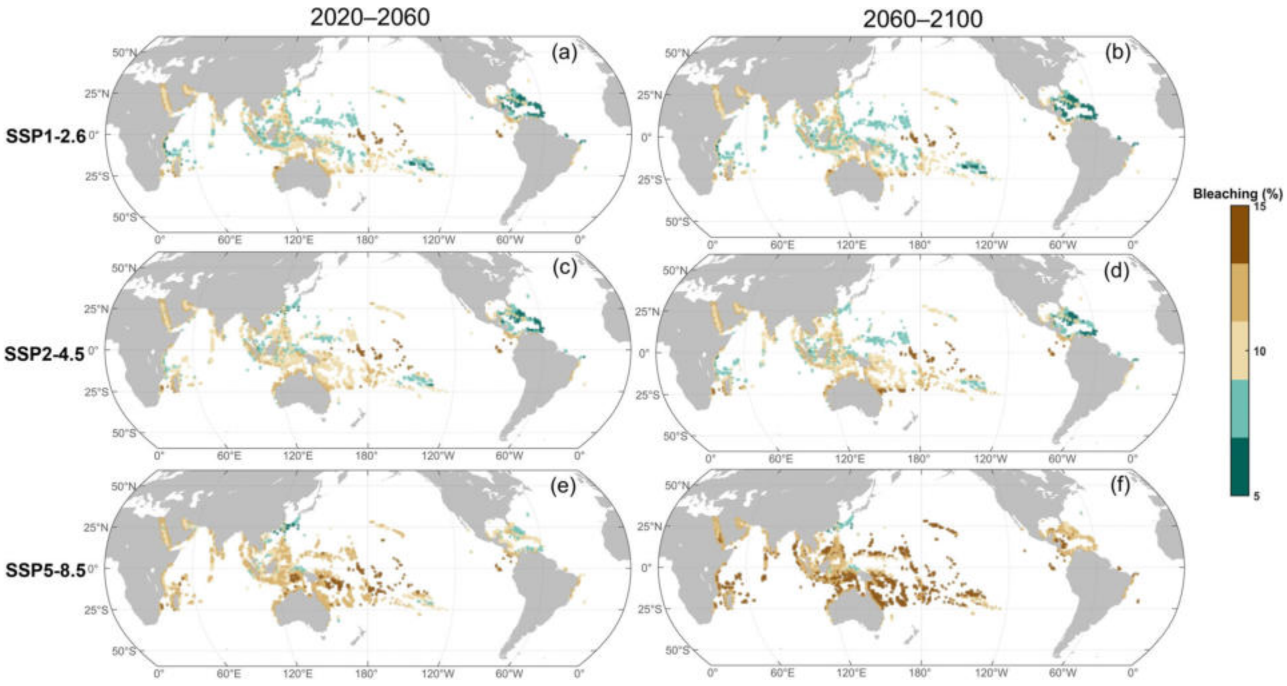

Fig. 4 | Projected bleaching under future climate scenarios. Projected mean annual coral bleaching under three climate scenarios: (**a**, **b**) low emission (SSP1-2.6), (**c**, **d**) medium emission (SSP2-4.5), and (**e**, **f**) high emission (SSP5-8.5) during the periods 2020–2060 (**a**, **c**, **e**) and 2060–2100 (**b**, **d**, **f**).

projected to experience relatively low bleaching (Fig. 4c, d). Meanwhile, the equatorial Pacific and Australian regions are expected to experience the highest bleaching rates (>15%) under both low and medium emission scenarios (Fig. 4a–d). These areas are likely to experience significant thermal stress, leading to higher rates of coral bleaching.

Under the high emission scenario (SSP5-8.5), which assumes minimal efforts to curb emissions, projections indicate widespread and severe bleaching (>15%) across most regions during 2060–2100 (Fig. 4e, f). This scenario reflects a future where global warming continues unabated, resulting in extensive coral bleaching. Notably, low bleaching (5–10%) is projected only in southeastern China, and southern Japan, where coral survival is already at its upper latitudinal limits. Correspondingly, these are the only regions globally where significant coral degradation is not projected to occur (Supplementary Fig. 7).

