nature portfolio

Peer Review File

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

Corresponding Author: Dr Peng Zhan

This file contains all editorial decision letters in order by version, followed by all author rebuttals in order by version.

Version 0:

Decision Letter:

** Please ensure you delete the link to your author home page in this e-mail if you wish to forward it to your coauthors **

Dear Dr Zhan,

Your manuscript titled "Inevitable Global Coral Reef Decline Under Climate Change-Induced Thermal Stresses" has now been seen by 3 reviewers, whose comments are appended below. You will see that they find your work of some potential interest. However, they have raised quite substantial concerns that must be addressed. In light of these comments, we cannot accept the manuscript for publication in its current form, but would be interested in considering a revised version that fully addresses these serious concerns.

Specifically, we require that you:
-demonstrate global coral reef decline under thermal stress
-fully justify the choice of model and variables/metrics therein
-account for spatial independence of data
-consider climate refugia in analysis.

We hope you will find the reviewers' comments useful as you decide how to proceed. Should additional work allow you to address these criticisms, we would be happy to look at a substantially revised manuscript. If you choose to take up this option, please either highlight all changes in the manuscript text file, or provide a list of the changes to the manuscript with your responses to the reviewers.

When resubmitting, please provide a point-by-point response to the reviewers' comments. Please submit your responses as a separate file, distinct from your cover letter where you can add responses to the Editors' comments that you do not want to be made available to the reviewers. Word files are preferred. We recommend that any figures, tables or graphs that are included in the response to reviewers are also included in the main article or Supplementary Information.

Please bear in mind that we will be reluctant to approach the reviewers again in the absence of substantial revisions.

If the revision process takes significantly longer than three months, we will be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

We are committed to providing a fair and constructive peer-review process. Please do not hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the reviewers' comments with a list of your changes to the manuscript text (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and any completed checklist:

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** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

Please do not hesitate to contact us if you have any questions or would like to discuss the required revisions further. Thank you for the opportunity to review your work.

Best regards,

Lidiane Gouvêa
External Editor
Communications Earth & Environment

Alice Drinkwater, PhD
Associate Editor
Communications Earth & Environment
Consulting Editor
Communications Sustainability

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• Life sciences
An updated and completed version of our Reporting Summary must be uploaded with the revised manuscript
You can download the form here:
https://www.nature.com/documents/nr-reporting-summary.zip

For your information, you can find some guidance regarding format requirements summarized on the following checklist: (https://www.nature.com/documents/commsj-phys-style-formatting-checklist-article.pdf) and formatting guide (https://www.nature.com/documents/commsj-phys-style-formatting-guide-accept.pdf).

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

Review of Zeng et al. COMMSENV-25-0388-T

The authors take a modeling approach to assess the range of factors that can help explain the variability in coral bleaching under different climate change scenarios. Interestingly, under most mitigation pathways significant bleaching still occurs at levels under which ecosystem stability cannot be maintained. The message is not unlike many other studies that include empirical data and modeling, or both. What is surprising is that the model, which includes >30,000 bleaching records and 32 variables, cannot pull out any other main findings other than that any projected temperature rate increases will result in more bleaching and ecosystem degradation. Not really all that surprising, especially for those of us who are realists and have been saying many coral reefs around the world are, or soon will be, going to succumb to climate change and there is nothing we can do on say, a 50 year time frame to change those outcomes. Additional comments follow below.

Given that there are no page or line numbers, making it difficult to identify specific issues, I will just discuss my concerns in the order they occur.

The authors discuss shifts “toward algal-dominated systems” but that endpoint is not the only one that can occur with many reefs transitioning to soft coral and sponge dominated communities. There are multiple studies/review papers that discuss this.

I agree that a multivariant approach is needed. But despite the authors concern about the variability in DHW as a single metric it still rises to the top of the pile explaining a large amount of the variance in coral bleaching. My problem with DHW is the spat of papers out there they reveal the significant errors in the metric. This reviewer believes the NOAA DHW is a flawed metric. DHW are notoriously variable and based on the premise, from the 1990’s, that bleaching occurs universally at 1°C above the mean monthly average for a geographic area. First, that doesn’t always hold true. Second, the data used are large scale, coarse, remotely sensed SST which looks at the skin temperature of the oceans (<<10 m). A recent study McClanahan et al. 2019, Nat Clim Change, 9:845-851, showed that DHW in either a multivariate or univariate model predicted only 5% and 9% of the variation between temperature and bleaching, and a recent paper by Mason et al. (2025) Nat Geosci 18: 120-123 also showed significant deviations between using DHW and DHM, that is derived from climate models, normalized to DHW for comparison to estimate coral bleaching. The data show significant overestimations using DHM. Now, the authors are not using DHM here but it also suggests that we do not understand the underlying variability in any of these metrics. Some of this variability is very likely due to a suite of factors that interact, such as temperature and irradiance, and those interactions are not captured in this model. In fact, 25/32 factors assessed in this manuscript are directly related to sea surface temperature so it is not surprising that temperature metrics rose to the top under all climate modeling scenarios.

One of the factors tested, presumably as a proxy to irradiance, was Turbidity based on diffuse attenuation coefficients (i.e., Kd490). I assume the authors got this data from a remote sensing platform that is unnamed. It is listed as a variable and never really discussed again. Additionally, there is no unique relationship between Kd490 and irradiance except in blue, Case I, waters. Where many coral reefs occur, especially in coastal Case II waters, the effects of CDOM confounds the relationship between Kd490 and irradiance. Additionally, one must be careful here because Kd490 has only been validated for the MODIS-Aqua platform. Since Kd490 is significantly affected by CDOM in coastal zones using it as a measure of turbidity should be done with caution with other platforms such as SeaWiFS data because it has not been validated by the remote sensing community.

In the Global Coral Bleaching Assessment section, the authors suggest that the Caribbean, and other locations, are resilient because of variability in the impacts of environmental stressors. I think it would also be essential to consider changes in the coral community as a result of previous bleaching events, i.e., winners vs. losers.

How did you justify removing SA from the regression analysis. Did you conduct an actual analysis that revealed SA as an outlier. Otherwise, you have no justification for doing so.

For the data in Figs. 4 and 5 there is no discussion of any application of statistics and the results. It’s all descriptive based on the mean model outputs (?). I see no value in forecasting with a model unless I understand the inherent variability of those forecasts and their significance or not. I am one that doesn’t believe that CI values (see Fig. 5) alone are sufficient to assess significant differences. While informative CI values should always be complimented with the results of a statistical analysis.

In the Discussion the authors state clearly that the timeframe to ameliorate climate change effects on many coral reefs is short and rapidly closing. I agree! But I already knew this intuitively and from countless other published studies. I don’t see the added value of this analysis to that thesis.

Many studies have made predictions about changes in both OA and irradiance as a result of climate change. The data are out there and these factors lower the thermal threshold for coral bleaching and changes in these factors also co-occur with thermal stress. The model presented has very little ecological realism and as the authors state the predictions are likely to be conservative. Nothing new here unfortunately, but the authors do recognize the shortcomings of the analysis presented.

Reviewer #2 (Remarks to the Author):

This study developed a multivariate model to test bleaching intensity under various climate scenarios and identify critical bleaching thresholds. In the era of significant global warming and increased frequency of bleaching events, this type of study is both relevant and timely. The authors thoroughly analyzed the historical data and bleaching intensity across regions, highlighting a grim future for coral reefs worldwide, even under the lowest emission scenarios. The manuscript is well-written and easy to follow. Overall, it was a pleasure to read and review this manuscript.

General comments:

My major comment concerns the composition of the Results section, which seems to mix methods, results, and discussion. I suggest that the authors consider rewriting the results accordingly. For example, lines 78-86 are methods, while lines 94-96 belong in the discussion. Lines 136-138 and 145-147 also belong to the discussion.

Lines 163-164: It would be beneficial to highlight the regions that experience bleaching despite efforts to reduce greenhouse gas emissions. This information is intertwined with the results of medium emission scenarios, making it difficult to follow. I would recommend either combining the low and medium scenarios into one paragraph or separating them entirely.

