Projeto de Lei PL./0077.0/2019

DISPÕE SOBRE A PROIBIÇÃO DE FABRICAÇÃO E COMERCIALIZAÇÃO DE PROTETORES SOLARES COM SUBSTÂNCIAS QUÍMICAS TÓXICAS PARA RECIFES DE CORAIS.

Art. 1º Ficam proibidos o registro, a fabricação, a importação, a exportação, a distribuição, a comercialização, o transporte, o armazenamento e o uso de protetores solares considerados tóxicos para os recifes de corais no âmbito do Estado de Santa Catarina.

§ 1º Para os efeitos desta Lei, são considerados tóxicos para os recifes de corais os protetores solares que contenham os seguintes ingredientes:
I – oxibenzona (BP3);
II – metoxicinamato de octila (EHMC);
III – octocrileno (OC);
IV – 4-metilbenzilideno-cânfora (4MBC);
V – triclosan;
VI – metilparabeno;
VII – etilparabeno;
VIII – propilparabeno;
IX – butilparabeno;
X – benzilparabeno;
XI – fenoxietanol.

§ 2º A critério do órgão ou entidade ambiental competente poderão ser considerados tóxicos, além dos produtos enquadrados no § 1º, protetores solares que contenham outros ingredientes comprovadamente prejudiciais aos recifes de corais.

Art. 2º – O Poder Executivo deverá regulamentar a presente Lei.

Art. 3º – As empresas que fabricam o produto terão o prazo de 180 dias para se adequarem a norma.

Art. 4º – As empresas que comercializam o produto terão o prazo de 365 dias para se adequarem a norma.

Art. 5º Esta lei entra em vigor na data de sua publicação.

Sala das Sessões, em

Deputado Kennedy Nunes

JUSTIFICATIVA

Os recifes de corais são os ecossistemas mais diversos dos mares por concentrarem, globalmente, a maior densidade de biodiversidade marinha.

Os corais construtores de recifes são animais de estrutura simples, pertencentes à classe dos antozoários, filo dos cnidários. Esses animais vivem em enormes colônias fixadas em substrato calcário secretado pelos pólipos, que é como se denominam os indivíduos em sua fase adulta. Os recifes são, portanto, "rochas vivas", pois possuem uma base mineral (o esqueleto calcário), sobre o qual uma colônia viva repousa. A fase larval é livre-natante, denominada "plânula". A vida dos corais construtores é dependente de uma relação simbiótica com microalgas chamadas zooxantelas, que vivem no interior dos seus tecidos e realizam fotossíntese, por meio da qual provêm os nutrientes necessários para a sobrevivência dos corais.

Estima-se que 14 mil toneladas de protetor solar vão parar nos oceanos a cada ano, e desse total, de 4 a 6 mil toneladas se acumulam sobre recifes de corais de todo o planeta, o que demonstra a gravidade do problema, principalmente quando consideramos que as pesquisas mencionadas constataram que pequenas quantidades das substâncias estudadas são tóxicas para os corais.

O mercado jó oferece protetores solares a base de minerais, que tem em sua composição dióxido de titânio e óxido de zinco, são eficazes e não comprometem a saúde humana e nem ajudam a exterminar os recifes de coral.

Uma pesquisa realizada pelo Departamento de Ecologia e Zoologia da UFSC (Universidade Federal de Santa Catarina) comprovou a presença de banco de corais na Reserva Biológica Marinha do Arvoredo, em Florianópolis. Em 2012, mais de 300 colônias de coral-sol da espécie Tubastraea coccinea foram descobertas na Ilha do Arvoredo, dentro da Reserva Biológica Marinha do Arvoredo. Além de Florianópolis, Bombinhas tem 75% do seu território preservado. Pesquisadores afirmam que a região abriga um dos cenários subaquáticos mais interessantes do mundo.

Apresento e peço aos nobres Pares a aprovação deste Projeto de Lei.

EXCELENTÍSSIMO SENHOR PRESIDENTE DA COMISSÃO DE CONSTITUIÇÃO E JUSTIÇA

PEDIDO DE DILIGÊNCIA AO PROJETO DE LEI Nº 0077.0/2019

Trata-se de Projeto de Lei de iniciativa do Deputado Kennedy Nunes, acima identificado, dispondo sobre a proibição de fabricação e comercialização de protetores solares com substâncias químicas tóxicas para recifes de corais.

O texto legislativo está organizado em cinco artigos que, resumidamente: (1) determinam a proibição de registro, fabricação, importação, exportação, distribuição, comercialização, transporte, armazenamento e uso de protetores considerados tóxicos; (2) elencam os ingredientes considerados tóxicos para os recifes de corais; (3) atribuem ao Poder Executivo a regulamentação da Lei; (4) estipulam o prazo de 180 dias para as empresas que fabricam o produto, e de 365 dias para as empresas que o comercializam se adequarem à norma; e (5) determinam a cláusula de vigência.

Nesse contexto, devido à complexidade da matéria, e antes de emitir parecer conclusivo no âmbito deste órgão fracionário, julgo importante possibilitar o pronunciamento da Agência Nacional de Vigilância Sanitária (ANVISA) sobre a proposição legislativa em tela.

Assim sendo, com apoio no inciso XIV do art. 71 do Regimento Interno deste Parlamento, solicito, após ouvidos os membros deste Colegiado, que seja promovida **DILIGÊNCIA** à Agência Nacional de Vigilância Sanitária (ANVISA), órgão vinculado ao Ministério da Saúde e ao Sindicato das Indústrias Químicas e Farmacêuticas do Estado de Santa Catarina (SINQFESC), para que encaminhe a este Parlamento manifestação quanto à iniciativa parlamentar em comento.

Sala das Comissões,

Deputado Fabiano da Luz
Relator

Folha de Votação

A Comissão de Constituição e Justiça, nos termos dos artigos 144, 147 e 148 do Regimento Interno,

☒aprovou ☒unanimidade ☐com emenda(s) ☐aditiva(s) ☐substitutiva global
☐rejeitou ☐maioria ☐sem emenda(s) ☐supressiva(s) ☐modificativa(s)

o RELATÓRIO do(a) Senhor(a) Deputado(a) Fabiano da Luz, referente ao processo PL./0077.0/2019, constante da(s) folha(s) número(s) 06.

OBS: Requerimento de diligenciamento.

ABSTENÇÃO	VOTO FAVORÁVEL	VOTO CONTRÁRIO
Dep. Romildo Titon	Dep. Romildo Titon	Dep. Romildo Titon
Dep. Coronel Mocellin	Dep. Coronel Mocellin	Dep. Coronel Mocellin
Dep. Fabiano da Luz	Dep. Fabiano da Luz	Dep. Fabiano da Luz
Dep. Ivan Naatz	Dep. Ivan Naatz	Dep. Ivan Naatz
Dep. João Amin	Dep. João Amin	Dep. João Amin
Dep. Luiz Fernando Vampiro	Dep. Luiz Fernando Vampiro	Dep. Luiz Fernando Vampiro
Dep. Maurício Eskudlark	Dep. Maurício Eskudlark	Dep. Maurício Eskudlark
Dep. Milton Hobus	Dep. Milton Hobus	Dep. Milton Hobus
Dep. Paulinha	Dep. Paulinha	Dep. Paulinha

Despacho: dê-se o prosseguimento regimental.

Sala da Comissão, 09 de julho de 2019

Dep. Romildo Titon

SINDICATO DAS INDÚSTRIAS QUÍMICAS E FARMACÊUTICAS
DO ESTADO DE SANTA CATARINA

PL/077/19
Dilig

Joinville(SC), 24 de julho de 2019

Lido no Expediente
819 Sessão de 11/09/19
Anexar a(o) PL/077/19
Diligência
Secretário

Exmo. Sr.

Deputado FABIANO DA LUZ

Relator do Projeto de Lei nº 0077.0/2019

Assembléia Legislativa do Estado de Santa Catarina

Florianópolis – SC

Ref. – Resposta ao Ofício GPS/DL/0633/2019 datado de 09.07.2019

Senhor Relator:

Esta entidade sindical, representante das indústrias químicas e farmacêuticas de nosso Estado, dentre elas as indústrias de cosméticos e em especial as que produzem e comercializam protetores solares, VEM, em atenção ao ofício acima referenciado, manifestar-se sobre o conteúdo, riscos e consequências do Projeto de Lei nº PL/0077.0/2019 de autoria do nobre Deputado Kennedy Nunes, <u>que tem por objetivo principal a proibição de fabricação e comercialização de protetores solares com substâncias químicas tóxicas para recifes de corais</u>, cujo projeto, se transformado em Lei, trará, indiscutivelmente aos consumidores de tais protetores solares, em especial os trabalhadores, que desempenham suas funções ao ar livre, como por exemplo os da agricultura, construção civil e outros, que por recomendações médicas, são obrigados a utilizarem ditos protetores, com vistas a se prevenirem contra o câncer de pele, que tem se alastrado de maneira significativa em face dos raios ultravioletas, que aumentam a incidência de câncer de pele, na população brasileira,

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Fone: 47 3461-3333 E-mail: sindicatos.secretaria@acij.com.br

acarretando aumento dos gastos do governo com a saúde pública e do próprio consumidor.

Além disso, merece também ser destacado, que significativo numero de trabalhadores das indústrias de tais produtos, serão prejudicados de forma direta, se tal proibição, assim ocorrer, pois, além do aumento do custo de produção de tais protetores solares, sem os ingredientes citados no projeto de lei, exigirá estudos e licenciamentos juntos aos órgãos competentes, longo tempo, para a devida apreciação, o que tem levado em média mais de 2(dois) anos, para a liberação de produção e comercialização desses produtos, com novas formulas.

Merece, ainda, ser destacado, que tramita a nível nacional, projeto semelhante (*projeto de Lei nº 616/2019 de autoria do Senador Lasier Martins, que altera a Lei nº 6.360 de 23.09.1976, que além de outros dispõe sobre a proibição de protetores solares considerados tóxicos para os recifes de corais* – cópia anexa), e cujo projeto encontra-se ainda em tramitação, com inúmeras manifestações de entidades representantes da comunidade em geral, face as suas gravíssimas consequências, no caso de sua aprovação.

Além disso, entende esta entidade, que dita matéria é de competência exclusiva da esfera federal, não podendo, o legislativo estadual, dispor sobre tal assunto, o que por si só, exige o seu ARQUIVAMENTO.

Para corroborar, esta manifestação, toma-se a liberdade de anexar a presente, cópia de parecer da ABIHPEC (*Associação Brasileira de Higiene Pessoal, Perfumaria e Cosméticos)* o qual se adota, para que fique fazendo parte desse arrazoado, que reproduz com clareza o cenário sobre a matéria e suas consequências, concluindo que:

"...