We also quantified the proportion of coral reef areas projected to experience annual bleaching across ten global regions (Fig. 3a) for the

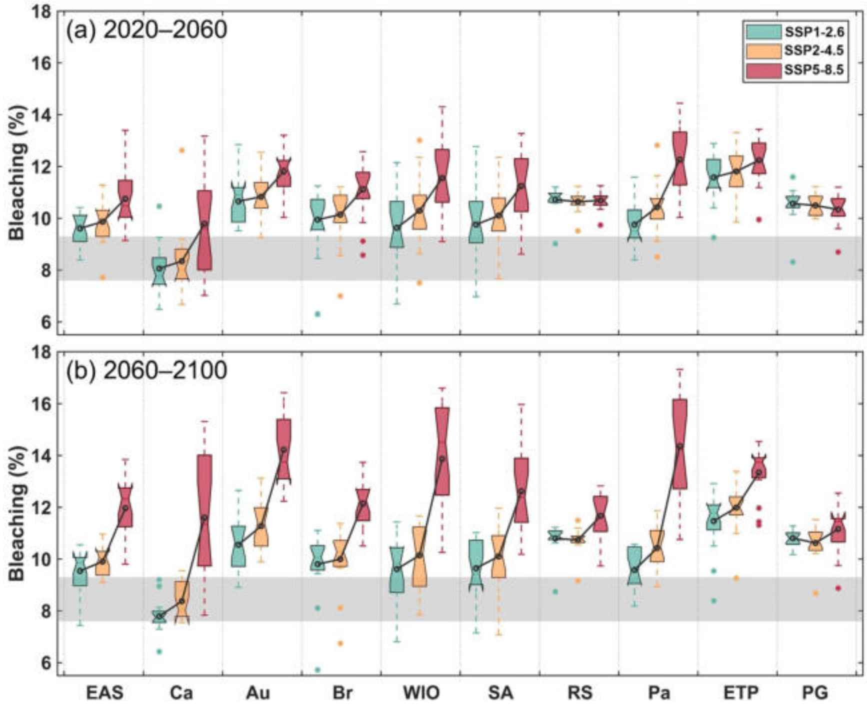

Fig. 5 | Regional bleaching projections under climate scenarios. Coral bleaching statistics in ten regions of the world for the periods 2020–2060 (a) and 2060–2100 (b) under three climate scenarios: low emission pattern SSP1-2.6 (green box), medium emission pattern SSP2-4.5 (yellow box), and high emission pattern SSP5-8.5 (red box). East Asian Seas (EAS), Caribbean (Ca), Australia (Au), Brazil (Br), West Indian Ocean (WIO), South Asia (SA), Red Sea (RS), Pacific (Pa), East Tropical Pacific (ETP), and Persian Gulf (PG). Horizontal shaded bands represent 95% confidence intervals for mean annual coral bleaching when coral decline is zero.

periods 2020–2060 and 2060–2100 under the three climate scenarios (Fig. 5). In the 2020–2060 period, projections under the low emission scenario (SSP1-2.6) show relatively lower bleaching across all regions, with values generally clustering around 8–12% (Fig. 5a). The Caribbean region experiences the least bleaching, while areas like the East Tropical Pacific and the Red Sea show slightly higher levels. Conversely, under the high emission scenario (SSP5-8.5), bleaching rates increase significantly, especially in the Pacific, where the highest mean annual bleaching exceeds 14% (Fig. 5a). The Red Sea and Persian Gulf experience bleaching that exceeds the critical threshold for coral decline, with little difference between emission scenarios. Severe bleaching effects under high-emission scenarios become more pronounced in the later decades of the 21st century (Fig. 5b), suggesting a potential lag effect in the response of coral reefs in these regions. This delayed onset of severe bleaching may be related to the relatively high thermal tolerance of corals in these areas[27], which raises the threshold at which bleaching occurs in response to climate change.

For the period 2060–2100, bleaching rates rise across all regions under all scenarios (Fig. 5b). Under the low emission scenario, bleaching rates remain moderate but show a noticeable increase compared to the earlier period. While the high emission scenario leads to a more pronounced increase in bleaching, especially in regions like Australia, the West Indian Ocean, and South Asia. Severe bleaching (exceeding 16%) is projected for the Pacific, West Indian Ocean, and Australia under the high emission scenario (SSP5-8.5) (Fig. 5b).