Lines 177-179: belong to discussion

Lines 196-198: belong to discussion

Lines 215-220: sound like conclusions

This is merely a suggestion for enhancing the study's scope. It seems pertinent to include analyses across depth concerning the significant focus of reef research—the role of blue mesophotic areas as refugia. Examining bleaching intensity across depth is particularly relevant given the observed inconsistencies in bleaching between shallow and deeper reefs (e.g., Chagos archipelago, Diaz et al. 2023). I believe that incorporating such analyses would be very relevant and would enhance the paper's impact.

Lines 275-276: Please insert appropriate reference here.

Figures:

The figures are clear and easy to read, but I have a few minor comments about the labeling of the axes and the legend.

Figure 1b: It would be great to maintain consistency in the terminology used – while the figure caption states predicted versus observed, the axes indicate estimated and ground truth. Please adhere to one choice of words.

Figure 4: The labels on the y-axis should be corrected from, for example, panels a and b: ssp 126 to SSP 1-2.6, and in the same manner for panels c-f.

Figure 5: Kindly refer to my comment for Figure 4 and adjust the legend accordingly.

Supplementary Information:

Please include references for the cited literature and consider exchanging Figures S2 and S3 –see my comment below.

Minor comments:

Lines 31-32: It would be helpful to clarify what differentiates mass coral bleaching events from regular bleaching events in one sentence. Are mass bleaching events synonymous with global bleaching events, or are they more regionally focused?

Lines 34-35: Could the cited reference [6], Veron et al. (2009), possibly be a typo? I assume so because it is not the primary reference and does not provide information regarding a 15% global coral loss.

Lines 89 and 102: Why does figure S3 appear in the text before figure S2?

Refer to the Supplementary Table here (Lines 134- 136).

Lines 141-145: Think about rephrasing this sentence for better clarity.

Line 161-163: Please consider revising this sentence.

Line 184: What does “we counted coral bleaching” refer to?

Methods: Please indicate which software was used for analyses.

Reviewer #3 (Remarks to the Author):

This work uses a Random Forest approach to identify which of a range of variables related to temperature stress exposure and other physical oceanographic parameters best predict observed bleaching in a global dataset, and then uses this model to perform hindcasts and forecasts of bleaching. The main finding of the study was that bleaching of 7.9 % annually is the critical point above which coral reefs will decline, but below which they will not. Overall the study was well done and well written, and it seems a good fit for Communications Earth and Environment. My detailed comments are:

- The frame of reference used for expression of percent bleaching or percent coral loss is not defined. Is this relative to the total area of benthic substrate, or to then total area of live coral? Please make this clear when a value of percent bleaching or coral loss is first stated in the manuscript.

- Line 70: cite reference for 'a degree of resilience'

- Line 123-125: 'The global assessment of annual average bleaching, based on our multivariate data-driven model, fills the gaps left by the ... field survey data': this is an overstatement. Your approach is a model only, and cannot fill the gaps left by field surveys - only additional acquisition of field data can do that. It would be more factual to state here that '...our multivariate data driven model has created projections of expected bleaching that cover the spatial and temporal gaps left by the field survey dataset'.

- Line 141-145: This latter half of this sentence needs attention to its grammar - it does not completely make sense at the moment.

The section titled "Future bleaching projections under SSP scenarios" (lines 156-220): Throughout this section, both the Geographic regions formally defined in Figure 3, and geographic regions that are common knowledge but not formally defined in Figure 3 (such as "south Pacific" and "equatorial Pacific" are used - some geographic areas within both classifications overlap and some do not. The use of two different Geographic classification schemes within one section is confusing. I suggest that you separate this section into two sections, with separate section headings for each: a first section containing the content that uses the common-knowledge geographic regions, and a second section containing the content that uses the Figure 3 geographic classification.

Line 228: 'warming': what level of warming?

Line 229: ' a general global bleaching': grammatically incorrect and does not fully make sense as written.

Line 248: It seems narrow-focused to single out 'Sterol availability and biosynthetic pathways' here: there are a range of other physiological factors that influence the coral-algae mutualism. Either list most of them here, or choose remove 'Sterol availability and biosynthetic pathways' and choose more general terms to refer to the full range of factors involved.

Line 255: Provide a reference at the end of the sentence ending on this line.

Line 270: '10-30 years to recover' following what?

Line 282-298: No lines of investigation with regard to MPAs are presented in this paper. Therefore, I would remove this paragraph above MPAs, as it is only reviewing information that is of indirect relevance to the main themes of the paper.

Lines 315-322: Sentences are fragments, please revise.

Line 337: Where did the variables turbidity, windspeed, cyclone frequency come from?

Line 340: State here that "we focus... on three Shared Socioeconomic Pathways (SSP)" and in the following line (341) state that '(1) SSP1-2.6, which is a remake of Representative Concentration Pathway (RCP) 2.6' etc.

Figure S1: How were the values in each dot calculated? Are they values for bleaching averaged at a particular 1 x 1 degree grid cell over the entire 40 year period, or something different?

Line 271: 'highly conservative' meaning what in this context?

Version 1:

Decision Letter:

** Please ensure you delete the link to your author home page in this e-mail if you wish to forward it to your coauthors **

Dear Dr Zhan,

Your manuscript titled "Inevitable Global Coral Reef Decline Under Climate Change-Induced Thermal Stresses" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment.

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

EDITORIAL REQUESTS:

Please review our specific editorial comments and requests regarding your manuscript in the attached "Editorial Requests Table".

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Please outline your response to each request in the right hand column. Please upload the completed table with your manuscript files as a Related Manuscript file.

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We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Alice Drinkwater, PhD
Associate Editor
Communications Earth & Environment
Consulting Editor
Communications Sustainability

REVIEWERS' COMMENTS:

Reviewer #2 (Remarks to the Author):

Thank you for your thoughtful revisions. I am overall satisfied with your responses and the current version of the manuscript.
Just two minor grammatical issues remain:
L275: Please add “to” between “need” and “increase.”
L323: “encompasses” should be used instead of the current form.
Otherwise, everything looks good.

Reviewer #3 (Remarks to the Author):

I felt that the authors have mostly addressed the comments of the three reviewers, which has improved the manuscript.
There were a few author responses to review comments that I feel need additional attention:

Regarding Reviewer 1's comment: 'In the Global Coral Bleaching Assessment section, the authors suggest that the Caribbean, and other locations, are resilient because of variability in the impacts of environmental stressors. I think it would also be essential to consider changes in the coral community as a result of previous bleaching events, i.e., winners vs. losers.'
The authors, in their response document, acknowledge that 'such shifts can provide an ecological explanation for the apparent regional resilience observed in areas like the Caribbean and the Coral Triangle.' However, their updated manuscript does not actually explicitly acknowledge this possibility. Secondly, I doubt that the loss of sensitive coral species due to repeated bleaching events is the cause of Coral Triangle resilience as this area has had a reputation for not bleaching often, limiting the number of events during which loss of sensitive species would likely occur - see the work of Joan Kleypas (https://onlinelibrary.wiley.com/doi/10.1111/gcb.12881).

Regarding Reviewer 3's first question about the frame of reference used for expression of percent bleaching and percent coral loss, I appreciate that the authors have included additional text to try to clarify the meaning of these terms. However, despite the addition of explanatory text, percent coral bleaching is still cryptic and not explicitly defined. I suggest modifying the explanatory text on percent coral bleaching to say:

"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' or 'bleaching extent' or 'bleaching threshold' in our Results. This allows for comparative analyses and the determination of geographical bleaching thresholds."

I think that further addition text added to define Coral Decline has helped, but I suggest the following modification to make the definition 100% clear:

“Coral decline, as defined in this report[6] and in our study, refers to the reduction in live coral cover as a percentage of the total benthic substrate area in the region assessed.”

Regarding a latter comment of Reviewer 3 ('Line 228: 'warming': what level of warming?'), the authors have included the following revised text in the discussion: "“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, with an average annual extent exceeding 10%. This level exceeding the range of bleaching thresholds that would lead to significant coral decline.”

