Projected coral bleaching in response to future sea surface temperature rises and the uncertainties among climate models

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Abstract

We quantitatively evaluated the effects of rising sea surface temperature (SST) on coral bleaching and the uncertainties resulting from differences in global warming projections. To do so, we used monthly SSTs in the 21st century obtained from 23 climate models under the A1B scenario (from the Special Report on Emissions Scenarios) and SST-based indices for coral bleaching. All of the projections indicated that severe bleaching or death of corals will be common and severe in wide areas of the tropical and subtropical oceans by the middle of

this century. However, decadal oscillation could modify the exact timing by around ±10 years. Such projections are important for conserving marine biodiversity and designing future strategies to avoid tropical and subtropical coral extinction. To obtain more reliable projections and reduce uncertainties, climate models should be improved by using higher spatiotemporal resolutions and more realistic biological indices should be embedded into existing models.

Keywords: Biodiversity, Coral bleaching, Future projection, Global warming, Rise in water temperature, Uncertainty

Introduction

Corals play a fundamental role in primary production and habitat formation for numerous other species in tropical and subtropical oceans. Thus, the degradation of coral habitats can cause fundamental modifications to coastal ecosystems. Although small-scale coral bleaching has been reported for at least 75 years (Yonge & Nichols, 1931), since the early 1980s, mass coral bleaching that might be connected to global climate change has increased rapidly in frequency, intensity, and geographical extent across tropical and subtropical oceans (e.g., Glynn, 1984, 1988, 1991, 1993; Brown, 1997; Hough-Guldberg, 1999, 2011, Nakano, 2004; Hough-Guldberg et al., 2007; Nojima & Okamoto, 2008). The largest such bleaching event, which occurred in 1998, is estimated to have killed 16% of the world's corals, primarily in the western Pacific and Indian Ocean (Wilkinson, 2004; IPCC, 2007b).

Coral bleaching is a general response to stress (Hough-Guldberg, 2011). Corals bleach in response to a range of conditions including sudden changes in light, temperature, and salinity, the presence of toxins, and microbial infections. The causal relationship between sea temperature and mass coral bleaching has been proven empirically (Hough-Guldberg and Smith, 1989; Glynn & D’Croz, 1990) and *in situ* (Brown, 1997; Hough-Guldberg, 1999). Using this causal relationship, mass bleaching events can be predicted with greater than 95% accuracy from satellite measurements of sea surface temperature (SST) anomalies relative to the maximum summer temperatures (e.g., Goreau & Hayes, 1994; Toscano et al., 2000).

Global warming and associated increases in seawater temperatures necessitate urgent precise projections of future coral bleaching and death, not only to conserve marine biodiversity but also to plan for the adaptation of human societies to these changes. Therefore, long-term future projections of the effects of global warming on corals derived from climate models, as well as short-term predictions from satellite SST measurements, are sought as guidelines to design our adaptive measures to climate change and global warming.

Using climate model outputs and simplified indices to express coral bleaching in response to future rises in water temperature, several modeling studies have attempted to project the future probability of coral bleaching and death (e.g., Done et al., 2003; Donner et al., 2005, 2009; Guinotte et al., 2003; Hoegh-Guldberg, 1999, 2005, 2011; Meissner et al., 2012; Sheppard et al., 2003; Tevena et al., 2012; Wooldridge et al., 2005; Yara et al., 2009, 2011, 2012; Frieler et al., 2012). These projected results are all qualitatively identical in that both the frequency and extent of the severe bleaching or death of corals are expected to intensify. Particularly, intermittent high water temperatures, which result in the severe bleaching or death of present-day corals, will appear perpetually in the latter half of the 21st century (e.g., Yara et al., 2009).

However, water temperature is projected differently by climate models with different spatial resolutions, which may generate uncertainties in the results, as discussed by Yara et al. (2009). Moreover, if the climate scenarios and indices used in projections are all different, it is difficult to directly examine the uncertainties underlying such projections. In substance, through the comparison of 23 different climate model outputs, Yara et al. (2011) demonstrated that there exists a high uncertainty in the projected poleward range expansion of coral habitats in response to rising water temperatures. Therefore, we may need to pay special attention to evaluating coral bleaching projections based on climate model water temperature outputs.