Discussion

Given the current response of corals to thermal stress, our projections suggest that the majority of coral reefs will experience extensive degradation in the coming decades. In the absence of proper emission reductions, suitable areas for coral survival will shrink dramatically, with potential refuges limited to localized high-latitude regions (Supplementary Fig. 7). Previous study has indicated that to protect at least 50% of the world's coral reefs, global warming must be limited to 1.2 °C relative to pre-industrial levels[28]. The window of opportunity to save most coral reefs appears to be small and is rapidly closing, especially with the deterioration of coral living environments. In addition, across all three emission scenarios (SSP1-2.6, SSP2-4.5, and SSP5-8.5), global warming—combined with the absence of increased thermal tolerance in corals and their symbionts—was associated with widespread bleaching. The average annual bleaching extent exceeded 10% consistently during both 2020–2060 and 2060–2100, surpassing the range of bleaching thresholds that would lead to significant coral decline.

Our comprehensive assessment evaluated the influence of geographic, hydrological, thermal, and wind-related climate variables on coral bleaching predictions. Among these, thermal anomalies emerged as the most significant factor influencing coral bleaching. Specifically, the variance in sea surface temperature anomalies was identified as the key variable influencing bleaching severity over a 40-year period. However, other stressors, such as ocean acidification[29,30] and fishing activities[25], also influence coral bleaching but are not captured here because of their relatively poor predictability and therefore lack of future global projections as inputs. Thus, the projections provided are relatively conservative and the true impact on coral reefs could be more severe than anticipated. Thermal stress has been confirmed as a major cause of coral bleaching[31]. However, coral bleaching is the ultimate response to a range of environmental factors[3]. Other environmental variables, such as solar radiation[32,33], particularly high light levels, can exacerbate the effects of thermal stress on corals, while reductions in light can mitigate these effects. Cloudiness also plays a role[8], with higher cloud fraction anomalies associated with reduced bleaching severity. Additionally, the performance of corals in novel physicochemical conditions, such as pH, salinity, and sedimentation, is influenced by their growth plasticity and acclimatization capacity[34,35]. Multiple physiological and biochemical factors in algal endosymbionts influence the stability and efficiency of their mutualistic relationship with coral hosts[36]. There is considerable spatio-temporal heterogeneity in coral bleaching, depending on the intensity of thermal-stress events, geographic location[17], habitat complexity, coral species composition[37], historical conditions[38], and regional influences[39].

Coral adaptation or domestication to increased thermal stress may help mitigate widespread coral degradation[2]. Some species of the symbiotic zooxanthellae are more thermally tolerant, which explains why some corals have survived mass bleaching events or in higher temperature environments[40,41]. A recent study suggests that, under the Paris Agreement scenario (SSP1-2.6), coral cover could be maintained at an additional 30% if thermal tolerance reaches levels sufficient to cope with expected thermal stress[42]. However, the intervals between bleaching events are critical for the replenishment and long-term sustainability of coral cover. Even when coral mortality is low, frequent low-intensity bleaching can slow coral growth, reduce replenishment rates, and diminish resilience to other disturbances[43,44]. The ability of coral communities in different regions to increase thermal tolerance at the levels proposed in this study is not yet known. Previous studies have shown that adaptive capacity may also vary according to geographic constraints, such as the diversity of symbiotic zooxanthellae[45] or connectivity between reefs[46,47]. Reefs with higher levels of physical isolation may recover much more slowly from mass coral bleaching events because of lower rates of larval transport and gene flow[46,48].

Considering that coral reef recovery may span several decades depending on disturbance severity and local conditions[10], our study is considered highly conservative, as it mainly incorporates thermal stress and excludes other co-occurring pressures such as pollution, physical damage, and biological competition. Thus, our projections likely represent minimum estimates of potential degradation. Minimum estimates of projected ocean warming suggest that corals and their symbionts need to increase their thermal tolerance by at least 0.5–1 °C over the next 50 years[44] to avoid dangerously bleaching events. Based on moderate estimates of warming, the total acclimatization required for most coral reefs may exceed 2 °C by the second half of this century[44]. Despite the recent discovery of some coral bleaching followed by a shift to more thermotolerant symbioses, there is no clear evidence that coral reefs around the world are capable of adapting to this predicted warming. If emission controls are delayed until a consensus is reached on the level of warming to which coral reefs can adapt, it may become too late to limit future warming to that level[49]. To ensure that the world's coral reefs are protected from the effects of climate change, there may be little margin for error in controlling emissions.