. *até o presente momento* ***não se confirmam nenhuma das justificativas que embasam o projeto ou que levaram ao alarme e às medidas iniciais;***

. Os filtros ***solares*** *tem uma utilização determinada e* ***são primordiais para os consumidores na prevenção de câncer de pele e queimaduras solares;***

. internacionalmente os estudos que avaliam a causa do branqueamento dos corais ainda estão em ***fase embrionária,*** *necessitando de um maior aprofundamento técnico.*

. . ."

Junta-se, também, manifestação da ABC (Associação Brasileira de Cosmetologia) que também concluiu de forma contrária a tais projetos, senão vejamos:

". . .

Com base nas evidências científicas citadas, concluímos que:

1. *Os estudos preliminares bem como o estudo publicado em 2016, utilizado como base para a proibição do uso dos protetores solares no Havaí e Palau, não refletem as condições reais em que vivem os recifes de corais, portanto não podem ser utilizados como ferramentas para definição de políticas públicas.*
2. *Os estudos evidenciam que, a maior causa do fenômeno de branqueamento dos corais é o aumento da temperatura dos oceanos, em função do aquecimento global. Portanto, proibir o uso de protetores solares contendo as substâncias citadas na PL616/2019, não é uma medida efetiva que contribui para a preservação dos recifes de corais.*
3. *A redução do número de substâncias de proteção UV restringe as opções de proteção eficaz do consumidor contra os raios ultravioletas, aumentando assim a incidência de câncer de pele na população brasileira e acarretando aumento dos gastos do governo com saúde pública.*

. . ."

Assim, *Senhor Deputado,* apesar de entender a preocupação do Ilustre Deputado autor do projeto em questão, dita matéria, repita-se, além de não ser de competência do Legislativo Estadual, não traz, muito pelo contrário, vem contrariar os interesses dos consumidores dos referidos protetores solares, assim como trará ao setor industrial um gravíssimo e irrecuperável ônus, motivo pelo qual, esta entidade, na defesa dos interesses de seus representados, **opina, <u>no sentido de que seja o dito projeto arquivado.</u>**

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Por fim, coloca-se, esta entidade a sua inteira disposição, para o que se fizer necessário, com vistas a prestação de maiores esclarecimentos sobre a matéria questionada.

Atenciosamente.

Ney Osvaldo Silva Filho

Presidente do SINQFESC

Projeto de Lei PL./0077.0/2019

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Sala das Sessões, em

Deputado Kennedy Nunes

JUSTIFICATIVA

Os recifes de corais são os ecossistemas mais diversos dos mares por concentrarem, globalmente, a maior densidade de biodiversidade marinha.

Os corais construtores de recifes são animais de estrutura simples, pertencentes à classe dos antozoários, filo dos cnidários. Esses animais vivem em enormes colônias fixadas em substrato calcário secretado pelos pólipos, que é como se denominam os indivíduos em sua fase adulta. Os recifes são, portanto, "rochas vivas", pois possuem uma base mineral (o esqueleto calcário), sobre o qual uma colônia viva repousa. A fase larval é livre-natante, denominada "plânula". A vida dos corais construtores é dependente de uma relação simbiótica com microalgas chamadas zooxantelas, que vivem no interior dos seus tecidos e realizam fotossíntese, por meio da qual provêm os nutrientes necessários para a sobrevivência dos corais.

Estima-se que 14 mil toneladas de protetor solar vão parar nos oceanos a cada ano, e desse total, de 4 a 6 mil toneladas se acumulam sobre recifes de corais de todo o planeta, o que demonstra a gravidade do problema, principalmente quando consideramos que as pesquisas mencionadas constataram que pequenas quantidades das substâncias estudadas são tóxicas para os corais.

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Apresento e peço aos nobres Pares a aprovação deste Projeto de Lei.

Minuta

PARECER Nº , DE 2019

Da COMISSÃO DE ASSUNTOS SOCIAIS, sobre o Projeto de Lei nº 616, de 2019, do Senador Lasier Martins, que *altera a Lei nº 6.360, de 23 de setembro de 1976, que* dispõe sobre a vigilância sanitária a que ficam sujeitos os medicamentos, as drogas, os insumos farmacêuticos e correlatos, cosméticos, saneantes e outros produtos, e dá outras providências, *para dispor sobre a regulação ambiental de cosméticos, e dispõe sobre a proibição de protetores solares considerados tóxicos para os recifes de corais.*

Relatora: Senadora **ZENAIDE MAIA**

I – RELATÓRIO

Vem à análise da Comissão de Assuntos Sociais (CAS) o Projeto de Lei (PL) nº 616, de 2019, de autoria do Senador Lasier Martins, que visa a impor – mediante alterações nos arts. 1º, 6º e 27 da Lei nº 6.360, de 23 de setembro de 1976, que *dispõe sobre a vigilância sanitária a que ficam sujeitos os medicamentos, as drogas, os insumos farmacêuticos e correlatos, cosméticos, saneantes e outros produtos, e dá outras providências* – a regulação ambiental de cosméticos, produtos de higiene e perfumes, para que não sejam nocivos ao meio ambiente. Esse é o teor do art. 1º.

Ao art. 1º da Lei nº 6.360, de 1976, é adicionado um parágrafo único, para determinar que os cosméticos, produtos de higiene e perfumes ficam sujeitos, além das normas de vigilância sanitária, à regulação ambiental.

Já o art. 27 é modificado em seu parágrafo único, para impedir que sejam registrados produtos dessas categorias que contenham substâncias consideradas nocivas ao meio ambiente em sua composição.

A alteração do art. 6º, por sua vez, cuida de incluir a eventual detecção de nocividade ao meio ambiente do produto, para todos aqueles abrangidos pela Lei nº 6.360, de 1976 e já registrados, sob pena de cancelamento do registro e da apreensão do produto; e a exigência da modificação da fórmula de sua composição e dos dizeres dos rótulos, das bulas e embalagens. A atual redação desse artigo admite apenas a prejudicialidade à saúde como causa para a adoção de tais medidas.

Conforme o art. 2º do projeto, ficam proibidos registro, fabricação, importação, exportação, distribuição, publicidade, comercialização, transporte, armazenamento, guarda, posse e uso de protetores solares que contenham substâncias tóxicas para os recifes de coral, aquelas listadas nos incisos do § 1º ou definidas a critério do órgão ou entidade ambiental competente (§ 2º).

O art. 3º submete o infrator às sanções da Lei de Crimes Ambientais (Lei nº 9.605, de 12 de fevereiro de 1998), sem prejuízo das punições de natureza sanitária.

O art. 4º da propositura – cláusula de vigência – estabelece que a proibição relativa ao registro, à fabricação e à importação de protetores solares com substâncias tóxicas para os recifes de coral vigorará cento e oitenta dias após a publicação da lei (inciso I); já a vedação à exportação, à distribuição, à publicidade, à comercialização, ao transporte, ao armazenamento, à guarda e à posse de tais produtos passarão a valer setecentos e trinta dias depois (inciso II).

O autor argumenta que os recifes de coral, que possuem enorme importância ambiental e econômica, estão ameaçados em todo o mundo pelo aumento da temperatura e pela acidificação dos oceanos, fenômenos influenciados pela poluição, que é, em parte, causada por substâncias que compõem os protetores solares, segundo pesquisas científicas. Por isso, justifica-se proibir esses componentes nocivos, uma vez que existem formulações alternativas disponíveis.

A matéria foi distribuída para a apreciação da CAS e da Comissão de Meio Ambiente (CMA), em decisão terminativa. No prazo regimental, não foi objeto de emendas.

II – ANÁLISE

É atribuição da CAS opinar sobre proposições que digam respeito à proteção e defesa da saúde, nos termos do inciso II do art. 100 do Regimento Interno do Senado Federal (RISF).

Nesse sentido, por alterar a Lei nº 6.360, de 1976 – norma legal que dispõe sobre a vigilância sanitária de medicamentos, insumos farmacêuticos, cosméticos, saneantes e outros produtos correlatos –, cabe a análise do PL nº 616, de 2019, por esta Comissão.

Cumpre ressaltar, contudo, que a despeito de a vigilância sanitária convergir vários campos do saber, o mote do projeto em comento é essencialmente ambiental.

De fato, ainda que a definição de "vigilância sanitária", dada pelo § 1º do art. 6º da Lei nº 8.080, de 19 de setembro de 1990 (Lei Orgânica da Saúde), englobe ações capazes de eliminar, diminuir ou prevenir problemas sanitários advindos do meio ambiente, isso é feito exclusivamente sob a perspectiva da mitigação dos riscos à saúde humana, com vistas a garantir a higidez da população. Não está entre as atribuições da vigilância sanitária o combate às agressões ao meio ambiente em si.

Por conseguinte, entendemos que as inovações promovidas pelo PL, para que se integrem de forma coerente ao ordenamento jurídico, não devem constar de norma que trata exclusivamente de vigilância sanitária, tal qual é a Lei nº 6.360, de 1976.

Com efeito, o objeto da proposição em comento não é a saúde humana, mas sim, a inclusão de requisitos ambientais na concessão do registro de protetores solares e outros cosméticos, que devem ser analisados por órgão ambiental competente.

Ressalte-se que esse tipo de análise multidisciplinar não é novidade em nosso ordenamento jurídico, pois a concessão de registro de agrotóxicos, por exemplo, deve atender a *diretrizes e exigências dos órgãos federais responsáveis pelos setores da saúde, do meio ambiente e da agricultura*, nos termos da Lei nº 7.802, de 11 de julho de 1989, que *dispõe sobre a pesquisa, a experimentação, a produção, a embalagem e rotulagem, o transporte, o armazenamento, a comercialização, a propaganda comercial, a utilização, a importação, a exportação, o destino final dos resíduos e embalagens, o registro, a classificação, o controle, a inspeção e* *a fiscalização de agrotóxicos, seus componentes e afins, e dá outras providências*. Assim, de acordo com o Decreto nº 4.074, de 4 de janeiro de 2002, que regulamenta a mencionada lei, trabalham conjunta e independentemente nesse tema o Ministério da Agricultura, Pecuária e Abastecimento, o Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA) e a Agência Nacional de Vigilância Sanitária (ANVISA). Também a título de exemplo, lembramos que os detergentes não biodegradáveis são proibidos no Brasil pela Lei nº 7.365, de 13 de setembro de 1985, por serem agentes poluidores.