In this study, using procedures similar to those of Yara et al. (2011), we quantitatively examine the potential effects of SST increases on coral bleaching, as well as the uncertainties resulting from differences in the SST warming trends identified among models and locations. The following section describes the experimental design of a SST-based index for coral bleaching and the SST datasets of the multiple climate models used in this study. The third section includes the results and discussion of projections of coral bleaching and their uncertainties. The last section draws conclusions based on the results and discussion.

Materials and methods

Simplified index for coral bleaching

The algorithm used with satellite data predicts that coral bleaching starts when a threshold of 1°C above a region’s mean SST during the warmest month is exceeded for more than 4 weeks (e.g., Goreau & Hayes, 1994; Toscano et al., 2000; Hoegh-Guldberg, 2011; Meissner et al., 2012). Several previous studies use Degree Heating Weeks (DHW (°C week)), a product of exposure intensity (°C above threshold) and duration (in weeks), developed by the National Oceanic and Atmospheric Administration (NOAA) Coral Reef Watch Program (Liu et al., 2003) to predict coral bleaching events (NOAA Hotspot Program; Hoegh-Guldberg, 1999; Strong et al., 2000). In this metric, coral bleaching is predicted to occur when DHW > 4, a condition that indicates that the period over which the threshold temperature is exceeded by 1°C lasts for more than 4 weeks. Coral bleaching becomes progressively worse at higher temperatures or for longer periods over which the threshold temperature is exceeded. Severe coral bleaching, which may lead to the extinction of corals, is predicted to occur by this metric when DHW > 8, that is, the period over which the threshold temperature is exceeded by 1°C (2°C) lasts for more than 8 (4) weeks.

However, most climate model outputs are available monthly rather than weekly, and the DHW cannot be applied to these outputs. Alternatively, the Degree Heating Month (DHM (°C month)) metric, derived from the DHW, has been used in modeling studies that only have access to monthly SST outputs (e.g., Donner et al., 2005; Yara et al., 2009; Tevena et al., 2012). By this metric, coral bleaching is predicted to occur when DHM > 1, i.e., the threshold temperature is exceeded by 1°C for more than 1 month. Similarly, severe coral bleaching is predicted to occur when DHM > 2, i.e., the threshold temperature is exceeded by 1°C (2°C) for more than 2 (1) months. The DHM value has proved to be a reasonable proxy for DHW value (Donner et al., 2005). In this study, DHM was used as a simplified index for predicting coral bleaching, basically following the procedure introduced by Yara et al. (2009).

Datasets of modeled water temperatures

We used SST outputs provided by multiple climate model projections from the World Climate Research Programme's (WCRP's) phase 3 of the Coupled Model Intercomparison Project (CMIP3; Meehl et al., 2007), which was performed for the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4; IPCC, 2007a). As noted by Yara et al. (2011), when evaluating projections based on the SST warming trends obtained from the CMIP3 models, it is important to consider the uncertainties in the SST trends.

Monthly mean SSTs from 23 CMIP3 model projections (Table 1; Yara et al., 2011) were used and combined with the DHM metric for coral bleaching projections. The climate models have different ocean models with different spatial resolutions. For example, the horizontal resolutions range from 0.2° to 5°. We employed the "20^{th} century climate in coupled models" (20C3M) simulations from 1980 to 1999 as predicted by the models using the global warming projections under the Special Report on Emissions Scenarios (SRES) A1B scenario, which assumes a future world of rapid economic growth with a balanced emphasis on all energy sources (IPCC, 2007a).

Values obtained by each model may depart from the real values (or the expected values in future projections), which are referred to as the model's biases. Such biases need to be corrected for the period of discussion, which is 2000 through 2099 in this study. We corrected biases in the monthly mean SST in each of the CMIP3 models as follows (Yara et al., 2009, 2011): First, we calculated monthly mean SST anomalies during 2000–2099 (i.e., 1,200 months) under the SRES A1B scenario projection ($SST_{SRESAiB}$) relative to the monthly mean climatology (the 20-year mean SST from 1980 to 1999) of the 20C3M simulation ($\overline{SST_{20C3M}}$). Second, the SST anomaly for each month during 2000–2099 was added to the observed monthly mean climatology (18-year mean SST from 1982 to 1999) of the NOAA Optical Interpolation Sea Surface Temperature (OISST; Reynolds et al. 2007), interpolated to a horizontal grid point in each of the CMIP3 models ($\overline{OISST}$). The modeled SST discussed in this study after the bias correction process described above is expressed as:

$$SST(x,y,t,n) = \underbrace{\overline{OISST}(x,y,t,n)}_{Climatology} + \underbrace{\left\{SST_{SRES\,A1B}(x,y,t,n) - \overline{SST_{20C3M}}(x,y,t,n)\right\}}_{Anomaly}, \qquad (1)$$

where x and y are the number of longitudinal and latitudinal grids in each model, respectively; t is the number of months, from the starting point of future simulations (January 2000) for SST and $SST_{SRESA1B}$, and the corresponding months from January to December for the monthly mean climatology ($\overline{SST_{20C3M}}$ and $\overline{OISST}$); n is the model number in Table 1.

We calculated the bias-corrected monthly mean SST from 23 CMIP3 models (Table 1) during 2000–2099. The CMIP3 multi-model SST outputs combined with the DHM were also compared to one another. This comparison was performed for four tropical/subtropical coral reefs for which coral bleaching has been monitored or projected in previous studies (e.g., Hoegh-Guldberg, 1999, 2011; Yara et al., 2009), the Sekisei Lagoon in the Ryukyu Islands, Japan (124.0°E, 24.3°N); Phuket, Thailand (98.4°E, 7.9°N); the US Virgin Islands in the Caribbean Sea (64.8°W, 18.3°N); and Heron Island, Australia, on the Great Barrier Reef (151.9°E, 23.4°S).

Although projected results are similar using any model outputs, different regional patterns and magnitudes in the SST warming trends of various model outputs lead to uncertainties in the projected results. This is because different models project different responses to the same external forcing as a result of their treatments of physical processes, numerical schemes, and other factors (e.g., Yara et al., 2011; Brown et al., 2012).

To evaluate quantitatively the uncertainties arising from these factors, using the same procedure as that of Yara et al. (2011), we divided the temporal fluctuation in modeled SST in the warmest months in the 21st century into four components: the climatology ($\overline{SST_c}$) obtained by averaging model results from 1980 to 1999, the global warming trend (ΔSST_{gw}), the decadal oscillation (ΔSST_d), and the interannual fluctuation (ΔSST_i). Then, the SST was expressed as the sum of the four temporal components as follows:

$$SST\ (x,y,t,n) = \underbrace{\overline{SST_c}(x,y,t,n)}_{Climatology} + \underbrace{\Delta SST_{gw}(x,y,t,n)}_{Global\ warming\ trend} + \underbrace{\Delta SST_d(x,y,t,n)}_{Decadal\ oscillation} + \underbrace{\Delta SST_i(x,y,t,n)}_{Interannual\ fluctuation}, \quad (2)$$

where x and y are the number of longitudinal and latitudinal grids in each model, respectively; t is the number of months, from the starting point of future simulations (January 2000) for SST, ΔSST_{gw}, ΔSST_d, and ΔSST_i, and the corresponding month from January to December for the monthly mean climatology ($\overline{SST_c}$); n is the model number in Table 1.

Results

The projected frequency of the severe bleaching or death of corals in the four sites from the 2000s to 2090s was obtained using SST outputs from all 23 CMIP3 climate models (Table 1) and DHM (Fig. 1). The frequency of the severe bleaching or death of corals is projected to be as low as zero in the 2000s and 2010s, but is projected to rise thereafter under the SRES A1B scenario.

In Equation (2), ΔSST_{gw} was calculated from the linear trend in monthly mean SST from 2000 to 2099. ΔSST_{d} was the decadal oscillation component generated by the ocean-atmosphere climate system, such as the Pacific Decadal Oscillation, and was defined by a 5-year running mean component of (SST – $\overline{SST_c}$ – ΔSST_{gw}). The remainder (SST – $\overline{SST_c}$ – ΔSST_{gw} – ΔSST_{d}) was regarded as the interannual fluctuation component (ΔSST_{i}), but is not discussed here because we considered the projected effects of global warming and the uncertainties with time scales longer than 10 years in this study. To evaluate the range of uncertainty derived from the decadal oscillation, we calculated the standard deviation of ΔSST_{d} and compared the values of the +2 and -2 standard deviation cases (+2SD and -2SD cases, respectively) to the standard case, which is defined as $\overline{SST_c}$ + ΔSST_{gw}. The difference between the +2SD and -2SD cases indicates the possible range in the timing caused by the decadal oscillation, that is, the uncertainty due to decadal variations in the timing of the continuous severe bleaching or death of corals.