Localized conservation measures, such as marine protected areas (MPAs), represent a complementary strategy to mitigate coral reef degradation, particularly in identified climate refugia. MPAs can buffer reefs against local stressors, such as overfishing and pollution, which exacerbate the effects of thermal stress. However, the efficacy of MPAs is intrinsically tied to global emission trajectories. Under high-emission scenarios (SSP5-8.5), even the most effectively managed MPAs are unlikely to prevent widespread bleaching, as the underlying driver—thermal stress—remains unaddressed. Conversely, under low-emission scenarios (SSP1-2.6), MPAs could play a pivotal role in preserving biodiversity and ecosystem functionality, particularly in identified climate refugia. Integrating MPA planning with projections of thermal refugia can optimize conservation outcomes and ensure resources are directed to the most promising locations. While global mitigation addresses the root cause of thermal stress, localized interventions can buy critical time for coral adaptation and recovery. For example, combining MPAs with active restoration techniques, such as coral gardening, assisted evolution and selective breeding, could enhance ecosystem resilience to both acute and chronic stressors.

In conclusion, our findings project a grim outlook for coral reefs under intensifying climate change, with spatially heterogeneous nature of their responses. Notable temporal trends reveal escalating bleaching severity across all emission scenarios, especially in the latter half of the century. Even under the most optimistic pathway (SSP1-2.6), moderate bleaching continues to rise, underscoring that mitigation alone is insufficient. The inevitability of long-term degradation in most reef regions—without significant shifts in coral thermal tolerance—signals that global emission reductions must be urgently complemented by strategies to enhance coral resilience. The extent of future degradation will vary depending on coral community composition, historical disturbance, and local environmental conditions. This highlights the necessity for a dual approach: while global climate action remains paramount, localized conservation measures, including thermal tolerance enhancement and strategic implementation of marine protected areas (MPAs), may offer critical pathways for impact mitigation. The window of opportunity to act is narrowing rapidly, and failure to address both global and local dimensions of this issue will have profound consequences for biodiversity, ecosystem services, and human livelihoods dependent on coral reefs. The integration of scientific innovation, policy interventions, and community-driven efforts is essential to preserve these invaluable ecosystems for future generations.

Methods

Datasets

The coral bleaching datasets are derived from the Global Coral-Bleaching Database, which encompasses 34,846 coral bleaching records from 14,405 sites in 93 countries, over 40 years, from 1980 to 2020 (Supplementary Fig. 1)[19]. The database includes data on both the presence and absence of coral bleaching, expressed as the percentage of coral colonies exhibiting bleaching symptoms relative to the total number of coral colonies recorded per site, which is what we refer to when we use the terms 'bleaching,' 'bleaching extent,' or 'bleaching threshold' in our Results. This allows for comparative analyses and the determination of geographical bleaching thresholds. Additionally, the database contains information on site exposure, distance to land, average turbidity, cyclone frequency, and various sea surface temperature metrics at the time of the survey. Specifically, the turbidity data were obtained from the MODIS-Aqua satellite database at a 4-km spatial resolution (https://oceandata.sci.gsfc.nasa.gov/MODIS-Aqua/Mapped/Monthly/4km/Kd_490/). Cyclone frequency data were derived from the International Best Track Archive for Climate Stewardship (IBTrACS; www.ncdc.noaa.gov/ibtracs/index.php?name=ibtracs-data), which provides storm track information as spatial points. Global coral cover are sourced from the sixth GCRMN Status of Coral Reefs of the World: 2020 report[6], which provides a comprehensive description of the status and trends of coral reefs worldwide. Coral decline, as defined in this report[6] and in our study, in this context, refers to the reduction in live coral cover as a percentage of the total benthic substrate area in the region assessed.