This updated text is still not 100% clear to me - what future period do all three scenarios consistently exceed 10% bleaching by? 2020-2060 or 2060-2100?

Finally, I cannot see a data and code availability statement in the manuscript - where are the raw outputs of the random forest models, and the Matlab code used in the analysis, archived?

Statement:

We would like to sincerely thank the editor's and reviewers' thoughtful and constructive feedback, which has helped us significantly improve the clarity, rigor, and overall quality of the manuscript. We have carefully addressed each comment point by point. Where appropriate, we have revised the manuscript accordingly and provided detailed justifications or clarifications in our responses. All changes in the revised manuscript are highlighted in red. Detailed responses to individual reviewer comments are provided in the following pages. **Please find our answers to comments in normal font and the changes to the original text in blue.**

REVIEWER COMMENTS:
Reviewer #1 (Remarks to the Author):
Review of Zeng et al. COMMSENV-25-0388-T

The authors take a modeling approach to assess the range of factors that can help explain the variability in coral bleaching under different climate change scenarios. Interestingly, under most mitigation pathways significant bleaching still occurs at levels under which ecosystem stability cannot be maintained. The message is not unlike many other studies that include empirical data and modeling, or both. What is surprising is that the model, which includes >30,000 bleaching records and 32 variables, cannot pull out any other main findings other than that any projected temperature rate increases will result in more bleaching and ecosystem degradation. Not really all that surprising, especially for those of us who are realists and have been saying many coral reefs around the world are, or soon will be, going to succumb to climate change and there is nothing we can do on say, a 50 year time frame to change those outcomes. Additional comments follow below.

Given that there are no page or line numbers, making it difficult to identify specific issues, I will just discuss my concerns in the order they occur.

Answer: We are sorry for the inconvenience. We have added the page and line numbers in the revised manuscript.

The authors discuss shifts "toward algal-dominated systems" but that endpoint is not the only one that can occur with many reefs transitioning to soft coral and sponge dominated communities. There are multiple studies/review papers that discuss this.

Answer: Thanks for your comments. In our manuscript, the shift toward algal-dominated systems is presented as one potential outcome, not as the sole possibility. To better reflect this complexity and prevent potential misinterpretation, we have revised the relevant statement in the revised manuscript (Page 2, Lines 46-48).

"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]."

I agree that a multivariant approach is needed. But despite the authors concern about the *variability in DHW as a single metric it still rises to the top of the pile explaining a large amount of the variance in coral bleaching. My problem with DHW is the spat of papers out there they reveal the significant errors in the metric. This reviewer believes the NOAA DHW is a flawed metric. DHW are notoriously variable and based on the premise, from the 1990's, that bleaching occurs universally at 1°C above the mean monthly average for a geographic area. First, that doesn't always hold true. Second, the data used are large scale, coarse, remotely sensed SST which looks at the skin temperature of the oceans (<<10 m). A recent study McClanahan et al. 2019, Nat Clim Change, 9:845-851, showed that DHW in either a multivariate or univariate model predicted only 5% and 9% of the variation between temperature and bleaching, and a recent paper by Mason et al. (2025) Nat Geosci 18: 120-123 also showed significant deviations between using DHW and DHM, that is derived from climate models, normalized to DHW for comparison to estimate coral bleaching. The data show significant overestimations using DHM. Now, the authors are not using DHM here but it also suggests that we do not understand the underlying variability in any of these metrics. Some of this variability is very likely due to a suite of factors that interact, such as temperature and irradiance, and those interactions are not captured in this model. In fact, 25/32 factors assessed in this manuscript are directly related to sea surface temperature so it is not surprising that temperature metrics rose to the top under all climate modeling scenarios.*

Answer: Thank you for your positive feedback on our multivariate prediction approach. As noted in the manuscript, we recognize the limitations of using DHW/DHM as a standalone metric, particularly given its inherent variability and the discrepancies reported in recent studies. In our manuscript, we explicitly highlight that coral bleaching is a complex phenomenon influenced by multiple interacting environmental factors beyond temperature alone. To address this complexity and the inherent variability of the DHW metric, we employed a robust multivariate random forest modeling approach. Initially, we considered 32 environmental indicators, encompassing thermal stress metrics, geographic factors, irradiance, and hydrological parameters. Through an exhaustive grid search and rigorous validation, our analysis ultimately identified an optimal subset of 22 variables. This approach was specifically designed to account for the multifaceted nature of coral bleaching and minimize overreliance on any single, potentially flawed metric such as DHW.

Although DHW-related metrics emerged as influential predictors within our multivariate model, their prominence was rigorously contextualized alongside other critical temperature metrics, including variance in SST anomalies and frequency of thermal anomalies. Notably, our findings underscore that the variability in sea surface temperature anomalies (SSTA variance) was equally, if not more, significant than DHW alone in explaining bleaching patterns. Furthermore, the inclusion of geographic and other environmental variables mitigated the model's dependence solely on DHW.

Regarding the concerns about data quality raised by the reviewer, our analysis utilized the Coral Reef Temperature Anomaly Database (CoRTAD), a dataset incorporating remotely sensed SST data that are widely accepted in the field, albeit with the recognized limitations inherent in satellite-derived SST measurements. We are aware of the concerns regarding coarse resolution and skin-temperature biases; however, the large spatial and temporal coverage provided by this dataset is essential for global-scale analyses and predictions. We clearly outline these limitations in the Discussion section of our manuscript and stress that our projections, though robust, represent conservative estimates that do not fully capture all potential interactions.

Lastly, we strongly concur with the reviewer's point about the necessity of capturing interactions between temperature and irradiance. In the revised manuscript, we have further emphasized this limitation and clearly stated the necessity for future research to integrate finer-scale datasets that can better represent local environmental conditions, such as irradiance and subsurface temperature profiles. Such improvements would substantially enhance the predictive capability of future coral bleaching models.

One of the factors tested, presumably as a proxy to irradiance, was Turbidity based on diffuse attenuation coefficients (i.e., Kd490). I assume the authors got this data from a remote sensing platform that is unnamed. It is listed as a variable and never really discussed again. Additionally, there is no unique relationship between Kd490 and irradiance except in blue, Case I, waters. Where many coral reefs occur, especially in coastal Case II waters, the effects of CDOM confounds the relationship between Kd490 and irradiance. Additionally, one must be careful here because Kd490 has only been validated for the MODIS-Aqua platform. Since Kd490 is significantly affected by CDOM in coastal zones using it as a measure of turbidity should be done with caution with other platforms such as SeaWiFS data because it has not been validated by the remote sensing community.

Answer: Thank you for your comments. The Kd490 parameter used in our manuscript is derived from the MODIS-Aqua platform, as detailed in the database referenced in the manuscript. In our study, we initially included a comprehensive set of environmental variables to evaluate their contributions to coral bleaching risk. After an exhaustive combination screening process, variables with lower importance, including Kd490, were excluded from the final model. Consequently, Kd490 was not utilized in constructing the predictive algorithm for coral bleaching.

We appreciate your valuable feedback and have clarified this point in the revised manuscript. Please refer to Page 12, Lines 367-370 for detailed revisions.

"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/)."

In the Global Coral Bleaching Assessment section, the authors suggest that the Caribbean, and other locations, are resilient because of variability in the impacts of environmental stressors. I think it would also be essential to consider changes in the coral community as a result of previous bleaching events, i.e., winners vs. losers.

Answer: Thanks for your comments and we agree with this point. Coral community shifts following repeated bleaching events—resulting in more resilient "winners" and the loss of more sensitive "losers"—are indeed important in explaining regional differences in bleaching impacts and ecological outcomes. In the revised manuscript, we have explicitly expanded the discussion section to better integrate this essential ecological dimension. Specifically, we now emphasize how the cumulative effects of repeated bleaching episodes drive shifts in coral community structures, with resilient taxa increasingly dominating reefs exposed to frequent thermal anomalies. We also note that such shifts can provide an ecological explanation for the apparent regional resilience observed in areas like the Caribbean and the Coral Triangle.