Uncertainties in the projected effects of SST warming on the severe bleaching or death of corals in the four sites were assessed for the warmest months in the CMIP3 multi-model projections (Fig. 2). The simulated results show that the severe bleaching or death of corals tends to start to occur continuously a decade earlier or later in the +2SD and -2SD cases, respectively, compared to the standard case. The time at which the probability of the severe bleaching or death of corals will exceed 50% (i.e., predicted by more than half of the total climate models) for the +2SD and -2SD cases is in the 2070s and 2090s in Sekisei Lagoon, in the 2070s and 2090s in Phuket, in the 2050s and 2090s in the US Virgin Islands, and in the 2080s and later than the 2090s in Heron Island, respectively.

Discussion

Projected coral bleaching and its uncertainties

Most of the climate models predict that extremely high SSTs will appear every year by the end of the 21st century. This means that the severe bleaching or death of corals will be a common and crucial issue over wide areas of tropical and subtropical oceans by the middle of this century, and we will need to take action to mitigate and adapt to global warming to avoid tropical and subtropical coral extinctions. Considering uncertainties in projected results, the difference in the timing of bleaching occurrence between the two cases is 20-40 years, although the timing is different among models, being mostly 10-20 years earlier and later, respectively, than the timing predicted by the standard case at each site. This means that the timing could be modified by around ±10 years by the decadal oscillation, which is the uncertainty relevant to global warming.

Limitations of this study

There are, however, a number of limitations that lead to uncertainties in our model results. Some result from the insufficient spatiotemporal resolution of climate models, whereas others stem from biological indices that are too simplified when combined with climate models.

The temporal and spatial resolutions of the model outputs are monthly and ~100 km, respectively (Table 1). A higher temporal resolution (~weekly) would project bleaching more accurately, as shown by favorable predictions based on DHW (e.g., Liu et al., 2003). A higher spatial resolution is required to reproduce physical processes in coral habitats in shallow coastal areas. Moreover, ocean current patterns are an important factor when considering the existence of corals in coastal areas because ocean currents transport coral eggs and larvae. To reproduce the future distribution of corals under rising water temperature and changing ocean currents with fewer uncertainties, climate models with higher spatial and temporal resolutions are required. Preferable models for such aims include climate models from phase 5 and later of the Coupled Model Intercomparison Project and those that embed the Regional Ocean Modeling System (ROMS), which provide results with high horizontal resolutions (e.g., Gruber et al., 2012).

Although all of these climate models use a set of primitive equations to reproduce physical processes in the ocean, different models tend to have strengths in different areas and at different spatial scales (Brown et al., 2012). Some models reproduce the Kuroshio Current well, whereas others reproduce El Niño-Southern Oscillation (ENSO) events well (e.g. Guilyardi et al., 2009; Brown et al., 2012; Ganachaud et al., 2013). For example, as oceanic conditions are controlled strongly by the Kuroshio Current in the Sekisei Lagoon, coral bleaching in this oceanic domain is expected to be reproduced well by the MIROC3.2_hires (Table 1) which has relative strength in reproducing the Kuroshio Current amongst the climate models. Yet, each model performance will continue to improve in future as climate models are updated. For example, both frequency and duration of ENSO events were reported to be reproduced better in the updated versions of MIROC (Watanabe et al., 2010; Sakamoto et al., 2012).

So far, we have not considered any potential for the thermal adaptation and acclimatization of corals to warming events. However, several previous studies have suggested that coral acclimatization and adaptation to extreme warming events will increase thermal tolerance (e.g., Brown et al., 2002; Castillo & Helmuth, 2005; Teneva et al., 2012;

Guest et al., 2012; Howells et al., 2012; Oliver & Palumbi, 2011; Hoegh-Guldberg et al., 2007; Csaszar et al., 2010; Maynard et al., 2008; Brown & Cossins, 2011; Tsuchiya & Fujita, 2009; Frieler et al., 2012), especially in regions subject to more variable temperature regimes. Such biological responses have the potential to alleviate much of the impact of warming on corals (e.g., Pandolfi et al., 2011). Recently, future projections of coral bleaching in response to global warming have included new, simplified indices of the adaptation of corals to future global warming (Frieler et al., 2012). We will need to further develop new indices of the adaptability of corals to coral bleaching events and embed these into climate models to further reduce the uncertainties and increase the reproducibility of simulated results.