Devemos pontuar, no entanto, que a justificação do projeto traz informações apenas sobre a comprovada prejudicialidade dos protetores solares aos recifes de coral, mas pretende estender suas restrições a uma enorme gama de produtos. Na prática, a alteração do art. 6º da Lei nº 6.360, de 1976, atingiria a todos os produtos abrangidos por esse diploma legal – quais sejam, medicamentos, insumos farmacêuticos, cosméticos, saneantes, produtos para a saúde etc. – sem apresentar, contudo, os fundamentos científicos para tanto.

Por essas razões, e no intuito de manter a coerência das políticas públicas, que devem ser fundamentadas em bases científicas, consideramos mais adequado impor as disposições do projeto apenas em relação aos protetores solares – para os quais já existem evidências conclusivas de seus agravos ao meio ambiente –, de maneira que somos favoráveis à supressão de seu art. 1º.

Mais ainda, como o escopo de projeto não é a proteção da saúde humana, nem a vigilância sanitária de bens, produtos ou serviços, recomendamos a retirada da expressão "sem prejuízo das sanções de natureza sanitária" contida no art. 3º.

Consideramos importante, também, tornar mais concisa a redação do atual art. 2º, bem como promover as adaptações da cláusula de vigência à supressão do art. 1º.

Todas essas modificações na redação da propositura demandam, a nosso ver, a apresentação de substitutivo ao projeto de lei.

Por fim, a despeito das considerações aqui expostas, em face da importância que os recifes de coral apresentam para a vida marinha e para a economia das regiões costeiras, somos favoráveis à proibição de protetores solares que sejam nocivos ao meio ambiente.

III – VOTO

Em vista do exposto, opinamos pela **aprovação** do Projeto de Lei nº 616, de 2019, nos termos do seguinte substitutivo:

EMENDA Nº (SUBSTITUTIVO)

PROJETO DE LEI Nº 616, DE 2019

Dispõe sobre a proibição de protetores solares considerados tóxicos aos recifes de coral.

O CONGRESSO NACIONAL decreta:

Art. 1º Os protetores solares não poderão conter em sua composição as seguintes substâncias consideradas tóxicas para os recifes de coral:

I – oxibenzona (BP3);

II – metoxicinamato de octila (EHMC);

III – octocrileno (OC);

IV – 4-metilbenzilideno-cânfora (4MBC);

V – triclosan;

VI – metilparabeno;

VII – etilparabeno;

VIII – propilparabeno;

IX – butilparabeno;

X – benzilparabeno;

XI – fenoxietanol.

Parágrafo único. Outras substâncias poderão ser adicionadas à lista que consta do *caput* deste artigo, a critério do órgão ou entidade ambiental competente.

Art. 2º O descumprimento do disposto nesta Lei sujeita os infratores às sanções estabelecidas pelos arts. 56 e 72 da Lei nº 9.605, de 12 de fevereiro de 1998.

Art. 3º Esta Lei entra em vigor cento e oitenta dias após a data de sua publicação.

Sala da Comissão,

, Presidente

, Relatora

SENADO FEDERAL

PROJETO DE LEI
Nº 616, DE 2019

Altera a Lei nº 6.360, de 23 de setembro de 1976, que dispõe sobre a vigilância sanitária a que ficam sujeitos os medicamentos, as drogas, os insumos farmacêuticos e correlatos, cosméticos, saneantes e outros produtos, e dá outras providências, para dispor sobre a regulação ambiental de cosméticos, e dispõe sobre a proibição de protetores solares considerados tóxicos para os recifes de corais.

AUTORIA: Senador Lasier Martins (PODE/RS)

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SENADO FEDERAL
Gabinete do Senador Lasier Martins

PROJETO DE LEI DO SENADO Nº , DE 2018

Altera a Lei nº 6.360, de 23 de setembro de 1976, que *dispõe sobre a vigilância sanitária a que ficam sujeitos os medicamentos, as drogas, os insumos farmacêuticos e correlatos, cosméticos, saneantes e outros produtos, e dá outras providências*, para dispor sobre a regulação ambiental de cosméticos, e dispõe sobre a proibição de protetores solares considerados tóxicos para os recifes de corais.

O CONGRESSO NACIONAL decreta:

Art. 1º A Lei nº 6.360, de 23 de setembro de 1976, passa a vigorar com as seguintes alterações:

"**Art. 1º** ....

Parágrafo único. Os cosméticos e demais produtos tratados no Título V desta Lei ficam sujeitos, além das normas de vigilância sanitária, à regulação ambiental, voltada à prevenção dos impactos ambientais causados pela sua utilização e pelos seus ingredientes." (NR)

"**Art. 6º** A comprovação de que determinado produto, até então considerado útil, é nocivo à saúde ou ao meio ambiente, ou não preenche requisitos estabelecidos em lei, implica a sua imediata retirada do comércio e a exigência da modificação da fórmula de sua composição e dos dizeres dos rótulos, das bulas e embalagens, sob pena de cancelamento do registro e da apreensão do produto, em todo o território nacional.

...." (NR)

"**Art. 27.** ....

....

Parágrafo único. A relação de substâncias a que se refere o inciso I deste artigo poderá ser alterada para exclusão de substâncias que venham a ser julgadas nocivas à saúde ou ao meio ambiente, ou para inclusão de outras, que venham a ser aprovadas." (NR)

Art. 2º Ficam proibidos o registro, a fabricação, a importação, a exportação, a distribuição, a publicidade, a comercialização, o transporte, o armazenamento, a guarda, a posse e o uso de protetores solares considerados tóxicos para os recifes de corais.

§ 1º Para os efeitos desta Lei, são considerados tóxicos para os recifes de corais os protetores solares que contenham os seguintes ingredientes:

I – oxibenzona (BP3);

II – metoxicinamato de octila (EHMC);

III – octocrileno (OC);

IV – 4-metilbenzilideno-cânfora (4MBC);

V – triclosan;

VI – metilparabeno;

VII – etilparabeno;

VIII – propilparabeno;

IX – butilparabeno;

X – benzilparabeno;

XI – fenoxietanol.

§ 2º A critério do órgão ou entidade ambiental competente poderão ser considerados tóxicos, além dos produtos enquadrados no § 1º, protetores solares que contenham outros ingredientes comprovadamente prejudiciais aos recifes de corais.

Art. 3º O descumprimento do disposto nesta Lei sujeita os infratores às sanções estabelecidas nos arts. 56 e 72 da Lei nº 9.605, de 12 de fevereiro de 1998, sem prejuízo das sanções de natureza sanitária.

Art. 4º Esta Lei entra em vigor na data de sua publicação, produzindo efeitos:

I – cento e oitenta dias após a data de sua publicação, em relação ao registro, à fabricação e à importação dos produtos a que se refere o art. 2º desta Lei;

II – setecentos e trinta dias após a data de sua publicação, relativamente à exportação, à distribuição, à publicidade, à comercialização, ao transporte, ao armazenamento, à guarda, à posse e ao uso dos produtos a que se refere o art. 2º desta Lei.

JUSTIFICAÇÃO

Os recifes de corais são os ecossistemas mais diversos dos mares por concentrarem, globalmente, a maior densidade de biodiversidade marinha. No Brasil, ocorrem desde o Amapá até o norte do Espírito Santo. Uma em cada quatro espécies marinhas vive nos recifes, incluindo 65% dos peixes. Estima-se que 500 milhões de pessoas residentes em países em desenvolvimento possuam algum tipo de dependência dos serviços ambientais oferecidos por esses ecossistemas. A "saúde" dos recifes afeta diretamente as pessoas.

SENADO FEDERAL
Gabinete do Senador **Lasier Martins**

Os corais construtores de recifes são animais de estrutura simples, pertencentes à classe dos antozoários, filo dos cnidários. Esses animais vivem em enormes colônias fixadas em substrato calcário secretado pelos pólipos, que é como se denominam os indivíduos em sua fase adulta. Os recifes são, portanto, "rochas vivas", pois possuem uma base mineral (o esqueleto calcário), sobre o qual uma colônia viva repousa. A fase larval é livre-natante, denominada "plânula". A vida dos corais construtores é dependente de uma relação simbiótica com microalgas chamadas zooxantelas, que vivem no interior dos seus tecidos e realizam fotossíntese, por meio da qual provêm os nutrientes necessários para a sobrevivência dos corais.

Não obstante sua enorme importância ambiental e econômica, os recifes de corais estão seriamente ameaçados em todo o mundo. Um fenômeno chamado de "branqueamento" está dizimando os recifes. Esse fenômeno é causado pela perda das algas zooxantelas, que além de nutrirem os corais, são responsáveis por sua coloração. A principal causa do branqueamento é o aumento da temperatura dos oceanos, provocada pelo aquecimento global, mas a poluição também induz o fenômeno.

Cientistas afirmam que 30% dos recifes de corais já foram degradados irreversivelmente e que, mantendo-se o atual ritmo de aquecimento do planeta, 90% dos recifes irão sucumbir até 2050. Não bastasse isso, outras ameaças foram descobertas recentemente, agravando ainda mais a situação dos corais e comprometendo os resultados dos esforços pela sua conservação. Entre essas ameaças, estão a acidificação dos oceanos, causada pelo aumento da quantidade de dióxido de carbono (CO_2) na atmosfera, que se dissolve na água (fenômeno associado ao aquecimento global), e o contato com substâncias tóxicas para os corais provenientes de resíduos de protetores solares.

Além disso, um estudo desenvolvido no Havaí e nas Ilhas Virgens Americanas, publicado em 2016 por pesquisadores de universidades dos Estados Unidos da América (EUA) e de Israel, demonstrou que a oxibenzona, um composto químico amplamente utilizado na composição de protetores solares, cuja função no produto é filtrar raios ultravioletas, é tóxico para as plânulas, e o contato dessa substância com recifes de coral é extremamente prejudicial para esses ecossistemas. Estudos posteriores comprovaram que além da oxibenzona, o metoxicinamato de octila, outro ingrediente comum nos protetores solares, também é altamente tóxico para os corais. Esses estudos levaram o estado do Havaí a aprovar legislação proibindo, a partir de 2021, a utilização de protetores solares que tenham esses dois produtos na sua composição.

Mais recentemente, em 2017, foi publicado um relatório científico sobre estudo conduzido em um sítio do Patrimônio Natural Mundial localizado na República de Palau, na Oceania, no qual foram identificadas 11 substâncias tóxicas para os corais que são comumente utilizadas na formulação de protetores solares. O referido estudo, realizado por cientistas de Palau, Espanha e EUA, e encomendado pela Organização das Nações Unidas para a Educação, a Ciência e a Cultura (UNESCO, na sigla em inglês), levou o parlamento de Palau a aprovar proposta do governo que proibiu a utilização de protetores solares que contenham entre seus ingredientes qualquer substância de uma lista de dez, das onze consideradas tóxicas pelos pesquisadores. A proibição entra em vigor em 2020.