We have incorporated relevant literature to substantiate these points, highlighting research on winners and losers among coral species, the role of thermal tolerance in shaping coral community structures, and the implications of these shifts for long-term reef resilience (see revised manuscript, Page 8, Lines 281–296). Furthermore, we acknowledge the limitations of current global-scale datasets in capturing detailed species-level responses, noting this as an important avenue for future research to enhance predictive modeling and conservation strategies. By explicitly addressing how historical bleaching events shape present and future coral community dynamics, our manuscript now provides a more comprehensive perspective on coral resilience and vulnerability to climate change-induced thermal stress.

"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]."

How did you justify removing SA from the regression analysis. Did you conduct an actual analysis that revealed SA as an outlier. Otherwise, you have no justification for doing so.

Answer: Thanks for your comments. In our initial regression analysis, South Asia (SA) emerged as a statistically influential data point. To evaluate this further, we conducted a standard diagnostic analysis including standardized residuals, leverage values, and Cook's Distance (as Figure 1 shows below and Figure S5 in the supporting in formation). The results identified SA as an outlier with a standardized residual of -1.22, leverage of 0.53, and Cook's Distance of 1.77, which significantly exceeds the common threshold of 4/n (where n is the number of observations). These indicators suggest that SA exerts disproportionate influence on the regression model. We have now clarified this justification in the revised manuscript (Page 4, Lines 136-140).

"Standard regression diagnostics (Figure S5) 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.”

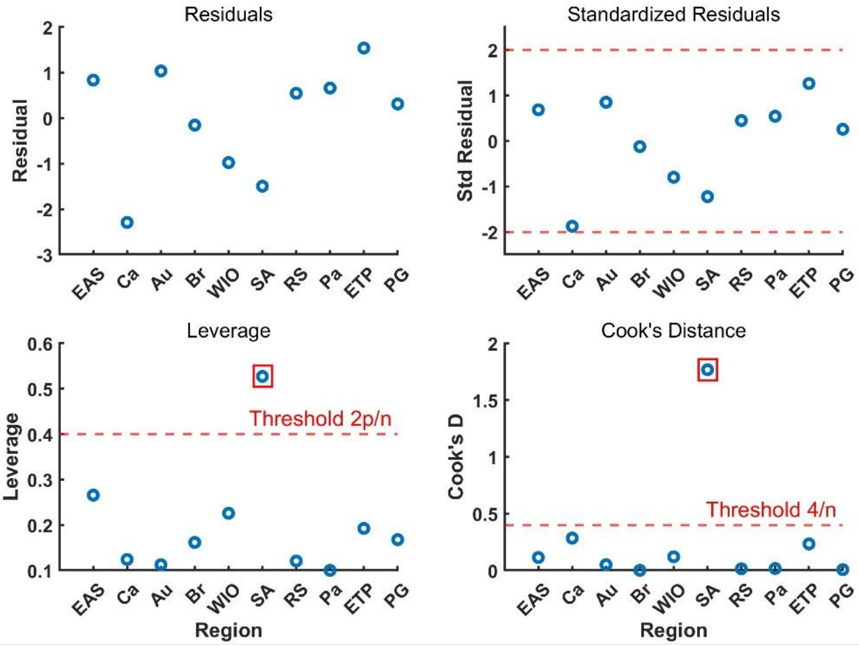

Figure 2. Standard diagnostic plots for the linear regression between coral reef decline rate (%) and bleaching severity across 10 tropical ocean regions. (a) Raw residuals plotted by region reveal deviations from model predictions. (b) Standardized residuals identify potential outliers; values beyond ±2 (dashed red lines) suggest possible concern. (c) Leverage values indicate each observation’s influence on model fit; the red dashed line marks the conventional threshold of 2p/n. (d) Cook’s Distance highlights influential data points; values above 4/n (dashed red line) are considered potentially influential. South Asia (SA) exceeds multiple thresholds and is flagged as an influential point.

However, we acknowledge that statistical outlier status alone does not automatically justify exclusion. We therefore supplemented this finding with a contextual assessment. South Asia, home to approximately 1.8 billion people, is uniquely vulnerable to climate change due to a combination of high population density, prevalent poverty, and strong dependence on agriculture and natural resources for livelihoods (Singh et al., 2021; Ahmed et al., 2019). These socio-environmental conditions contribute to regionally distinct stressors that may obscure or amplify bleaching responses independent of the temperature-related drivers that our regression aimed to isolate.

Given both the statistical influence and contextual divergence of SA, we excluded it from the main model to ensure that our results more accurately reflect the global relationship between coral decline and temperature-driven bleaching.

Ahmed, Ahsan Uddin, Arivudai Nambi Appadurai, and Sharmind Neelormi. 2019. 'Status of Climate Change Adaptation in South Asia Region.' in Mozaharul Alam, Jeongho Lee and Puja Sawhney (eds.), Status of Climate Change Adaptation in Asia and the Pacific (Springer International Publishing: Cham).

Singh, Bhupendra Bahadur, Manmeet Singh, and Dharmaveer Singh. 2021. 'An

Overview of Climate Change Over South Asia: Observations, Projections, and Recent Advances.' in R. B. Singh, Soumendu Chatterjee, Mukunda Mishra and Andrews José de Lucena (eds.), Practices in Regional Science and Sustainable Regional Development: Experiences from the Global South (Springer Singapore: Singapore).

For the data in Figs. 4 and 5 there is no discussion of any application of statistics and the results. It's all descriptive based on the mean model outputs (?). I see no value in forecasting with a model unless I understand the inherent variability of those forecasts and their significance or not. I am one that doesn't believe that CI values (see Fig. 5) alone are sufficient to assess significant differences. While informative CI values should always be complimented with the results of a statistical analysis.

Answer: Thanks for your comments. To address your concerns regarding the statistical rigor of our model outputs, we have incorporated a variance-based diagnostic analysis of the Random Forest (RF) predictions, following the method proposed by Wager, Hastie, and Efron (2014). The results are presented in the Figure 3 shows below and in Supplementary Figure S3.

Figure 2a displays the prediction variance for each test sample, calculated from the distribution of outputs across the RF ensemble. This variance captures the sample-level uncertainty inherent in the predictions. Figure 2b summarizes the distribution of prediction variances for all test samples, highlighting the overall heterogeneity in model confidence. We also include the interquartile range (IQR) to better visualize the spread and identify high-variance samples where prediction reliability is lower. Results indicate that 75% of the test samples have bleaching prediction variances concentrated within the range of -0.03% to 26.3% (Figure 2b), reflecting reasonable variability across most predictions.

These variance-based diagnostics provide an important complement to the mean predictions and associated confidence intervals (CIs). While CIs represent the uncertainty around the average estimate, the prediction variances offer insight into the epistemic uncertainty—that is, the internal disagreement among trees within the RF ensemble—thereby enhancing the interpretability and statistical robustness of our forecasts. Corresponding revisions have been made in the manuscript (Page 2, Lines 84–87).

"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% (Figure S3), reflecting reasonable variability across most predictions. "

Wager, Stefan, Trevor Hastie, and Bradley Efron. 2014. 'Confidence Intervals for Random Forests: The Jackknife and the Infinitesimal Jackknife', Journal of Machine Learning Research, 15: 1625-51.