In addition to these emerging insights, we should also pay attention to understanding the responses of coral communities to multiple environmental stressors (e.g., Manzello, 2010). Although there is no doubt that high water temperatures are a major cause of coral bleaching, other factors are also considered to be multiple stressors that can cause coral bleaching simultaneously (e.g., Langdon & Atkinson, 2005; Anthony et al., 2008 and 2011; Meissner et al., 2012; Yara et al., 2012). For example, experiments have shown that exposure to low pH and the saturation state of the mineral carbonate aragonite caused by ocean acidification, another global phenomenon, makes corals more prone to bleaching (Anthony et al., 2011). Other regional and local factors such as destructive fishing, overfishing, siltation, pollution, crown-of-thorns starfish predation, and diseases presumably co-affect future coral bleaching events along with global warming. Improving such biological knowledge, along with improving physical projections as described above, would contribute significantly to projecting the future status of corals.

Acknowledgements

The authors appreciate the helpful comments of two anonymous reviewers. We thank the modeling groups, the Program for Climate Model Diagnosis and Intercomparison (PCMDI), and the WCRP's Working Group on Coupled Modelling (WGCM) for their roles in making the WCRP phase 3 of the Coupled Model Intercomparison Project (CMIP3) multi-model dataset available. Support for this dataset was provided by the Office of Science of the US Department of Energy. This study was supported by the Global Environment Research Fund (S-5 and S-9) of the Ministry of the Environment, Program for Risk Information on Climate Change of Ministry of Education, Culture, Sports, Science and Technology, Japan, and Hokkaido University's Sustainable Low Carbon Society Project.

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Table 1. List of climate models of which monthly mean SSTs are used in this study and the spatial resolution, ocean model and references

Model (Country)	Spatial resolution (longitude×latitude×the number of vertical layer)	Ocean model	References
1. BCCR-BCM2.0 (Norway)	1.5°×0.5-1.5°×35	NBRSC-MICOM1.0	(1)
2. CGCM3.1_T47 (Canada)	1.85°×1.85°×29	CCCMA(OGCM3.1)	(2),(3),(4)
3. CGCM3.1_T63 (Canada)	1.4°×0.94°×29	CCCMA(OGCM3.1)	(2),(3),(4)
4. CNRM-CM3 (France)	2°×0.5-2°×31	OPA8.1	(5),(6)
5. CSIRO-MK3.0 (Australia)	1.88°×0.84°×31	MOM2.2	(7)
6. CSIRO-MK3.5 (Australia)	1.88°×0.84°×31	MOM2.2	(7)
7. GFDL-CM2.0 (USA)	1.0°×0.33-1.0°×50	OM3	(8)
8. GFDL-CM2.1 (USA)	1.0°×0.33-1.0°×50	OM3.1	(8)
9. GISS-AOM (USA)	4°×3°×16	AOM 4×3	(9)
10. GISS-EH (USA)	2°×2°×16	HYCOM	(10)
11. GISS-ER (USA)	5°×4°×13	Russell Ocean	(9),(11)
12. FGOALS-g1.0 (China)	1.0°×1.0°×33	LICOM1.0	(12),(13)
13. INGV-SXG (Italy)	2°×1-2°×31	OPA 8.2	(5)
14. INM-CM3.0 (Russia)	2.5°×2°×33	INM-CM3.0	(14),(15)
15. IPSL-CM4 (France)	2°×1-2°×31	OPA	(5)
16. MIROC3.2_hires (Japan)	0.28°×0.19°×47	COCO3.3	(16)
17. MIROC3.2_medres (Japan)	1.4°×0.5-1.4°×43	COCO3.3	(16)
18. ECHO-G (Germany/Korea)	2.8°×0.5-2.8°×20	HOPE-G	(17)
19.ECHAM5-MPI-OM (Germany)	1.5°×1.5°×40	MPI-OM	(18),(19)
20. MRI-CGCM2.3.2 (Japan)	2.5°×0.5-2.0°×23	MRI-CGCM2.3.2a	(20),(21),(22)
21. NCAR-PCM1 (USA)	1-1.13°×0.27-1°×32	POP1.0	(23),(24)
22. UKMO-HadCM3 (UK)	1.25°×1.25°×20	HadCM3	(25),(26)
23. UKMO-HadGEM1 (UK)	1.0°×0.3-1.0°×40	HadGEM1	(27)