Além do Havaí e de Palau, a ilha caribenha de Bonaire, pertencente aos Países Baixos, também impôs restrições aos protetores solares, proibindo os de base química. O México também proibiu esses protetores em unidades de conservação da natureza.

Estima-se que 14 mil toneladas de protetor solar vão parar nos oceanos a cada ano, e desse total, de 4 a 6 mil toneladas se acumulam sobre recifes de corais de todo o planeta, o que demonstra a gravidade do problema, principalmente quando consideramos que as pesquisas mencionadas constataram que pequenas quantidades das substâncias estudadas são tóxicas para os corais.

A proteção aos corais, por meio da proibição das substâncias tóxicas que os afetam, pode ainda trazer repercussões positivas sobre a saúde humana. Muitos estudos demonstram que os componentes químicos dos protetores solares que são tóxicos aos corais também são nocivos às pessoas. O uso da oxibenzona como filtro solar tem sido associado a danos celulares e até ao câncer de pele. Essa substância, assim como o triclosan e outros bactericidas usados como ingredientes de cosméticos, possivelmente provocam distúrbios hormonais, segundo pesquisadores.

Há alternativa no mercado aos protetores solares de base química. Os protetores a base de minerais, como dióxido de titânio e óxido de zinco, são eficazes e não comprometem a saúde humana e nem ajudam a exterminar os recifes de coral. Precisamos legislar no sentido de levar a indústria a produzir protetores ambientalmente amigáveis.

Sendo o Brasil um país tropical com vasta zona costeira, grande parte dela rica em recifes de coral, é necessário que estejamos na vanguarda da proteção dos recifes, dando exemplo ao mundo. Além de proteger nossa biodiversidade, a proibição de substâncias tóxicas nos protetores solares permitirá que os corais continuem contribuindo economicamente com as cidades costeiras brasileiras, pois sua ocorrência é um grande atrativo que movimenta a indústria do turismo.

Neste projeto, optamos por propor diretamente a proibição de protetores solares tóxicos aos corais porque o seu uso está intimamente associado ao lazer em ambientes marinhos, o que converte seu potencial de dano ambiental em degradação concreta. Mas fomos além, propondo o aperfeiçoamento da legislação regulatória sobre cosméticos para que estes sejam objeto também de regulação ambiental, e não apenas sanitária. Caberá ao Poder Executivo decidir como essa regulação se dará, sendo ela hoje inexistente.

Peço, portanto, aos nobres pares, o apoio a este projeto de lei que possibilitará a conservação do enorme patrimônio natural representado pelos nossos recifes de corais, o fortalecimento da economia vinculada ao turismo costeiro, e ainda, a melhoria da proteção à saúde da população humana.

Sala das Sessões,

Senador LASIER MARTINS

LEGISLAÇÃO CITADA

- Lei nº 6.360, de 23 de Setembro de 1976 - Lei de Vigilância Sanitária sobre Produtos Farmacêuticos - 6360/76
  https://www.lexml.gov.br/urn/urn:lex:br:federal:lei:1976;6360
- Lei nº 9.605, de 12 de Fevereiro de 1998 - Lei dos Crimes Ambientais; Lei da Natureza; Lei dos Crimes contra o Meio Ambiente - 9605/98
  https://www.lexml.gov.br/urn/urn:lex:br:federal:lei:1998;9605
    - artigo 56
    - artigo 72

PL 616/19 | Protetor Solar

Proíbe o uso de protetores solares tóxicos para recifes de corais

Cenário

A Associação Brasileira da Indústria de Higiene Pessoal, Perfumaria e Cosméticos (ABIHPEC) é a instituição que atua em defesa dos interesses desse setor, contribuindo diretamente para o seu crescimento e fortalecimento. Tem como associadas mais de 400 empresas, o que corresponde aproximadamente a 90% do PIB do setor.

Em linha com a sua missão e com os seus objetivos institucionais, a ABIHPEC estimula o setor para o desenvolvimento e aprimoramento contínuo de sua capacidade de inovação, para a adoção de práticas sustentáveis de produção e para a fabricação de produtos cada vez mais eficientes, atraentes e tecnológicos, que **promovam os cuidados com a saúde à valorização da autoestima e do bem-estar do brasileiro.**

Representado pela ABIHPEC - Associação Brasileira da Indústria de Higiene Pessoal, Perfumaria e Cosméticos, o setor apresenta considerações para o PL 616/2019 de autoria do Senador Lasier Martins que altera a Lei nº 6.360/1976, que dispõe sobre a vigilância sanitária a que ficam sujeitos os medicamentos, as drogas, os insumos farmacêuticos e correlatos, cosméticos, saneantes e outros produtos, e dá outras providências, para dispor sobre a regulação ambiental de cosméticos, e dispõe sobre a proibição de protetores solares considerados tóxicos para os recifes de corais.

Por se tratar de uma temática sensível e ao mesmo tempo complexa, entendemos que o assunto deva ser tratado com o maior aprofundamento técnico possível. Portanto, apresentamos nossas contribuições e reforçamos abaixo os impactos deste para o avanço da inovação em prol da saúde do consumidor.

Setor brasileiro de HPPC

A indústria brasileira de Higiene Pessoal, Perfumaria e Cosméticos (HPPC) está **voltada aos cuidados com a saúde, bem-estar e melhor qualidade de vida da população, além de ter grande relevância na contribuição econômica do País.**

No Brasil, existem cerca de **2.718 indústrias de HPPC** que gerou em 2017, mais de **5,7 milhões de oportunidades de trabalho**, com a participação cada vez mais crescente da mulher no mercado. A importância de construir uma indústria essencial se espelha na própria força de seu mercado consumidor, **o quarto maior do mundo**, atrás apenas dos Estados Unidos, China e Japão.

A indústria de HPPC tem como princípio **preservar a segurança de seus consumidores e são cientes do seu papel no desenvolvimento sustentável do setor com responsabilidade social e ambiental,** tendo na proteção do meio ambiente uma de suas prioridades de atuação, tais como na:

- Formulação de regras corporativas de conduta ética;
- Inovação e desenvolvimento de novos produtos; e
- Interlocução com autoridades, especialistas, representantes da sociedade civil e organismos nacionais e internacionais envolvidos com a discussão e regulação do tema no Brasil e no mundo.

Aspectos Regulatórios

Informações técnicas - filtros solares

No Brasil, os produtos do setor comercializados são demandados, por lei, a cumprir com os regulamentos da Agência Nacional de Vigilância Sanitária - ANVISA e Instituto Nacional de Metrologia, Qualidade e Tecnologia – Inmetro que são fundamentados pelo Código de Defesa do Consumidor (CDC), sob pena de sanções legais no caso do não cumprimento. Em alguns casos, a infração é considerada crime hediondo, salientando que tais regulamentos se aplicam tanto para os produtos fabricados em território nacional, como para os produtos importados.

A Resolução RDC Nº 69, de 23 de março de 2016 da Anvisa lista os filtros ultravioletas com uso permitidos para utilização em produtos de higiene pessoal, cosméticos e perfumes, e está harmonizada no Mercosul por meio da Resolução GMC Nº 44/15 e baseia-se na necessidade de proteção da saúde da população considerando-se o risco sanitário.

A indústria de produtos de HPPC tem o compromisso de colocar no mercado produtos seguros para o consumidor, em consonância com os mais altos padrões internacionais de qualidade, a Benzofenona-3 (BP-3; oxibenzona) é um importante filtro solar encontrado em muitos produtos cosméticos, pois de acordo com a Academia Americana de Dermatologia

(AAD), a oxibenzona é um dos poucos ingredientes protetores solares disponíveis que protegem eficazmente a pele de ambos os raios UVA e UVB que podem contribuir para o câncer de pele e envelhecimento prematuro da pele.

Um estudo publicado recentemente na *Archives of Environmental Contamination and Toxicology* sugere que este ingrediente pode ser prejudicial para os corais e contribuir para o declínio dos recifes ao redor do mundo. **Esta conclusão é baseada em pesquisas realizadas em laboratório em condições que não refletem com precisão a complexidade do ambiente marinho natural.**

A degradação dos recifes de coral do mundo é uma preocupação séria. De acordo com a *US National Oceanic* e o Programa de Conservação de Recifes de Coral da Administração Atmosférica (NOAA), os recifes de coral são ameaçados por uma crescente gama de impactos - principalmente a mudança climática global, pesca insustentável e outros fatores. **Não há evidências científicas conclusivas de que, sob condições naturais, ingredientes de proteção solar, que têm sido usados com segurança em todo o mundo há décadas, estão contribuindo para esta questão.**

Embora concordemos que a saúde dos corais é de grande importância, uma grande preocupação semelhante é a prevalência de diagnósticos e mortes por câncer de pele. Mais de 10.000 pessoas morrem de melanoma todos os anos nos Estados Unidos da América, e há mais novos casos de câncer de pele a cada ano do que câncer de mama, próstata, cancros do pulmão e do cólon combinados.

Informações técnicas – Conservantes

Os demais ingredientes listados no Art. 1 do referido PL são ingredientes conservantes amplamente utilizados em produtos cosméticos no mundo e com seu uso permitido pela Anvisa por meio da Resolução RDC 29 de 1° de junho de 2012 como o Triclosan, na justificativa do projeto comenta-se que seu uso provoca" distúrbios hormonais".

Ressaltamos que não há evidências convincentes de que os ingredientes usados em produtos cosméticos e de cuidados pessoais causem disrupção endócrina em humanos. Muitas substâncias, tanto naturais como produzidas pelo homem, podem ter algum potencial para imitar os hormônios naturais em condições de laboratório. Por exemplo, os estrogênios vegetais (também conhecidos como fitoestrogênios) encontrados na soja, repolho, sementes de gergelim, vinho tinto e outros alimentos demonstraram ter fraca atividade endócrina. No entanto, a atividade estrogênica desses materiais, medida em condições de laboratório, é geralmente muito menor do que a observada para o estradiol - a forma natural de estrogênio no corpo humano. E seu corpo não pode dizer a diferença entre substâncias naturais ou artificiais. Além disso, os níveis nos quais os ingredientes com possíveis propriedades hormonais ocorrem em produtos cosméticos e de cuidados pessoais estão significativamente abaixo dos níveis que foram associados com a atividade endócrina demonstrada em laboratório.