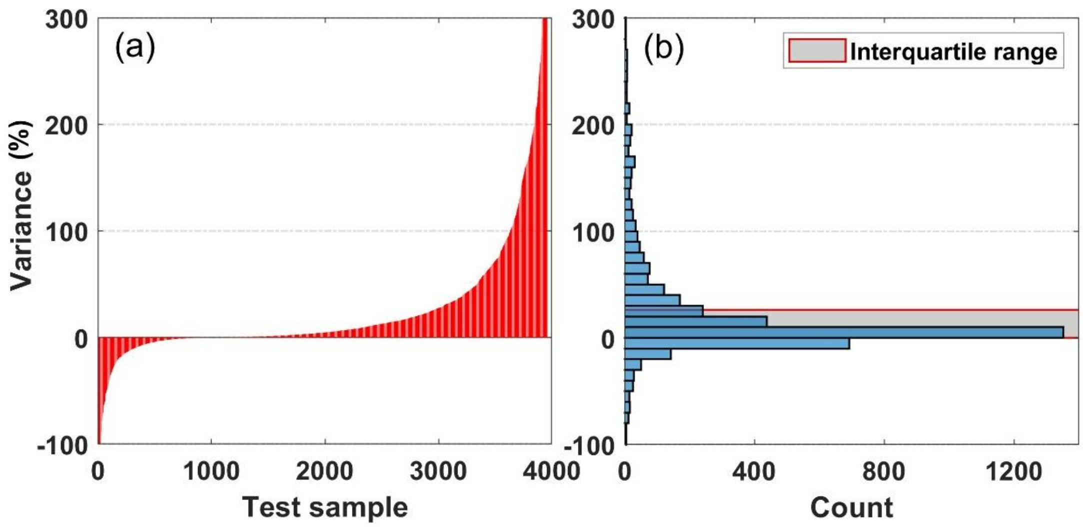

Figure 3. Diagnostic analysis of model uncertainty based on Random Forest (RF) prediction variance. (a) Prediction variance for each test sample derived from the RF ensemble, quantifying individual-level uncertainty. (b) Distribution of prediction variances across all test samples; the interquartile range (IQR) indicates the typical spread of uncertainty, highlighting the proportion of samples with low variance and thus higher prediction confidence.

In the Discussion the authors state clearly that the timeframe to ameliorate climate change effects on many coral reefs is short and rapidly closing. I agree! But I already knew this intuitively and from countless other published studies. I don't see the added value of this analysis to that thesis.

Answer: We appreciate the reviewer's thoughtful perspective and fully recognize the widespread understanding that the timeframe to address climate change impacts on coral reefs is narrowing. However, our study offers novel contributions that go beyond reiterating this general consensus by providing quantitative, spatially and temporally explicit evidence that refines this understanding in actionable terms.

First, by integrating a multivariate Random Forest model trained on nearly 35,000 field observations with projections from CMIP6 ensemble climate models, we identify a critical annual bleaching threshold of 7.9%—a tipping point beyond which coral reef decline becomes significantly more likely. This threshold provides a measurable benchmark that is both statistically derived and ecologically meaningful, which is rarely quantified in prior global assessments. It enables direct translation of model outputs into risk-based coral reef management targets.

Second, our analysis pinpoints when and where coral reefs are projected to exceed this critical bleaching threshold under different emissions scenarios, providing high-resolution spatiotemporal forecasts of vulnerability. For example, our projections show that even under SSP1-2.6, some coral regions will surpass the degradation threshold by mid-century, underscoring the need for both urgent mitigation and targeted adaptation.

Third, we show that the persistence of bleaching—rather than individual extreme events—is the key driver of long-term coral loss, and we back this with a mechanistic connection between modeled bleaching rates and observed coral cover decline across 10 global regions. This finding bridges a major gap in previous work by offering not just the existence of a threat, but a model-based diagnostic framework to quantify and anticipate ecological tipping points.

In summary, while the urgency of climate action for coral reef protection is well established, our study adds significant value by providing a predictive, threshold-based, and regionally differentiated framework for understanding coral reef trajectories. These insights offer concrete metrics and decision-relevant projections for policymakers, enabling prioritization of interventions both temporally and geographically. We believe this rigorously derived, actionable perspective advances the discourse on coral reef conservation under climate change.

Many studies have made predictions about changes in both OA and irradiance as a result of climate change. The data are out there and these factors lower the thermal threshold for coral bleaching and changes in these factors also co-occur with thermal stress. The model presented has very little ecological realism and as the authors state the predictions are likely to be conservative. Nothing new here unfortunately, but the authors do recognize the shortcomings of the analysis presented.

Answer: Thanks for your comments. Our primary objective was to assess the contribution of temperature-related variables to coral bleaching risk and to project future trends under different emission scenarios. We acknowledge that other environmental stressors—such as ocean acidification (OA) and changes in irradiance—play roles in lowering the thermal threshold for coral bleaching, and these factors often co-occur with thermal stress.

While we recognize that data on OA and irradiance projections do exist, incorporating them into a global predictive framework requires spatially and temporally consistent, high-resolution projections aligned with the emissions scenarios we employed (e.g., SSP1–2.6, SSP2–4.5, SSP5–8.5). Such scenario-consistent, reef-scale global datasets for OA and irradiance are not yet readily available with the same resolution and reliability as thermal metrics derived from CMIP6 models. Therefore, to maintain methodological consistency and avoid introducing poorly constrained inputs, we limited our model to the most robust and widely validated drivers available—primarily thermal and geospatial predictors.

As emphasized in the revised Discussion (Page 8, Lines 244–261), we explicitly acknowledge the role of additional stressors—including OA, irradiance, salinity, and sedimentation—and highlight how their interactions with temperature can exacerbate coral vulnerability. Furthermore, we have cited recent literature on solar radiation and pH variability to emphasize that our predictions likely represent a lower bound on future bleaching risk. This acknowledgment is a deliberate and transparent part of our analysis, reinforcing that our threshold-based projections are conservative by design.

"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 spatiotemporal heterogeneity in coral bleaching, depending on the intensity of thermal-stress events, geographic location[17], habitat complexity, coral species composition[37], historical conditions38, and regional influences[39]. "

Importantly, our contribution lies not just in reiterating that corals are at risk, but in offering a quantitative, threshold-based framework that connects thermal anomalies to a critical tipping point in coral cover decline. This is a significant step forward in operationalizing climate risk for coral reef managers and policy advisors. By establishing a 7.9% annual bleaching threshold and mapping its exceedance under multiple emission scenarios, our study provides a tool for prioritizing conservation responses and evaluating the sufficiency of proposed mitigation pathways.

We recognize that further improving ecological realism in global coral bleaching models requires integration of more multifactorial drivers, and we view this as a key direction for future research. Our approach, by clearly delineating both the strengths and limitations of thermal-based prediction, lays a transparent foundation for such advancement.

Reviewer #2 (Remarks to the Author):

This study developed a multivariate model to test bleaching intensity under various climate scenarios and identify critical bleaching thresholds. In the era of significant global warming and increased frequency of bleaching events, this type of study is both relevant and timely. The authors thoroughly analyzed the historical data and bleaching intensity across regions, highlighting a grim future for coral reefs worldwide, even under the lowest emission scenarios. The manuscript is well-written and easy to follow. Overall, it was a pleasure to read and review this manuscript.

General comments:

My major comment concerns the composition of the Results section, which seems to mix methods, results, and discussion. I suggest that the authors consider rewriting the results accordingly. For *example, lines 78-86 are methods, while lines 94-96 belong in the discussion. Lines 136-138 and 145-147 also belong to the discussion.*

Answer: Thanks for your comments. We have carefully revised the Results section to ensure a clearer separation between methods, results, and discussion. Specifically, the methodological content originally included in Lines 78–86 has now been moved to the Methods section (see revised manuscript, Page 11, Lines 391–395).

"Initially, a total of 32 environmental indicators were compiled, including sea surface temperature anomalies, thermal stress metrics, and geographic features (Table S2). 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, … "

Taking into account the suggestions provided by several reviewers, we have refined the wording in Lines 145–147 to improve clarity and accuracy. The updated version can be found in the revised manuscript (Page 4, Lines 143–146):

"…, 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). "

Regarding the content in Lines 94–96 and 136–138, we recognize that these sentences contain brief interpretative remarks. However, they are directly tied to the presentation of results and serve to contextualize and clarify the empirical findings rather than initiate broader discussion. As such, we consider them necessary for guiding the reader's understanding of the data and believe that moving them to the Discussion section would interrupt the logical flow of the results. Therefore, we have retained these explanatory statements within the Results section to maintain clarity and narrative coherence.

Lines 163-164: It would be beneficial to highlight the regions that experience bleaching despite efforts to reduce greenhouse gas emissions. This information is intertwined with the results of medium emission scenarios, making it difficult to follow. I would recommend either combining the low and medium scenarios into one paragraph or separating them entirely.