The global coral reef locations were obtained from the merged data sources[50] (https://data.unep-wcmc.org/datasets/1) including the Millennium Coral Reef Mapping Project[51] and the World Atlas of Coral Reefs[52]. For each coral reef location, the temperature-related variables were matched to assess the projection of global coral reef bleaching using Version 6 of the Coral Reef Temperature Anomaly Database (CoRTAD)[53], which is a sea surface temperature (SST) and related thermal stress metrics dataset (Global 1982–2021, 4 km, https://doi.org/10.25921/ffw7-cs39). The CoRTAD contains weekly-averaged SSTs, SST anomaly (SSTA, weekly SST minus weekly climatological SST), thermal stress anomaly (TSA, weekly SST minus the maximum weekly climatological SST), SSTA Degree Heating Week (SSTA_DHW, sum of previous 12 weeks when SSTA is greater than or equal to 1 °C), SSTA Frequency (number of times over previous 52 weeks that SSTA is greater than or equal to 1 °C), TSA DHW (TSA_DHW, also known as a Degree Heating Week, sum of previous 12 weeks when TSA is greater than or equal to 1 °C), and TSA Frequency (number of times over previous 52 weeks that TSA is greater than or equal to 1 °C). In addition, the CoRTAD includes ancillary marine wind speed data.

In this study, 17 Coupled Model Intercomparison Project Phase 6 (CMIP6) models were evaluated (see Supplementary Table 2), and here we focus on the projected temperature-related variables from three Shared Socioeconomic Pathways (SSP) emission scenarios[54]: (1) SSP1-2.6, which is a remake of the optimistic scenario with 2.6 W/m^2 by the year 2100 and was designed with the aim of simulating a development that is compatible with the 2 °C target. This scenario assumes climate protection measures are being taken. (2) SSP2-4.5, which represents the medium pathway of future greenhouse gas emissions with an additional radiative forcing of 4.5 W/m^2 by the year 2100. This scenario assumes that climate protection measures are being taken. (3) SSP5-8.5, which is fossil-fuel aggressive and represents the upper boundary of the range of scenarios described in the literature with an additional radiative forcing of 8.5 W/m^2 by the year 2100. The websites of https://pcmdi.llnl.gov/CMIP6/ and https://es-doc.org/cmip6-models/ provide detailed information on the CMIP6 models[55]. All data was interpolated onto 1°×1° grids, to suit comparisons with observations.

The Data-driven model

Random forests[56] is a machine learning method that employs repeated random classifications to capture complex interactions among explanatory variables. The random forest method is a powerful ensemble learning technique widely used for tasks such as classification and regression. It randomly samples the original data to build multiple tree models during training, making the overall model more robust. When making projections, random forest determines the final output through majority voting or by averaging the results of each tree, effectively avoiding overfitting and handling numerous features, making it suitable for high-dimensional data[57]. Random forests are a suitable method for predicting coral bleaching and could be used more extensively in studies of coral ecology.

The hyperparameters used in the model-training process are vital for the performance of data-driven models. To optimize our random forest projection model, we used a grid search method to identify the best hyperparameter settings. Grid search is an intuitive and comprehensive strategy for hyperparameter optimization that finds the global optimum by exhaustively considering all parameter combinations within a preset range. Additionally, grid search can perform parallel computing to reduce search time, making it particularly suitable for small- to medium-sized search spaces. We then use iteration with a loop to explore and test which combination of variables best predicted the degree of bleaching. Random forest models were developed using different sets of predictor variables and observed bleaching reports. Initially, a total of 32 environmental indicators were compiled, including sea surface temperature anomalies, thermal stress metrics, and geographic features (Supplementary Table 3). To determine the optimal model configuration, we systematically tested all possible functions of environmental variables and evaluated their performance in predicting global coral bleaching. To assess model performance and validate its generalization ability for each test, we randomly split the dataset into a training set (80%) and a test set (20%). In addition, we averaged the results of 10 trainings as the final output to avoid the instability of the projection model due to the random selection of the training dataset. All data processing, statistical analyses, and model development were performed using MATLAB R2022b (MathWorks, USA).