Também se encontram listados no PL os Parabenos, pontuamos que estes ingredientes são comumente utilizados como conservante em cosméticos e produtos de higiene pessoal. Eles são altamente eficazes na prevenção do crescimento de fungos, bactérias e leveduras, e, portanto, ao utilizá-los aumenta-se assim a vida útil e a segurança dos produtos. A Food and Drug Administration (FDA) avaliou estudos que alegam possíveis efeitos endócrinos para alguns ingredientes cosméticos e concluiu que não há motivo para preocupação dos consumidores. Parabenos são um desses exemplos. Embora alguns parabenos possam agir de maneira semelhante ao estrogênio, eles demonstraram ter muito menos atividade estrogênica do que o estrogênio natural do organismo. Um estudo de 1998 (Routledge et al., Em Toxicologia e Farmacologia Aplicada) descobriu que o parabenos mais potente testado no estudo, o butilparabeno, mostrou de 10.000 a 100.000 vezes menos atividade do que o estradiol natural. Além disso, os parabenos são usados em níveis muito baixos em cosméticos e alimentos. Em uma revisão da atividade estrogênica dos parabenos, (Golden et al., Em Critical Reviews in Toxicology, 2005), **o autor concluiu que, com base nas estimativas de exposição diária máxima, era implausível que os parabenos aumentassem o risco associado à exposição a produtos químicos estrogênicos.**

Conclusão

- Até o presente momento **não se confirmam nenhuma das justificativas que embasam o projeto ou que levaram ao alarme e às medidas iniciais;**
- **Os filtros solares** têm uma utilização determinada e **são primordiais para os consumidores na prevenção de câncer de pele e queimaduras solares;**
- Internacionalmente os estudos que avaliam a causa do branqueamento dos corais ainda estão em **fase embrionária**, necessitando de um maior aprofundamento técnico.

São Paulo, 05 de junho de 2019.

Aos Senhores

Senador Lasier Martins (PODE/RS)
Gabinete: Senado Federal Anexo 2, Ala Alexandre Costa, Subsolo, Gabinete 03
Escritório de apoio: Rua General Andrade Neves, Nº 14 – Sala 801, Centro Histórico, Porto Alegre, RS. CEP: 90010-210

Senadora Zenaide Maia (PROS/RN)
Gabinete: Senado Federal Anexo 1, 8º Pavimento
Escritório de apoio: Rua Desembargador Antônio Soares, 1249. D. Tirol, Natal, RN. CEP: 59022-170

Assunto: *Defesa contrária à PL 616/2019 – proibição do uso de protetores solares com determinados ingredientes classificados mundialmente como filtros UV e conservantes.*

Prezados Senhores,

A **Associação Brasileira de Cosmetologia – ABC**, como entidade científica representante do setor cosmético, vem através desta manifestar-se em relação ao que propõe a PL 616/2019.

Consideramos louvável a preocupação e interesse dos Senadores, em relação ao impacto das substâncias químicas ao meio ambiente, porém como entidade científica e representante do setor cosmético, nos sentimos na responsabilidade de expor alguns fatos relacionados a este tema:

✓ **Da incidência e mortes por câncer de pele no Brasil**

De acordo com o INCA (Instituto Nacional de Câncer) e SBD (Sociedade Brasileira de Dermatologia), o câncer de pele representa 33% de todos os diagnósticos desta doença no Brasil. O impacto dos gastos do governo no tratamento do câncer de pele, bem como os custos por morte oriundos da mesma causa são muito altos, sem considerar os efeitos colaterais do tratamento (perda dos cabelos, baixa imunidade, etc.) que acabam gerando outros fatores como: baixa autoestima, depressão, perda da qualidade de vida. Com base nestes dados podemos concluir que o impacto do câncer de pele na saúde pública é significante.

Estatísticas

	Homens	**Mulheres**	**Total**
Estimativa novos casos no Brasil	85.170	80.140	165.580
Número de mortes no Brasil	1.147	821	1.958

ABC - Associação Brasileira de Cosmetologia
Rua Ana Catharina Randi, 25 - Jardim Petrópolis - São Paulo - SP – Brasil - CEP 04637-130
Fone: 55-11-5044-5466 / FAX: 55-11-5044-5528 abc@abc-cosmetologia.org.br / diretoria@abc-cosmetologia.org.br

Medidas de prevenção

O INCA indica o uso do protetor solar como medida preventiva para o câncer de pele, principalmente em longos períodos de exposição ao sol (aumento do risco). Por uma questão de saúde, a proteção é necessária não somente aos indivíduos que frequentam áreas de banho como, por exemplo, as regiões praianas, mas também aos indivíduos que laboram nas ruas (carteiros, varredores de rua, etc.) ou que por qualquer outro motivo se expõe ao sol por um longo período.

No Chile, por exemplo, o filtro solar é EPI (Equipamento de Proteção Individual) e seu uso é obrigatório por pessoas que laboram em condições de exposição ao sol (Lei 20.096/2006 que descreve as condições de exposição à radiação ultravioleta e sanções para quem as violar) – **ver anexo I.**

✓ **Da segurança dos ingredientes em uso humano**

Atualmente o Brasil possui listas de ingredientes harmonizadas entre os países do grupo Mercosul e permitidos em cosméticos.

Para autorização do uso destas substâncias, as agências de cada país contam com um processo robusto de avaliação dos relatórios de análise toxicológica, de cada ingrediente, expedido pelos comitês científicos da Comunidade Europeia e EUA:

- SCCS (Scientific Committee on Consumer Safety)
- CIR (Cosmetic Ingrediente Review)

De acordo com as referências citadas acima, as substâncias mencionados na PL e utilizadas na composição química dos protetores solares, são seguras para uso humano nas condições e concentrações máximas permitidas nas legislações vigentes.

Enfatizamos que as listas de ingredientes permitidos, bem como a lista de ingredientes proibidos em cosméticos são temas permanentes na agenda do Mercosul. Portanto, sempre que necessário, as mesmas são atualizadas de acordo com novos estudos toxicológicos e novos posicionamentos com base em relatórios científicos reconhecidos internacionalmente.

Além da segurança, enfatizamos também que as moléculas de filtro UV atualmente disponíveis no mercado são o resultado de anos de estudo e investimento, representando uma evolução tecnológica em termos de espectro de proteção UV e sensorial aceitável pelo consumidor.

✓ **Dos estudos científicos sobre o impacto dos filtros solares em recifes de corais**

Em 2016 foi publicado o artigo *"Toxicopathological Effects of the sunscreen UV filter, Oxybenzone (Benzophenone-3), on Coral Planulae and Cultured Primary Cells and Its Environmental Contamination in Hawaii and the U.S. Virgin Slands"*, o qual propõe avaliar os efeitos da substância Benzophenone-3 (oxibenzona; BP-3) no fenômeno de branqueamento dos recifes de corais. Este foi utilizado como base cientifica para proibir o uso de protetores solares que contenham Benzophenone-3 no Havaí e Palau.

O estudo em questão foi realizado em condições *in vitro*, envolvendo somente parâmetros intrínsecos e desconsiderando as condições *in situ*, bem como o bioma nos quais os corais vivem.

Como é de conhecimento, a Austrália é o país onde existe a maior barreira de corais do mundo. Em função disto, diversos estudos são realizados pelos pesquisadores das Universidades locais com objetivo de conservá-los. Um dos mais renomados pesquisadores a frente destes estudos é o **Dr. Terry Hughes (Professor, Diretor do Centre of Excellence for Coral Reef Studies on Australia da James Cook University em Queensland/Austrália e Líder do Programa 1: People and Ecosystems)**, que afirma não existirem evidências suficientes, que demonstrem que a composição química dos protetores solares causam dano ou potencializam o fenômeno de branqueamento dos corais. Complementando, citamos alguns pontos evidenciados pelo Dr. Terry Hughes, que contra argumentam a credibilidade do estudo publicado em 2016 **(ver anexo II)**:

- A maneira pela qual os tecidos dos corais foram expostos aos filtros solares não representam a dispersão e diluição de poluentes da pele de um turista (e outras fontes) em águas de recifes e em corais existentes na natureza.

- Os experimentos que expõem os corais às substâncias oriundas da composição química de determinados protetores solares, normalmente utilizam concentrações muito mais altas do que os que já foram medidos em um recife nas condições *in situ* (condições reais). Uma revisão recente da quantidade de benzophne-3 em águas onde vivem os recifes de corais demonstrou que tipicamente, as concentrações são dificilmente detectáveis.

- O estudo foi realizado com base em uma única amostragem, ou seja, as amostras não foram replicadas. Isto desqualifica o estudo, uma vez que se desconhece a reprodutibilidade dos resultados.

- Mesmo os recifes de corais mais antigos são vulneráveis ao estresse por calor. Os mecanismos fisiológicos e a escala temporal do branqueamento térmico, devido ao aquecimento global, são muito diferentes das respostas rápidas dos corais, à exposição experimental a altas concentrações de substâncias químicas.

Corroborando com Dr. Terry Hughes, outros artigos foram publicados reforçando que o branqueamento dos corais em uma escala global, tem como **principal causa o aquecimento global** que provoca o aumento da temperatura dos oceanos, seguido de outros fatores locais como: pesca excessiva, poluição oriunda de esgotos e escoamento agrícola **(ver anexo III)**.

Conclusão

Com base nas evidências científicas citadas, concluímos que:

1. Os estudos preliminares bem como o estudo publicado em 2016, utilizado como base para proibição do uso dos protetores solares no Havaí e Palau, não refletem as condições reais em que vivem os recifes de corais, portanto não podem ser utilizados como ferramentas para definição de politicas públicas.

2. Os estudos evidenciam que, a maior causa do fenômeno de branqueamento dos corais é o aumento da temperatura dos oceanos, em função do aquecimento global. Portanto, proibir o uso de protetores solares contendo as substâncias citadas na PL 616/2019, não é uma medida efetiva que contribui para a preservação dos recifes de corais.
3. A redução do número de substâncias de proteção UV restringe as opções de proteção eficaz do consumidor contra os raios ultravioletas, aumentando assim a incidência de câncer de pele na população brasileira e acarretando aumento dos gastos do governo com saúde pública.

Para finalizar e reforçar o posicionamento do setor cosmético, anexamos as declarações de desapontamento de entidades internacionais renomadas, em relação à tal medida **(ver anexo IV)**.

Certos do acolhimento deste pleito, colocamo-nos à disposição para quaisquer esclarecimentos necessários.