References noted here are: (1) www.bcm.uib.no; (2) Flato & Boer (2001); (3) Kim et al. (2002); (4) Kim et al. (2003); (5) Madec et al. (1998); (6) Salas-Mélia et al. (2005); (7) Gordon et al. (2002); (8) Gnanadesikan et al. (2006); (9) Russell et al. (1995); (10) Bleck (2002); (11) Russell et al. (2000); (12) Yongqiang et al. (2002); (13) Yongqiang et al. (2004); (14) Diansky et al. (2002); (15) Diansky & Volodin (2002); (16) K-1 model developers (2004); (17) Legutke & Maier-Reimer (1999); (18) Haak et al. (2003); (19) Marsland et al. (2003); (20) Yukimoto et al. (2001); (21) Yukimoto et al. (2006a); (22) Yukimoto et al. (2006b); (23) Smith et al. (1995); (24) Washington et al. (2000); (25) Johns et al. (1997); (26)

Gordon et al. (2000); (27) Johns et al. (2006).

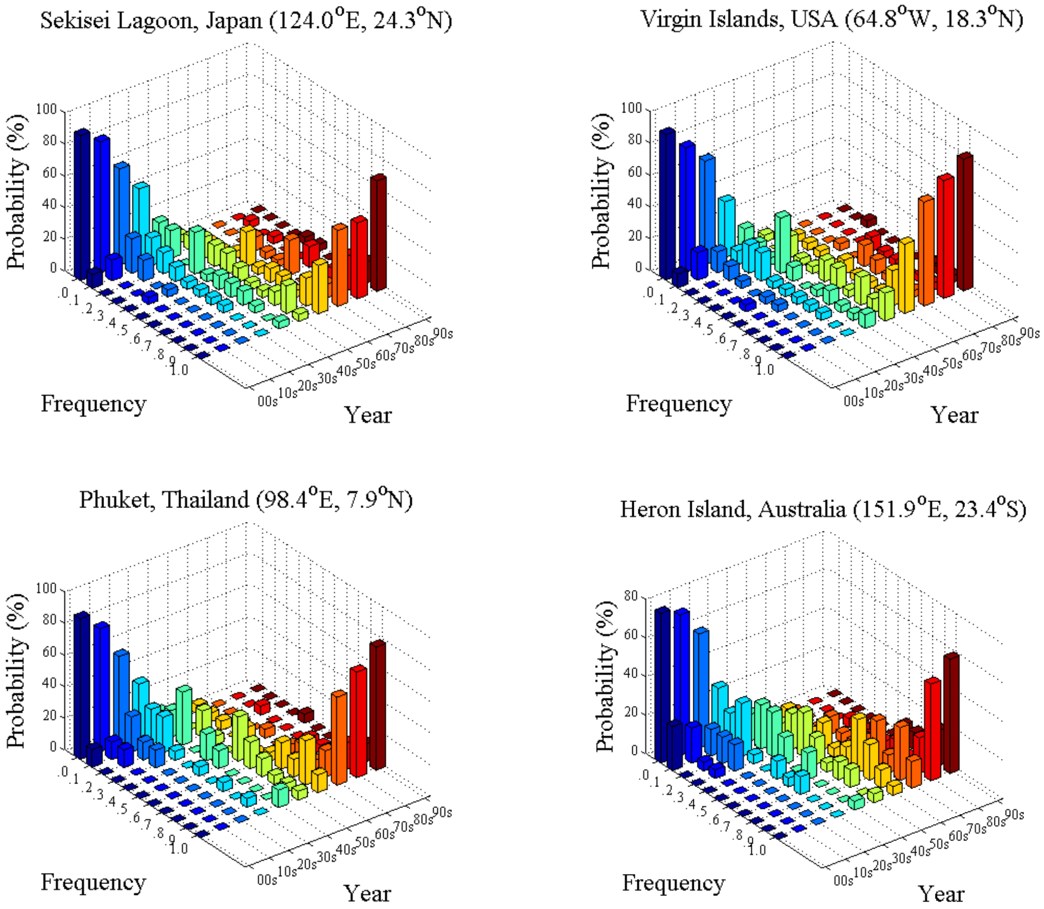

Fig. 1. Projected frequency and probability (%) of high SST that would potentially induce severe coral bleaching or death in Sekisei Lagoon in the Ryukyu Islands, Japan (124.0°E, 24.3°N), Phuket, Thailand (98.4°E, 7.9°N), the US Virgin Islands in the Caribbean Sea (64.8°W, 18.3°N), and Heron Island, Australia, on the Great Barrier Reef (151.9°E, 23.4°S) for the 2000s to the 2090s, obtained