Model performance evaluation

In this study, we encountered a regression problem aimed at predicting the impacts of environmental factors on coral bleaching. In Random Forests, variable importance is assessed using an accuracy-based approach that leverages the out-of-bag (OOB) samples—subsets of the data that were not utilized during the construction of individual trees. The importance of a specific variable is determined through the following process: First, the predictive accuracy of the model is calculated using the OOB sample. This serves as a reference for comparison. The values of the variable in question are then randomly shuffled within the OOB sample, while all other variables are kept constant. This shuffling disrupts any potential relationship between the variable and the outcome. The model's predictive accuracy is recalculated using the shuffled OOB sample. The difference in accuracy before and after shuffling is recorded. The process is repeated across all trees in the forest, and the mean decrease in accuracy is computed. This mean decrease serves as a measure of the variable's importance (I_v), reflecting how crucial the variable is for maintaining predictive accuracy. A substantial decrease in accuracy indicates high importance, while a negligible or negative change suggests that the variable contributes little to the model's predictions. Negative importance scores, which may arise due to random noise, are generally interpreted as zero importance. Ultimately, the relative importance of the variables ($\bar{I}_v$) after N times of random forest training is:

$$\bar{I}_v = \frac{\sum_{i=1}^{N} I_v}{N} \tag{1}$$

In addition, to comprehensively assess the predictive performance of the model, we employed the root mean square error (*RMSE*) and coefficient of determination (R^2) as statistical metrics. The standard deviation (*SD*) was used to measure the dispersion of the data. The formulas for these statistical metrics are as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (\hat{y} - y_i)^2}{n}} \tag{2}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (y_i - \hat{y})^2}{\sum_{i=1}^{n} (y_i - \bar{y})^2} \tag{3}$$

$$SD = \sqrt{\frac{\sum_{i=1}^{n} (y_i - \bar{y})^2}{n}} \tag{4}$$

where n represents the number of data values, $\hat{y}$ represents the predicted values, y_i represents the data values in the set, and $\bar{y}$ represents the average value of the dataset.

Data availability

Global coral bleaching projections and coral coverage data are available at https://zenodo.org/records/16934979.

Code availability

MATLAB code is available on GitHub: https://github.com/ZengKai94/Random-forest-predicts-global-coral-bleaching.

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References

1. de Groot, R. et al. Global estimates of the value of ecosystems and their services in monetary units. *Ecosyst. Serv.* **1**, 50–61 (2012).
2. Rowan, R. Thermal adaptation in reef coral symbionts. *Nature* **430**, 742–742 (2004).
3. Hughes, T. P. et al. Global warming and recurrent mass bleaching of corals. *Nature* **543**, 373–377 (2017).
4. Head, C. E. I. et al. Coral bleaching impacts from back-to-back 2015–2016 thermal anomalies in the remote central Indian Ocean. *Coral Reefs* **38**, 605–618 (2019).
5. Hughes, T. P. et al. Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. *Science* **359**, 80–83 (2018).
6. Souter, D. et al. Status of coral reefs of the world: 2020 report. Global Coral Reef Monitoring Network (GCRMN) and International Coral Reef Initiative (ICRI) (2021).
7. McClanahan, T. R. et al. Highly variable taxa-specific coral bleaching responses to thermal stresses. *Mar. Ecol. -Prog. Ser.* **648**, 135–151 (2020).
8. Gonzalez-Espinosa, P. C. & Donner, S. D. Cloudiness reduces the bleaching response of coral reefs exposed to heat stress. *Glob. Change Biol.* **27**, 3474–3486 (2021).
9. Leggat, W. P. et al. Rapid Coral Decay Is Associated with Marine Heatwave Mortality Events on Reefs. *Curr. Biol.* **29**, 2723–2730.e2724 (2019).
10. Baker, A. C., Glynn, P. W. & Riegl, B. Climate change and coral reef bleaching: An ecological assessment of long-term impacts, recovery trends and future outlook. *Estuar., Coast. Shelf Sci.* **80**, 435–471 (2008).
11. Winslow, E. M. et al. Corals survive severe bleaching event in refuges related to taxa, colony size, and water depth. *Sci. Rep.* **14**, 9006 (2024).
12. Norma, O. L., Carolina, G. C., Víctor Hugo, H. E., César, I. A. & Alejandra Rojas-, M. in *Corals in a Changing World* (eds Beltran Carmenza Duque & Camacho Edisson Tello) Ch. 5 (IntechOpen, 2017).
13. van Woesik, R. et al. Coral-bleaching responses to climate change across biological scales. *Glob. Change Biol.* **28**, 4229–4250 (2022).
14. Lachs, L. et al. Emergent increase in coral thermal tolerance reduces mass bleaching under climate change. *Nat. Commun.* **14**, 4939 (2023).
15. Lawman, A. E., Dee, S. G., DeLong, K. L. & Correa, A. M. S. Rates of Future Climate Change in the Gulf of Mexico and the Caribbean Sea:

Implications for Coral Reef Ecosystems. *J. Geophys. Res.: Biogeosciences* **127**, e2022JG006999 (2022).
16. Shlesinger, T. & van Woesik, R. Oceanic differences in coral-bleaching responses to marine heatwaves. *Sci. Total Environ.* **871**, 162113 (2023).
17. Sully, S., Burkepile, D. E., Donovan, M. K., Hodgson, G. & van Woesik, R. A global analysis of coral bleaching over the past two decades. *Nat. Commun.* **10**, 1264 (2019).
18. Sully, S., Hodgson, G. & van Woesik, R. Present and future bright and dark spots for coral reefs through climate change. *Glob. Change Biol.* **28**, 4509–4522 (2022).
19. van Woesik, R. & Kratochwill, C. A global coral-bleaching database, 1980–2020. *Sci. Data* **9**, 20 (2022).
20. Anthony, K. et al. New interventions are needed to save coral reefs. *Nat. Ecol. Evolution* **1**, 1420–1422 (2017).
21. Gove, J. M. et al. Coral reefs benefit from reduced land–sea impacts under ocean warming. *Nature* **621**, 536–542 (2023).
22. Pezner, A. K. et al. Increasing hypoxia on global coral reefs under ocean warming. *Nat. Clim. Change* **13**, 403–409 (2023).
23. Gleeson, M. W. & Strong, A. E. Applying MCSST to coral reef bleaching. *Adv. Space Res.* **16**, 151–154 (1995).
24. Whitaker, H. & DeCarlo, T. Re(de)fining degree-heating week: coral bleaching variability necessitates regional and temporal optimization of global forecast model stress metrics. *Coral Reefs* **43**, 969–984 (2024).
25. Zaneveld, J. R. et al. Overfishing and nutrient pollution interact with temperature to disrupt coral reefs down to microbial scales. *Nat. Commun.* **7**, 11833 (2016).
26. Lin, B., Zeng, Y., Asner, G. P. & Wilcove, D. S. Coral reefs and coastal tourism in Hawaii. *Nat. Sustainability* **6**, 254–258 (2023).
27. Evensen, N. R., Fine, M., Perna, G., Voolstra, C. R. & Barshis, D. J. Remarkably high and consistent tolerance of a Red Sea coral to acute and chronic thermal stress exposures. *Limnol. Oceanogr.* **66**, 1718–1729 (2021).
28. Frieler, K. et al. Limiting global warming to 2 °C is unlikely to save most coral reefs. *Nat. Clim. Change* **3**, 165–170 (2013).
29. Hughes, D. J. et al. Coral reef survival under accelerating ocean deoxygenation. *Nat. Clim. Change* **10**, 296–307 (2020).
30. Hoegh-Guldberg, O. et al. Coral Reefs Under Rapid Climate Change and Ocean Acidification. *Science* **318**, 1737–1742 (2007).
31. Hoegh-Guldberg, O. Climate change and coral reefs: Trojan horse or false prophecy?. *Coral Reefs* **28**, 569–575 (2009).
32. Bouwmeester, J. et al. Solar radiation, temperature and the reproductive biology of the coral Lobactis scutaria in a changing climate. *Sci. Rep.* **13**, 246 (2023).
33. Ban, S. S., Graham, N. A. J. & Connolly, S. R. Evidence for multiple stressor interactions and effects on coral reefs. *Glob. Change Biol.* **20**, 681–697 (2014).
34. Barott, K. L. et al. Coral bleaching response is unaltered following acclimatization to reefs with distinct environmental conditions. *Proc Natl Acad Sci USA.* **118**, 8 (2021).
35. Castillo, K. D. et al. Gene expression plasticity facilitates acclimatization of a long-lived Caribbean coral across divergent reef environments. *Sci. Rep.* **14**, 7859 (2024).
36. Yoshioka, Y. et al. Genes possibly related to symbiosis in early life stages of Acropora tenuis inoculated with Symbiodinium microadriaticum. *Commun. Biol.* **6**, 1027 (2023).