Cordialmente,

Vania R. Leite e Silva
Presidente ABC

Referências bibliográficas

- Instituto Nacional do Câncer (Ministério da Saúde): https://www.inca.gov.br/tipos-de-cancer
- Sociedade Brasileira de Dermatologia: http://www.sbd.org.br/dermatologia/pele/doencas-e-problemas/cancer-da-pele/64/
- European Committee; Scientific Committees on Consumer Safety https://ec.europa.eu/health/scientific_committees/consumer_safety_pt

- Ministério da Saúde: http://portalms.saude.gov.br/saude-de-a-z/cancer-de-pele

- ACHS: Asociación Chilena de Seguridad (https://www.achs.cl/portal/ACHS-Corporativo/newsletters/infoempresas/Paginas/Medidas-de-proteccion-solar-para-los-trabajadores.aspx

- ARC Centre of Excellence for Coral Reef Studies (https://www.coralcoe.org.au/# and https://www.coralcoe.org.au/person/terry-hughes)

- PCPC Personal Care Products Council 9 https://www.personalcarecouncil.org/statement/statement-from-the-consumer-healthcare-products-association-chpa-and-the-personal-care-products-council-pcpc-regarding-sunscreen-ingredient-ban/)

- AAD American Academy of Dermatology Association (https://www.aad.org/media/news-releases/aada-statement-on-sunscreen-access)

- CHPA Cosumer Health Products Association (https://www.chpa.org/SunscreenBan2018.aspx)

Proporcionalmente, SC tem maior índice de câncer de pele do Brasil

Soma de fatores de risco coloca o Estado no topo da lista nos diagnósticos da doença

Compartilhar

Maria, de Joinville, não tinha costume de proteger a pele até descobrir um melanoma, em 2015
Foto: Salmo Duarte / A Notícia

Cláudia Morriesen e Lucas Paraizo
claudia.morriesen@somosnsc.com.br;lucas.paraizo@somosnsc.com.br

O **câncer** de incidência mais elevada no mundo está no maior órgão do corpo humano: na pele. Mesmo assim, figura entre os mais esquecidos quando se trata de cuidados no dia a dia. No verão, quando a incidência dos raios solares aumenta e as pessoas ficam ainda mais expostas a eles, a pele precisa de observação extra — o que não significa que, em outros períodos do ano, ela possa ficar desprotegida. O Instituto Nacional do Câncer (Inca) registra, a cada ano, 180 mil novos casos de câncer de pele no Brasil, o que corresponde a 33% de todos os diagnósticos desta doença.

A maior taxa de incidência, proporcionalmente, é em Santa Catarina: na última pesquisa feita pelo Inca, a estimativa era de 9.890 pessoas diagnosticadas com melanoma e não melanoma em 2016 no Estado – cerca de 160 a cada 100 mil habitantes, enquanto o segundo estado com maior incidência, o Rio Grande do Sul, te cerca de 120 a cada 100 mil habitantes. São Paulo e Paraná vêm em seguida na lista.

Em Santa Catarina, o maior número de mortes pela doença estão em Joinville, Florianópolis e Blumenau, respectivamente: das 1.190 mortes que ocorreram por causa do câncer de pele em Santa Catarina entre 201 2015, 110 foram em Joinville, 87 em Florianópolis e 66 em Blumenau.

– A incidência é muito maior em Santa Catarina porque temos uma soma de fatores de risco aqui: a pele ma clara de grande parte da população, fruto da descendência europeia no Sul; a exposição maior ao sol por cau do tamanho e da valorização do litoral; e a área mais fina da camada de ozônio na nossa região, o que permi a entrada com maior intensidade dos raios solares – explica a oncologista Viviane Dallagasperina.

Entre a população branca, a frequência do melanoma é mais de 20 vezes maior do que entre a população co pele negra e de descendência hispânica, já que a baixa produção do pigmento de melanina resulta na menor capacidade de defesa dos raios ultravioleta do sol. Na última pesquisa do IBGE, em 2010, 83,97% dos catarinenses declararam ter pele branca.

Além disso, o Cinturão de Van Allen, aglomerados de partículas em formato de aneis que protegem o plane de raios radioativos, apresenta uma alteração sobre a América do Sul, fazendo com que a radiação consiga penetrar com mais intensidade na região. Chamada de Anomalia do Atlântico Sul, esta falha é ainda mais intensa sobre os estados do Sul do Brasil, o que, para alguns especialistas, tem relação com o alto índice de câncer de pele na região.

Questão cultural atrapalha a prevenção

Há também uma questão cultural que atinge todo o país. Se para a geração que hoje tem mais de 60 anos r havia informações nem campanhas de prevenção sobre os riscos de ficar exposto aos raios solares, e era comum trabalhar na área rural, atualmente a população mais jovem, mesmo sabendo as consequências, nã

Dermatologia divulgou um relatório que apontava que pelo menos 6 milhões de brasileiros adultos assumir que não se protegiam de nenhuma forma ao irem à praia, à piscina e a banhos de rio.

– As pessoas precisam criar o hábito de utilizar o protetor solar, e não apenas nas atividades de lazer, mas n dia a dia, mesmo naqueles que estão nublados. O ideal, também, era ter pelo menos uma consulta com dermatologista por ano. O câncer de pele, como todos os tipos de câncer, tem muito mais chances de cura s houver um diagnóstico precoce – analisa Viviane.

Apesar do número alto de incidência, a mortalidade por causa do câncer de pele é baixa. A maioria dos caso são do tipo não melanoma (carcinoma basocelular e carcinoma espinocelular) e tem índice de cura de até 90%, principalmente se detectado nos estágios iniciais. Já o melanoma cutâneo, menos frequente, é mais agressivo, se espalha mais rápido e, por isso, é tido como o responsável pela maioria dos óbitos registrados câncer de pele.

Herança na pele, exames e respostas rápidas em Blumenau

Em terceiro lugar no ranking do câncer de pele em Santa Catarina, Blumenau carrega um histórico que já fo alvo de diversos estudos sobre a incidência da doença em moradores da cidade. Somente até outubro deste ano o número de atendimentos ambulatoriais para pacientes com a doença na rede pública do município ultrapassou de 4 mil, um crescimento superior a 20% em relação aos 3.222 procedimentos em 2016.

As origens alemãs que trouxeram a pele clara de parte dos moradores e um alto índice de raios solares – fru de algo que especialistas apontam como uma fraqueza na camada de ozônio sobre o Vale do Itajaí – elevam número de tumores na pele dos blumenauenses. Fatores que estão entre os apontados pelos médicos ao morador Sérgio Augusto Gomes de Borba, que já viu o diagnóstico de câncer duas vezes.

Aos 60 anos, Borba é exemplo da importância dos exames e da resposta rápida contra os tumores. Dez ano atrás uma mancha na perna chamou a atenção e o fez procurar um dermatologista que confirmou o tumor. Como estava em estágio inicial, apenas uma cauterização resolveu o problema.

Cerca de dois anos atrás a situação se repetiu: uma verruga que não sarava no braço o fez voltar ao médico, que retirou o tumor em uma cirurgia e comprovou na biópsia que se tratava de um novo câncer. Com o diagnóstico, uma segunda cirurgia foi feita para garantir que nenhum resquício permanecesse na pele.

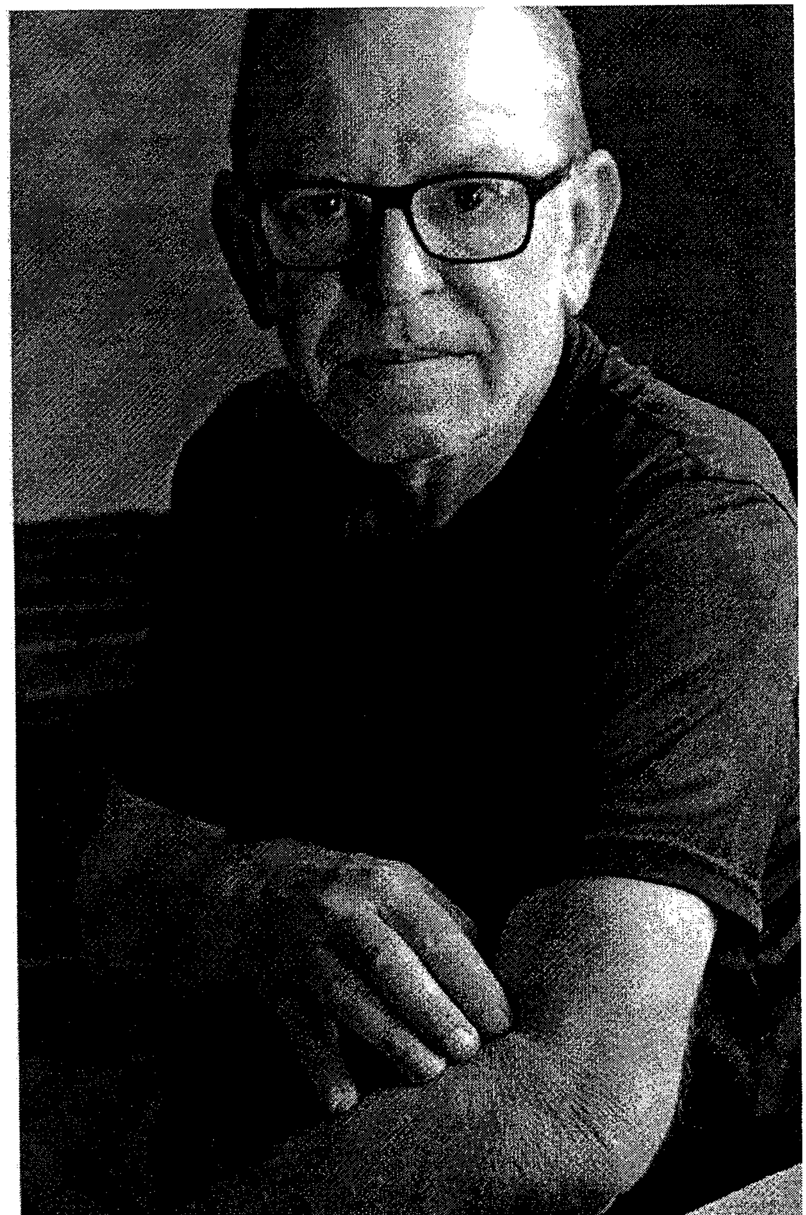

Foto: Patrick Rodrigues / NSC Comunicação

Com os casos vivenciados, o analista de sistemas aprendeu também a se prevenir e passar isso adiante aos filhos. Se antes o hábito de usar filtro solar era menos frequente e somente diante do sol forte, hoje o item é indispensável até na sombra da praia.