using the projected monthly-mean SSTs of multiple climate models and a simplified evaluation metric of Degree Heating Month (DHM). For example, a frequency of 1 or 0.5 indicates that such high SSTs appear every year or five times a decade, respectively. The probability of occurrence of the severe bleaching or death of corals for each frequency in each decade is evaluated by how many climate models predicted the occurrence for each frequency in each decade. For example, the predicted probability of the continuous severe bleaching or death of corals in the 2090s is 70% because 16 of 23 climate models predict this with a frequency of 1 for that decade.

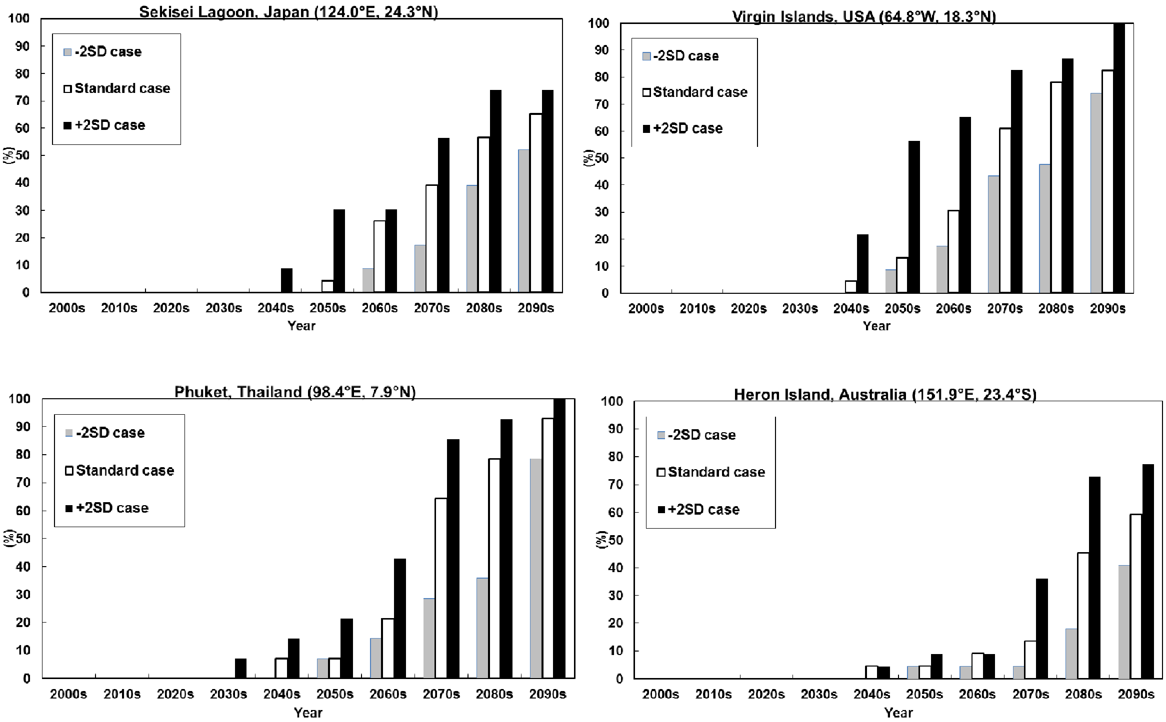

Fig. 2. Cumulative probability (%) distribution of the timing of the continuous severe bleaching or death of corals in Sekisei Lagoon, Phuket, Virgin Islands, and Heron Island for the -2SD case (in gray bars), standard case (in white bars), and +2SD case (in black bars), respectively, from the 2000s through the 2090s, as projected by the climate models. A probability of 50%, for example, indicates that half of the total climate models project the timing of the continuous severe bleaching or death of corals.