Answer: Thanks for your comments. In the original manuscript, we indeed discussed the low- and medium-emission scenarios in separate paragraphs to allow a clearer comparison between the two pathways. However, we realize that the phrase "in both time periods (Figure 4a–b)" may have caused confusion—it refers to the two future time periods (2020–2060 and 2060–2100), not to the emission scenarios. We have revised the phrasing for clarity in the revised manuscript (Page 5, Lines 159–166).

"These projections, based on CMIP6 data, cover two time periods: 2020–2060 and 2060–2100 (Figure 4 and Figure S6). 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 (Figure 4a-b). Correspondingly, in these two regions, the projected coral degradation rate over the 40-year periods remains below zero (Figure S7), indicating no significant degradation.

In the medium emission scenario (SSP2-4.5), which reflects moderate emission reductions and moderate levels of global warming, …"

Lines 177-179: belong to discussion

Answer: Thanks for your comments. We have moved the interpretative content to a more appropriate place within the Discussion section, as suggested. Please refer to the revised manuscript (Page 7, Lines 218–222).

"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 (Figure S7)."

Lines 196-198: belong to discussion

Answer: Thanks for your comments. This sentence offers a brief speculative explanation for the observed delayed bleaching response in coral reefs of the Red Sea and the Persian Gulf. As it directly relates to the empirical findings presented in the Results section, we consider it a necessary clarification rather than an interpretive discussion. Furthermore, we have provided a more comprehensive discussion of coral thermal tolerance mechanisms later in the Discussion section. For this reason, we have not relocated this sentence.

Lines 215-220: sound like conclusions

Answer: Thanks for your comments. To improve the logical flow and avoid redundancy, we have removed these lines and integrated their key insights into the concluding paragraph. This ensures a clearer distinction between results and conclusions, while preserving the emphasis on the long-term implications of escalating bleaching risk under various climate scenarios. Please refer to the revised manuscript (Page 9, Lines 302–314).

"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."

This is merely a suggestion for enhancing the study's scope. It seems pertinent to include analyses across depth concerning the significant focus of reef research—the role of blue mesophotic areas *as refugia. Examining bleaching intensity across depth is particularly relevant given the observed inconsistencies in bleaching between shallow and deeper reefs (e.g., Chagos archipelago, Diaz et al. 2023). I believe that incorporating such analyses would be very relevant and would enhance the paper's impact.*

Answer: Thanks for your comments. We agree that depth-related variation in bleaching responses—particularly the potential role of mesophotic coral ecosystems as thermal refugia—is an important and growing focus in coral reef research. In our study, depth was included as one of the predictor variables in the multivariate model. As shown in the revised manuscript (Fig. 1a), depth exhibited a notable contribution to the model's predictive performance, underscoring its relevance to coral bleaching patterns. We have explicitly described this point in the manuscript (Page 3, Lines 94–97).

"Notably, geographic locations and water depth, also exhibited considerable significance (Figure 1a). This suggests that coral bleaching responses can vary dramatically across regions, even under similar climatic conditions."

Lines 275-276: Please insert appropriate reference here.

Answer: Thanks for your comments. We have added the appropriate reference at the indicated location:

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. Global Change Biology 11, 2251-2265 (2005). https://doi.org/https://doi.org/10.1111/j.1365-2486.2005.01073.x

Figures:
The figures are clear and easy to read, but I have a few minor comments about the labeling of the axes and the legend.
Figure 1b: It would be great to maintain consistency in the terminology used – while the figure caption states predicted versus observed, the axes indicate estimated and ground truth. Please adhere to one choice of words.

Answer: Thanks for your comments. We have revised the figure caption to match the axis labels used in the plot.

Figure 4: The labels on the y-axis should be corrected from, for example, panels a and b: ssp 126 to SSP 1-2.6, and in the same manner for panels c-f.

Answer: Thanks for your comments. We have revised it as suggested.

Figure 5: Kindly refer to my comment for Figure 4 and adjust the legend accordingly.

Answer: Thanks for your comments. We have revised it as suggested.

Supplementary Information:
Please include references for the cited literature and consider exchanging Figures S2 and S3 –see my comment below.

Answer: Thanks for your comments. We have addressed the issues you raised as follows:

(1) References cited in the Supplementary Information have now been properly listed at the end of the Supplementary file.

(2) Regarding the suggestion to switch Figures S2 and S3, we have followed your recommendation and adjusted the order accordingly to improve the logical flow and clarity of presentation.

Minor comments:

Lines 31-32: It would be helpful to clarify what differentiates mass coral bleaching events from regular bleaching events in one sentence. Are mass bleaching events synonymous with global bleaching events, or are they more regionally focused?

Answer: Thanks for your comments. Mass bleaching events are broadly synonymous with global bleaching events, as they are typically driven by large-scale climate anomalies. To improve clarity, we have revised the sentence. Please refer to the revised manuscript (Page 1, Lines 31–33).

"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]."

Lines 34-35: Could the cited reference [6], Veron et al. (2009), possibly be a typo? I assume so because it is not the primary reference and does not provide information regarding a 15% global coral loss.

Answer: Thanks for your comments. You are correct that Veron et al. (2009) is not the primary source for the global coral loss estimate. As this reference is also relatively dated, we have traced the original source and replaced it with a more recent and authoritative assessment:

Souter, D., Planes, S., Wicquart, J., Logan, M., Obura, D., Staub, F. (eds). Status of coral reefs of the world: 2020 report. Global Coral Reef Monitoring Network (GCRMN) and International Coral Reef Initiative (ICRI) (2021). DOI: 10.59387/WOTJ9184

This updated reference has been incorporated into the revised manuscript.

Lines 89 and 102: Why does figure S3 appear in the text before figure S2?

Answer: Thanks for your comments. In the original manuscript, Figure S2 appeared for the first time before Figure S3; however, the instance you referred to was the second mention of Figure S2. To avoid confusion, we have revised the text accordingly and also rechecked the entire manuscript. The order of figures in the Supplementary Information has now been adjusted to ensure consistency with their first appearance in the main text.

Refer to the Supplementary Table here (Lines 134- 136).

Answer: Thanks for your comments. We have added a reference to Supplementary Table S3 at the appropriate location in the revised manuscript (Page 4, Line 131).

"…we further examined the relationship between the average coral bleaching rate and the average decline rate of coral reefs across 10 global regions (Figure 3a, b, Table S3)."

Lines 141-145: Think about rephrasing this sentence for better clarity.

Answer: Thanks for your comments. We have conducted an additional analysis excluding South Asia as a potential outlier and revised the sentence accordingly to improve clarity. Please see the revised manuscript on Page 4, Lines 136–146.

"Standard regression diagnostics (Figure S5) 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 (Figure 3b, $R^2 = 0.6$, p-value = 0.01). This indicates a consistent trend of coral degradation linked to increased bleaching and unveiled a critical threshold: annual bleaching rates exceeding 7.9% (95% CI: 7.6–9.3%) were associated with significant coral degradation represented the annual average bleaching rate at which the decline rate is zero."

Line 161-163: Please consider revising this sentence.

Answer: Thanks for your comments. We have revised the text for improved clarity and grammatical correctness. Please see the updated version in the revised manuscript on Page 5, Lines 160–162.

"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."

Line 184: What does "we counted coral bleaching" refer to?

Answer: Thanks for your comments. The sentence refers to our quantification of predicted coral bleaching occurrences in ten global regions based on model outputs (shown in Figure 4). To improve clarity, we have revised the wording in the manuscript accordingly. Please see the updated version in the revised manuscript (Page 6, Lines 186–188).

"We also quantified the proportion of coral reef areas projected to experience annual bleaching across ten global regions (Figure 3a) for the periods 2020–2060 and 2060–2100 under the three climate scenarios (Figure 5)."

Methods: Please indicate which software was used for analyses.

Answer: Thanks for your comments. The multivariate modeling and data analyses were performed using MATLAB (MathWorks, USA). We have added this information in the appropriate section of the Methods. Please refer to the revised manuscript (Page 11, Lines 399–401).

"All data processing, statistical analyses, and model development were performed using MATLAB R2022b (MathWorks, USA)."