Mudança de comportamento em Joinville

Descobrir, aos 65 anos, que tinha um câncer considerado maligno, foi um susto para Maria Bandoch. Há um ano e meio ela percebeu que um sinal nas costas estava, estranhamente, coçando muito. E pouco tempo, a pinta tinha crescido e ficado "do tamanho de uma moeda". Moradora de Joinville, ela foi à policlínica no bairro Boa Vista e, lá, ouviu que seria encaminhada com urgência para biópsia.

– O câncer já estava enraizado. Precisaram abrir de fora a fora nas costas e tinha o risco de ter se espalhado recorda Maria.

Além de cirurgia, ela precisou passar por um mês de sessões de quimioterapia. Na época, deixou a atividad de costureira de lado porque não podia fazer movimentos que afetassem o local da cirurgia. Agora, ela faz acompanhamento médico a cada quatro meses e comemora o fato de não terem sido encontrados outros

A principal mudança, no entanto, foi de comportamento. Até os 20 anos, Maria viveu em um sítio em Indai e ajudava a família na lavoura. Desde a infância ela se expôs aos raios solares sem nunca pensar em proteçã para a pele.

– Eu pegava muito sol e ninguém falava sobre cuidar. Agora, sempre saio com a sombrinha e de protetor so – conta.

Conheça os sinais e os sintomas:

O câncer de pele pode se assemelhar a pintas, eczemas ou outras lesões benignas. Conhecer bem a pele e sal em quais regiões existem pintas faz toda a diferença na hora de detectar. Somente um exame clínico feito pc um médico especializado ou uma biópsia podem diagnosticar o câncer da pele, mas é importante estar aten aos sintomas:

Uma lesão na pele de aparência elevada e brilhante, translúcida, avermelhada, castanha, rósea ou multicolorida, com crosta central e que sangra facilmente;

Uma pinta preta ou castanha que muda de cor, textura, torna-se irregular nas bordas e cresce de tamanho;

Uma mancha ou ferida que não cicatriza, que continua a crescer apresentando coceira, crostas, erosões ou sangramento.

Os dados do Inca de 1979 a 2015 apontam que o maior número de mortes foi registrado de pessoas com idade entre 50 e 69 anos. Confira:

MUNICÍPIOS	0 A 4	5 A 9	10 A 14	15 A 19	20 A 29	30 A 39	40 A 49	50 A 59	60 A 69	70 A 79	80 OU MAIS	IDADE IGNORADA	TO
Blumenau	0	1	0	1	9	23	27	38	53	52	45	0	[illegible]
Brusque	0	0	0	0	2	9	8	9	12	11	12	0	[illegible]
Chapecó	0	0	0	0	3	6	11	25	14	13	8	1	[illegible]
Criciúma	0	0	0	0	5	6	14	19	19	23	16	0	[illegible]
Florianópolis	1	0	0	1	6	23	44	60	52	51	62	0	[illegible]
Itajaí	0	0	0	0	3	6	12	17	17	20	28	0	[illegible]
Jaraguá do Sul	0	0	0	0	4	3	19	41	25	15	21	0	[illegible]
Joinville	1	0	0	2	10	30	44	80	60	58	54	0	[illegible]
Lages	0	0	0	0	1	5	8	12	10	18	19	0	[illegible]
Palhoça	0	0	0	1	3	2	14	9	12	10	11	0	[illegible]
Porto União	0	0	0	0	1	1	3	12	10	11	13	0	[illegible]
Rio do Sul	0	0	0	0	0	2	7	9	11	9	9	0	[illegible]
São Bento do Sul	0	0	0	0	2	5	11	12	9	16	4	0	[illegible]
São José	0	0	0	1	6	15	20	29	32	16	22	0	[illegible]
Tubarão	0	0	0	0	3	7	8	9	14	19	13	0	[illegible]
Outros Municípios	1	0	6	14	81	177	268	428	402	369	376	0	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Foto:

MORTES POR CÂNCER DE PELE

Joinville, Florianópolis e Blumenau registraram o maior número de mortes por câncer de pele no Estado, conforme dados do Instituto Nacional de Câncer entre 1979 e 2015. Veja o histórico:

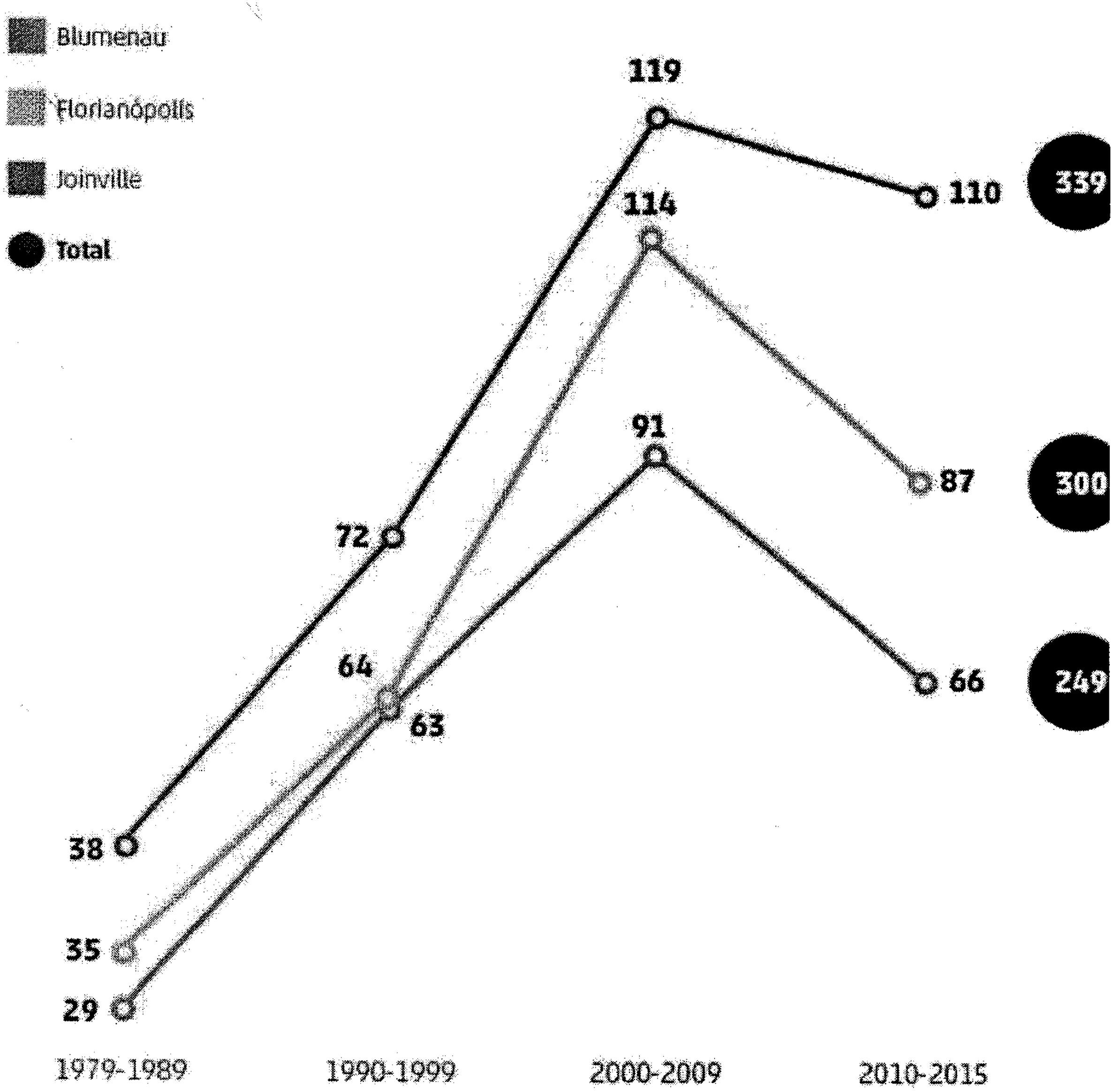

Foto:

abc ASSOCIAÇÃO BRASILEIRA DE COSMETOLOGIA

Ao Expediente da Mesa
Em 12/09/19
Deputado Laércio Schuster
1º Secretario

São Paulo, 11 de Setembro de 2019.

Lido no Expediente
083ª Sessão de 17/09/19
- Anexar ao PL. 077/19
Secretário

Ao Senhor:

Laércio Schuster
Deputado Estadual (PSB/SC)
Assembleia Legislativa do Estado de Santa Catarina (ALESC)
Rua Dr. Jorge da Luz Fontes, 310 – Centro, Florianópolis - SC
CEP: 88020-900

Assunto: *Defesa contrária à PL./0077.0/2019 – proibição do uso de protetores solares com determinados ingredientes classificados mundialmente como filtros UV e conservantes.*

Prezado Senhor,

A **Associação Brasileira de Cosmetologia – ABC**, como entidade científica representante do setor cosmético, vem através desta manifestar-se em relação ao que propõe a PL./0077.0/2019.

Consideramos louvável a preocupação e interesse dos deputados, em relação ao impacto das substâncias químicas ao meio ambiente, porém como entidade científica e representante do setor cosmético, nos sentimos na responsabilidade de expor alguns fatos relacionados a este tema:

✓ **Da incidência e mortes por câncer de pele no Brasil**

De acordo com o INCA (Instituto Nacional de Câncer) e SBD (Sociedade Brasileira de Dermatologia), o câncer de pele representa 33% de todos os diagnósticos desta doença no Brasil. O impacto dos gastos do governo no tratamento do câncer de pele, bem como os custos por morte oriundos da mesma causa são muito altos, sem considerar os efeitos colaterais do tratamento (perda dos cabelos, baixa imunidade, etc.) que acabam gerando outros fatores como: baixa autoestima, depressão, perda da qualidade de vida. Com base nestes dados podemos concluir que o impacto do câncer de pele na saúde pública é significante.

Estatísticas

	Homens	**Mulheres**	**Total**
Estimativa novos casos no Brasil	85.170	80.140	165.580
Número de mortes no Brasil	1.147	821	1.958

Medidas de prevenção

O INCA indica o uso do protetor solar como medida preventiva para o câncer de pele, principalmente em longos períodos de exposição ao sol (aumento do risco). Por uma questão de saúde, a proteção é necessária não somente aos indivíduos que frequentam áreas de banho como, por exemplo, as regiões praianas, mas também aos indivíduos que laboram nas ruas (carteiros, varredores de rua, etc.) ou que por qualquer outro motivo se expõe ao sol por um longo período.

No Chile, por exemplo, o filtro solar é EPI (Equipamento de Proteção Individual) e seu uso é obrigatório por pessoas que laboram em condições de exposição ao sol (Lei 20.096/2006 que descreve as condições de exposição à radiação ultravioleta e sanções para quem as violar) – **ver anexo I**.