37. Loya, Y. et al. Coral bleaching: the winners and the losers. *Ecol. Lett.* **4**, 122–131 (2001).
38. Thompson, D. M. & van Woesik, R. Corals escape bleaching in regions that recently and historically experienced frequent thermal stress. *Proc. R. Soc. B: Biol. Sci.* **276**, 2893–2901 (2009).
39. van Woesik, R. et al. Climate-change refugia in the sheltered bays of Palau: analogs of future reefs. *Ecol. Evolution* **2**, 2474–2484 (2012).
40. Baker, A. C., Starger, C. J., McClanahan, T. R. & Glynn, P. W. Corals' adaptive response to climate change. *Nature* **430**, 741–741 (2004).
41. Little, A. F., van Oppen, M. J. H. & Willis, B. L. Flexibility in Algal Endosymbioses Shapes Growth in Reef Corals. *Science* **304**, 1492–1494 (2004).
42. Lachs, L. et al. Natural selection could determine whether Acropora corals persist under expected climate change. *Science* **386**, 289-1294 (2024).
43. Baird, A. H. & Marshall, P. A. Mortality, growth and reproduction in scleractinian corals following bleaching on the Great Barrier Reef. *Mar. Ecol. -Prog. Ser.* **237**, 133–141 (2002).
44. Donner, S. D., Skirving, W. J., Little, C. M., Oppenheimer, M. & Hoegh-Guldberg, O. Global assessment of coral bleaching and required rates of adaptation under climate change. *Glob. Change Biol.* **11**, 2251–2265 (2005).
45. LaJeunesse, T. C. et al. Low symbiont diversity in southern Great Barrier Reef corals, relative to those of the Caribbean. *Limnol. Oceanogr.* **48**, 2046–2054 (2003).
46. Hughes, T. P. et al. Climate Change, Human Impacts, and the Resilience of Coral Reefs. *Science* **301**, 929–933 (2003).
47. Slattery, M., Lesser, M. P., Brazeau, D., Stokes, M. D. & Leichter, J. J. Connectivity and stability of mesophotic coral reefs. *J. Exp. Mar. Biol. Ecol.* **408**, 32–41 (2011).
48. Ayre, D. J. & Hughes, T. P. Climate change, genotypic diversity and gene flow in reef-building corals. *Ecol. Lett.* **7**, 273–278 (2004).
49. O'Neill, B. C. & Oppenheimer, M. Climate change impacts are sensitive to the concentration stabilization path. *Proc. Natl. Acad. Sci.* **101**, 16411–16416 (2004).
50. UNEP-WCMC, Centre, W., WRI & TNC. (ed Cambridge (U. K.): UN Environment World Conservation Monitoring Centre) (IMaRS-USF and IRD (2005), IMaRS-USF (2005) and Spalding et al. (2001), 2010).
51. IMaRS-USF, I. I. d. R. p. I. D. *IMaRS-USF, IRD (Institut de Recherche pour le Developpement)*. (UNEP World Conservation Monitoring Centre, 2005).
52. MD, S., C, R. & EP, G. *World Atlas of Coral Reefs*. (The University of California Press, 2001).
53. Saha, K. et al. (NOAA National Centers for Environmental Information, 2018).
54. Moss, R. H. et al. The next generation of scenarios for climate change research and assessment. *Nature* **463**, 747–756 (2010).
55. Eyring, V. et al. Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geosci. Model Dev.* **9**, 1937–1958 (2016).
56. Breiman, L. Random Forests. *Mach. Learn.* **45**, 5–32 (2001).
57. Capitaine, L., Genuer, R. & Thiébaut, R. Random forests for high-dimensional longitudinal data. *Stat. Methods Med. Res.* **30**, 166–184 (2021).

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Author contributions

K.Z. and P.Z. conceived and designed the study; K.Z. developed the computer code, analyzed the results, and wrote the first draft of the paper; K.Z., S.H. and P.Z. critically revised the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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