Reviewer #3 (Remarks to the Author):

This work uses a Random Forest approach to identify which of a range of variables related to temperature stress exposure and other physical oceanographic parameters best predict observed bleaching in a global dataset, and then uses this model to perform hindcasts and forecasts of bleaching. The main finding of the study was that bleaching of 7.9 % annually is the critical point above which coral reefs will decline, but below which they will not. Overall the study was well done and well written, and it seems a good fit for Communications Earth and Environment. My detailed comments are:

- *The frame of reference used for expression of percent bleaching or percent coral loss is not defined. Is this relative to the total area of benthic substrate, or to then total area of live coral? Please make this clear when a value of percent bleaching or coral loss is first stated in the manuscript.*

> **Answer:** Thanks for your comments. In our study, coral bleaching is expressed as the percentage of bleached coral colonies relative to the total number of colonies surveyed at a given site. Coral loss refers to the decline in live coral cover area relative to the total benthic area in a given region. We have revised the manuscript to include these clarifications (see Page 10, Lines 324-328 and 338-340).
>
> "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. This allows for comparative analyses and the determination of geographical bleaching thresholds."
>
> "Coral decline, as defined in this context, refers to the reduction in live coral cover as a percentage of the total benthic substrate area in the region assessed."

- *Line 70: cite reference for 'a degree of resilience'*

> **Answer:** As suggested, we have added an appropriate reference to support the statement regarding the resilience of coral reefs (see revised manuscript, Page 2, Line 70):
>
> Lachs, L. et al. Emergent increase in coral thermal tolerance reduces mass bleaching under climate change. Nature Communications 14, 4939 (2023). https://doi.org/10.1038/s41467-023-40601-6

- *Line 123-125: 'The global assessment of annual average bleaching, based on our multivariate data-driven model, fills the gaps left by the ... field survey data': this is an overstatement. Your approach is a model only, and cannot fill the gaps left by field surveys - only additional acquisition of field data can do that. It would be more factual to state here that '...our multivariate data driven model has created projections of expected bleaching that cover the spatial and temporal gaps left by the field survey dataset'.*

> **Answer:** Thanks for your comments. We agree with your point that model-based projections cannot replace empirical field data. We have revised the sentence accordingly to better reflect the scope and limitation of our approach (see revised manuscript Page 4, Lines 121-123).

“Our multivariate data-driven model has created projections of expected bleaching that cover the spatial and temporal gaps left by the field survey dataset.”

- Line 141-145: This latter half of this sentence needs attention to its grammar - it does not completely make sense at the moment.

Answer: Thanks for your comments. We agree that the original sentence was not clearly structured and included a grammatical error. We have revised the sentence to clarify the relationship between bleaching rates and coral degradation and to clearly define the critical threshold. Please see the revised version on Page 4, Lines 140–146 of the manuscript.

“After excluding this outlier, a significant positive linear correlation emerged between the average annual bleaching rate and the coral decline rate globally (Figure 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).”

The section titled "Future bleaching projections under SSP scenarios" (lines 156-220): Throughout this section, both the Geographic regions formally defined in Figure 3, and geographic regions that are common knowledge but not formally defined in Figure 3 (such as "south Pacific" and "equatorial Pacific" are used - some geographic areas within both classifications overlap and some do not. The use of two different Geographic classification schemes within one section is confusing. I suggest that you separate this section into two sections, with separate section headings for each: a first section containing the content that uses the common-knowledge geographic regions, and a second section containing the content that uses the Figure 3 geographic classification.

Answer: Thanks for your suggestion. The geographic regions formally defined in Figure 3 were used to quantify regional coral decline rates. In contrast, general geographic terms such as "South Pacific" and "Equatorial Pacific" were employed to qualitatively describe projected global bleaching patterns shown in Figures 2 and 4 of the manuscript.

To avoid confusion, we carefully reviewed the manuscript and have ensured that references to specific regions are accompanied by clear figure citations, indicating whether the classification is formal (based on Figure 3) or general.

Line 228: 'warming': what level of warming?

Answer: In the revised manuscript, we have specified that the projected global annual bleaching extent exceeding 10% refers to outcomes across all three emission scenarios (SSP1-2.6, SSP2-4.5, and SSP5-8.5). While the severity and spatial extent of bleaching vary among these scenarios, this threshold is consistently exceeded, particularly in the absence of increased coral thermal tolerance. Please see the revised text on Page 7, Lines 225–230 for the updated clarification.

“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, with an average annual extent exceeding 10%. This level exceeding the range of bleaching thresholds that would lead to significant coral decline."

Line 229: ' a general global bleaching': grammatically incorrect and does not fully make sense as written.

Answer: We have revised the sentence to improve clarity and grammar. As addressed in our previous response, we now clarify that the projected annual average bleaching extent exceeding 10% refers to results under all three emission scenarios, and the phrase "general global bleaching" has been replaced with a more precise and grammatically correct expression. Please refer to the revised text on Page 7, Lines 225–230 for the updated clarification.

"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, with an average annual extent exceeding 10%. This level exceeding the range of bleaching thresholds that would lead to significant coral decline."

Line 248: It seems narrow-focused to single out 'Sterol availability and biosynthetic pathways' here: there are a range of other physiological factors that influence the coral-algae mutualism. Either list most of them here, or choose remove 'Sterol availability and biosynthetic pathways' and choose more general terms to refer to the full range of factors involved.

Answer: Thanks for your suggestion. The original sentence aimed to provide a specific example following the broader statement on coral performance under novel physicochemical conditions (e.g., pH, salinity, sedimentation). However, we acknowledge that focusing solely on sterol metabolism may appear too narrow. To address this, we have revised the sentence to reflect a wider range of physiological and biochemical factors influencing the coral–algae mutualism. Please refer to the revised text on Page 8, Lines 248–250.

"Multiple physiological and biochemical factors in algal endosymbionts influence the stability and efficiency of their mutualistic relationship with coral hosts[36]."

Line 255: Provide a reference at the end of the sentence ending on this line.

Answer: We have added an appropriate reference at the end of the sentence to support the statement.

Rowan, R. Thermal adaptation in reef coral symbionts. *Nature* **430**, 742-742 (2004). https://doi.org/10.1038/430742a

Line 270: '10-30 years to recover' following what?

Answer: The original statement was mainly based on the following reference:

Baker, A. C., Glynn, P. W., & Riegl, B. (2008). Climate change and coral reef bleaching: An ecological assessment of long-term impacts, recovery trends and future outlook. Estuarine, Coastal and Shelf Science, 80(4), 435–471. https://doi.org/10.1016/j.ecss.2008.09.003

We have revised the sentence to reflect the variability and uncertainty in reef recovery times.

The updated version uses more general terms to avoid an overly specific numerical range. Please see the revised text on Page 8, Lines 270-274.

"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."

Line 282-298: No lines of investigation with regard to MPAs are presented in this paper. Therefore, I would remove this paragraph above MPAs, as it is only reviewing information that is of indirect relevance to the main themes of the paper.

Answer: Thanks for your comments. We agree that this paragraph does not present new investigations into MPAs. However, one of the aims of this study is to identify potential climate refugia for coral reefs. In this context, MPAs remain relevant as they are a key conservation strategy often implemented in areas identified as refugia. Therefore, we retained this discussion as part of our broader consideration of management implications under future climate scenarios.

To clarify the relevance of this paragraph to the overall theme of the manuscript, we added a sentence at the beginning of the paragraph to explicitly link it to the climate refugia discussion. In the revised manuscript, we have added a brief introductory sentence to the paragraph to explicitly state its connection to the paper's main themes. This addition clarifies the relevance of MPAs in the context of climate refugia and reinforces how localized interventions complement global mitigation efforts in safeguarding coral reefs. Additionally, we have streamlined the paragraph to focus more directly on the synergy between MPA planning and thermal refugia projections, ensuring a tighter alignment with the paper's overall goals. Please see the revised text on Page 9, Lines 286–295.

"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…"

Lines 315-322: Sentences are fragments, please revise.

Answer: Thanks for your comments. In the revised version, we have restructured the sentences to ensure they are syntactically complete and convey the intended meaning more effectively. Please see the revised text on Page 10, Lines 322–330.

"The coral bleaching datasets are derived from the Global Coral-Bleaching Database, which encompassing 34,846 coral bleaching records from 14,405 sites in 93 countries, over 40 years, from 1980–2020 (Figure S1)[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. 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….”

Line 337: Where did the variables turbidity, windspeed, cyclone frequency come from?

Answer: The turbidity data were obtained from NASA's Earth Observing System Data and Information System (EOSDIS), specifically the MODIS-Aqua satellite database at a 4-km spatial resolution (https://oceandata.sci.gsfc.nasa.gov/MODIS-Aqua/Mapped/Monthly/4km/Kd_490/). Wind speed data were sourced from the Coral Reef Temperature Anomaly Database (CoRTAD version 6). 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.

We have added the relevant data source descriptions to the revised manuscript (see Page 12, Lines 330–356) accordingly. Additionally, a detailed overview of these environmental variables can be found in the coral bleaching database by van Woesik and Kratochwill (2022):

van Woesik, R. & Kratochwill, C. A global coral-bleaching database, 1980–2020. Scientific Data, 9, 20 (2022). https://doi.org/10.1038/s41597-022-01121-y.

“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…. In addition, the CoRTAD includes ancillary marine wind speed data.”

Line 340: State here that "we focus... on three Shared Socioeconomic Pathways (SSP)" and in the following line (341) state that '(1) SSP1-2.6, which is a remake of Representative Concentration Pathway (RCP) 2.6' etc.

Answer: Thanks for your suggestion. We have revised it. Please see the revised text on Page 10, Lines 359.

“…and here we focus on the projected temperature-related variables from three Shared Socioeconomic Pathways (SSP) emission scenarios…”

Figure S1: How were the values in each dot calculated? Are they values for bleaching averaged at a particular 1 x 1 degree grid cell over the entire 40 year period, or something different?

Answer: The values shown in Figure S1 represent individual coral bleaching records from field surveys conducted over 40 years (1980–2020), rather than spatially averaged data within 1° × 1° grid cells. Each dot corresponds to a specific observation recorded at a unique survey site and time. These 34,846 records, spanning 14,405 sites in 93 countries, are directly derived from the global coral bleaching database developed by van Woesik and Kratochwill (2022). We have revised the caption of Figure S1 to clarify this point.

Please see the updated legend for Figure S1 and refer to the database:

van Woesik, R. & Kratochwill, C. A global coral-bleaching database, 1980–2020. Scientific Data 9, 20 (2022). https://doi.org/10.1038/s41597-022-01121-y.

Line 271: 'highly conservative' meaning what in this context?

Answer: In this context, "highly conservative" means that our projections may underestimate the full extent of coral reef degradation, because the model primarily focuses on thermal stress as the driving factor. Other important stressors such as pollution, physical damage, and biological competition were not included in the model. Therefore, our results represent a minimum estimate of potential future coral bleaching and degradation. We have revised the text to clarify this point. Please see the updated sentence on Page 10, Lines 270–272.

"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."

Statement:

We would like to sincerely thank the editor and reviewers for their thoughtful and constructive feedback, as well as for their recognition of our revised manuscript. We have carefully addressed each comment point by point. Where appropriate, we have revised the manuscript accordingly and provided detailed justifications or clarifications in our responses. All changes in the revised manuscript are highlighted in red. Detailed responses to individual reviewer comments are provided in the following pages. **Please find our answers to comments in normal font and the changes to the original text in blue.**

REVIEWERS' COMMENTS:
Reviewer #2 (Remarks to the Author):
Thank you for your thoughtful revisions. I am overall satisfied with your responses and the current version of the manuscript. Just two minor grammatical issues remain:
L275: Please add "to" between "need" and "increase."

Answer: Thanks for your suggestion. We have revised it.

L323: "encompasses" should be used instead of the current form.

Answer: Thanks for your suggestion. We have revised it.

Otherwise, everything looks good.

Answer: We appreciate the recognition that the manuscript is in good shape after the revisions.

Reviewer #3 (Remarks to the Author):

I felt that the authors have mostly addressed the comments of the three reviewers, which has improved the manuscript. There were a few author responses to review comments that I feel need additional attention:
Regarding Reviewer 1's comment: 'In the Global Coral Bleaching Assessment section, the authors suggest that the Caribbean, and other locations, are resilient because of variability in the impacts of environmental stressors. I think it would also be essential to consider changes in the coral community as a result of previous bleaching events, i.e., winners vs. losers.'
The authors, in their response document, acknowledge that 'such shifts can provide an ecological explanation for the apparent regional resilience observed in areas like the Caribbean and the Coral Triangle.' However, their updated manuscript does not actually explicitly acknowledge this possibility. Secondly, I doubt that the loss of sensitive coral species due to repeated bleaching events is the cause of Coral Triangle resilience as this area has had a reputation for not bleaching often, limiting the number of events during which loss of sensitive species would likely occur - see the work of Joan Kleypas (https://onlinelibrary.wiley.com/doi/10.1111/gcb.12881).

Answer: We sincerely appreciate your positive assessment of our revision. Regarding the ecological explanation of “winners versus losers,” our intention was only to acknowledge this as a possible mechanism: shifts in coral community composition following repeated bleaching events can, in some cases, partly explain the apparent resilience observed, such as in the Seychelles Islands (Graham, Wilson et al., 2024). However, as you point out, for regions like the Caribbean and the Coral Triangle there is a lack of conclusive data to support this hypothesis, and the evidence presented by Kleypas (2015) suggests that repeated bleaching-driven species loss may not be a primary factor in the Coral Triangle, given its relatively limited bleaching history. For these reasons, we deliberately avoided presenting this as a confirmed explanation in the manuscript. We agree that the causes of regional coral resilience require a comprehensive analysis that integrates both environmental drivers and biological processes, and this remains an important avenue for future research.

Graham, N. A. J., et al. (2024). Increased resilience and a regime shift reversal through repeat mass coral bleaching. Ecology Letters, 27(12): e14454.

Kleypas, J. A., et al. (2015). "The impact of ENSO on coral heat stress in the western equatorial Pacific." Global Change Biology 21(7): 2525–2539.

Regarding Reviewer 3's first question about the frame of reference used for expression of percent bleaching and percent coral loss, I appreciate that the authors have included additional text to try to clarify the meaning of these terms. However, despite the addition of explanatory text, percent coral bleaching is still cryptic and not explicitly defined. I suggest modifying the explanatory text on percent coral bleaching to say:
"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' or 'bleaching extent' or 'bleaching threshold' in our Results. This allows for comparative analyses and the determination of geographical bleaching thresholds."

Answer: Thank you for your comments. We have revised it as suggested.

I think that further addition text added to define Coral Decline has helped, but I suggest the following modification to make the definition 100% clear:
“Coral decline, as defined in this report[6] and in our study, refers to the reduction in live coral cover as a percentage of the total benthic substrate area in the region assessed.”

Answer: Thank you for your comments. We have revised it as suggested.

Regarding a latter comment of Reviewer 3 ('Line 228: 'warming': what level of warming?'), the authors have included the following revised text in the discussion: "“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, with an average annual extent exceeding 10%. This level exceeding the range of bleaching thresholds that would lead to significant coral decline.”
This updated text is still not 100% clear to me - what future period do all three scenarios consistently exceed 10% bleaching by? 2020-2060 or 2060-2100?

Answer: Thank you for your comments. Under all three emission scenarios (SSP1-2.6, SSP2-4.5, and SSP5-8.5), the average annual bleaching extent consistently exceeds 10% during both future periods, 2020–2060 and 2060–2100. We have clarified this point in the revised manuscript to avoid ambiguity. This clarification has been incorporated into the revised text (Page 7, Lines 228–230).

"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."

Finally, I cannot see a data and code availability statement in the manuscript - where are the raw outputs of the random forest models, and the Matlab code used in the analysis, archived?

Answer: Thank you for your comments. We have now added a data and code availability statement to the revised manuscript.

"**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."