✓ **Da segurança dos ingredientes em uso humano**

Atualmente o Brasil possui listas de ingredientes harmonizadas entre os países do grupo Mercosul e permitidos em cosméticos.

Para autorização do uso destas substâncias, as agências de cada país contam com um processo robusto de avaliação dos relatórios de análise toxicológica, de cada ingrediente, expedido pelos comitês científicos da Comunidade Europeia e EUA:

- SCCS (Scientific Committee on Consumer Safety)
- CIR (Cosmetic Ingrediente Review)

De acordo com as referências citadas acima, as substâncias mencionados na PL e utilizadas na composição química dos protetores solares, são seguras para uso humano nas condições e concentrações máximas permitidas nas legislações vigentes.

Enfatizamos que as listas de ingredientes permitidos, bem como a lista de ingredientes proibidos em cosméticos são temas permanentes na agenda do Mercosul. Portanto, sempre que necessário, as mesmas são atualizadas de acordo com novos estudos toxicológicos e novos posicionamentos com base em relatórios científicos reconhecidos internacionalmente.

Além da segurança, enfatizamos também que as moléculas de filtro UV atualmente disponíveis no mercado são o resultado de anos de estudo e investimento, representando uma evolução tecnológica em termos de espectro de proteção UV e sensorial aceitável pelo consumidor.

✓ **Dos estudos científicos sobre o impacto dos filtros solares em recifes de corais**

Em 2016 foi publicado o artigo *"Toxicopathological Effects of the sunscreen UV filter, Oxybenzone (Benzophenone-3), on Coral Planulae and Cultured Primary Cells and Its Environmental Contamination in Hawaii and the U.S. Virgin Slands"*, o qual propõe avaliar os efeitos da substância Benzophenone-3 (oxibenzona; BP-3) no fenômeno de branqueamento dos recifes de corais. Este foi utilizado como base cientifica para proibir o uso de protetores solares que contenham Benzophenone-3 no Havaí e Palau.

O estudo em questão foi realizado em condições *in vitro*, envolvendo somente parâmetros intrínsecos e desconsiderando as condições *in situ*, bem como o bioma nos quais os corais vivem.

Como é de conhecimento, a Austrália é o país onde existe a maior barreira de corais do mundo. Em função disto, diversos estudos são realizados pelos pesquisadores das Universidades locais com objetivo de conservá-los. Um dos mais renomados pesquisadores a frente destes estudos é o **Dr. Terry Hughes (Professor, Diretor do Centre of Excellence for Coral Reef Studies on Australia da James Cook University em Queensland/Austrália e Líder do Programa 1: People and Ecosystems)**, que afirma não existirem evidências suficientes, que demonstrem que a composição química dos protetores solares causam dano ou potencializam o fenômeno de branqueamento dos corais. Complementando, citamos alguns pontos evidenciados pelo Dr. Terry Hughes, que contra argumentam a credibilidade do estudo publicado em 2016 **(ver anexo II)**:

- A maneira pela qual os tecidos dos corais foram expostos aos filtros solares não representam a dispersão e diluição de poluentes da pele de um turista (e outras fontes) em águas de recifes e em corais existentes na natureza.

- Os experimentos que expõem os corais às substâncias oriundas da composição química de determinados protetores solares, normalmente utilizam concentrações muito mais altas do que os que já foram medidos em um recife nas condições *in situ* (condições reais). Uma revisão recente da quantidade de benzophenone-3 em águas onde vivem os recifes de corais demonstrou que tipicamente, as concentrações são dificilmente detectáveis.

- O estudo foi realizado com base em uma única amostragem, ou seja, as amostras não foram replicadas. Isto desqualifica o estudo, uma vez que se desconhece a reprodutibilidade dos resultados.

- Mesmo os recifes de corais mais antigos são vulneráveis ao estresse por calor. Os mecanismos fisiológicos e a escala temporal do branqueamento térmico, devido ao aquecimento global, são muito diferentes das respostas rápidas dos corais, à exposição experimental a altas concentrações de substâncias químicas.

Corroborando com Dr. Terry Hughes, outros artigos foram publicados reforçando que o branqueamento dos corais em uma escala global, tem como **principal causa o aquecimento global** que provoca o aumento da temperatura dos oceanos, seguido de outros fatores locais como: pesca excessiva, poluição oriunda de esgotos e escoamento agrícola **(ver anexo III)**.

Conclusão

Com base nas evidências científicas citadas, concluímos que:

1. Os estudos preliminares bem como o estudo publicado em 2016, utilizado como base para proibição do uso dos protetores solares no Havaí e Palau, não refletem as condições reais em que vivem os recifes de corais, portanto não podem ser utilizados como ferramentas para definição de politicas públicas.

2. Os estudos evidenciam que, a maior causa do fenômeno de branqueamento dos corais é o aumento da temperatura dos oceanos, em função do aquecimento global. Portanto, proibir o uso de protetores solares contendo as substâncias citadas na PL 616/2019, não é uma medida efetiva que contribui para a preservação dos recifes de corais.
3. A redução do número de substâncias de proteção UV restringe as opções de proteção eficaz do consumidor contra os raios ultravioletas, aumentando assim a incidência de câncer de pele na população brasileira e acarretando aumento dos gastos do governo com saúde pública.

Para finalizar e reforçar o posicionamento do setor cosmético, anexamos as declarações de desapontamento de entidades internacionais renomadas, em relação à tal medida **(ver anexo IV)**.

Certos do acolhimento deste pleito, colocamo-nos à disposição para quaisquer esclarecimentos necessários.

Cordialmente,

Vania R. Leite e Silva
Presidente ABC

Referências bibliográficas

- Instituto Nacional do Câncer (Ministério da Saúde): https://www.inca.gov.br/tipos-de-cancer
- Sociedade Brasileira de Dermatologia: http://www.sbd.org.br/dermatologia/pele/doencas-e-problemas/cancer-da-pele/64/
- European Committee; Scientific Committees on Consumer Safety https://ec.europa.eu/health/scientific_committees/consumer_safety_pt

- Ministério da Saúde: http://portalms.saude.gov.br/saude-de-a-z/cancer-de-pele

- ACHS: Asociación Chilena de Seguridad (https://www.achs.cl/portal/ACHS-Corporativo/newsletters/infoempresas/Paginas/Medidas-de-proteccion-solar-para-los-trabajadores.aspx

- ARC Centre of Excellence for Coral Reef Studies (https://www.coralcoe.org.au/# and https://www.coralcoe.org.au/person/terry-hughes)

- PCPC Personal Care Products Council 9 https://www.personalcarecouncil.org/statement/statement-from-the-consumer-healthcare-products-association-chpa-and-the-personal-care-products-council-pcpc-regarding-sunscreen-ingredient-ban/)

- AAD American Academy of Dermatology Association (https://www.aad.org/media/news-releases/aada-statement-on-sunscreen-access)

- CHPA Cosumer Health Products Association (https://www.chpa.org/SunscreenBan2018.aspx)

ASSOCIAÇÃO BRASILEIRA DE COSMETOLOGIA

ANEXO I

Chile
Ley Num. 20096/2006

Tipo Norma :Ley 20096
Fecha Publicación :23-03-2006
Fecha Promulgación :04-02-2006
Organismo :MINISTERIO SECRETARÍA GENERAL DE LA PRESIDENCIA
Título :ESTABLECE MECANISMOS DE CONTROL APLICABLES A LAS SUSTANCIAS AGOTADORAS DE LA CAPA DE OZONO
Tipo Versión :Única De : 23-03-2006
Inicio Vigencia :23-03-2006
Id Norma :248323
URL :https://www.leychile.cl/N?i=248323&f=2006-03-23&p=

LEY NUM. 20.096

ESTABLECE MECANISMOS DE CONTROL APLICABLES A LAS SUSTANCIAS AGOTADORAS DE LA CAPA DE OZONO

Teniendo presente que el H. Congreso Nacional ha dado su aprobación al siguiente

Proyecto de ley:

"Título I
Disposiciones generales

Artículo 1°.- Las disposiciones de esta ley establecen y regulan los mecanismos de control aplicables a las sustancias agotadoras de la capa de ozono estratosférico y a los productos cuyo funcionamiento requiera del uso de dichas sustancias, las medidas destinadas a la prevención, protección y evaluación de los efectos producidos por el deterioro de la capa de ozono, por la exposición a la radiación ultravioleta, y las sanciones aplicables a quienes infrinjan dichas normas.

Artículo 2°.- Los mecanismos de control y demás medidas que regula esta ley tienen por finalidad la adecuada implementación del Protocolo de Montreal, relativo a las sustancias que agotan la capa de ozono, suscrito y ratificado por Chile y promulgado mediante el decreto supremo N° 238, de 1990, del Ministerio de Relaciones Exteriores, y sus enmiendas posteriores, además de resguardar la salud humana y los ecosistemas que se vean afectados por la radiación ultravioleta.

Artículo 3°.- Conforme a lo previsto en el artículo anterior, los mecanismos de control que establece esta ley permiten registrar y fiscalizar la importación y exportación de sustancias agotadoras de la capa de ozono y de los productos que las utilicen en su funcionamiento, aplicar las restricciones y prohibiciones tanto a dichas operaciones como a la producción nacional de las sustancias indicadas cuando corresponda de conformidad con las estipulaciones del Protocolo de Montreal, y cautelar que la utilización y aplicación de tales sustancias y productos se realice de acuerdo con normas mínimas de seguridad para las personas.

Artículo 4°.- Para el adecuado resguardo de la salud de la población frente a los efectos producidos por el deterioro de la capa de ozono, esta ley establece un conjunto de medidas de difusión, prevención y evaluación tendientes a generar y proporcionar información idónea y oportuna a los sujetos expuestos a riesgo y a estimular conductas seguras frente a éste.

Título II

De las sustancias y productos controlados y de los mecanismos de control

Artículo 5°.- Para los efectos de esta ley, se entenderá por "sustancias controladas" aquellas definidas como tales por el Protocolo de Montreal, relativo a las sustancias que agotan la capa de ozono, individualizadas en sus Anexos A, B, C y E, ya sea en estado puro o en mezclas.

Para los efectos de esta ley, se entenderá por "productos controlados" todo equipo o tecnología, sea nuevo o usado, que contenga las sustancias señaladas en el inciso anterior, individualizados en el Anexo D del Protocolo de Montreal. Sin que la enumeración sea taxativa, se comprenden en esta categoría las unidades de aire acondicionado para vehículos motorizados, ya sea incorporadas o no a estos últimos, las unidades de aire acondicionado doméstico o industrial, los refrigeradores domésticos o industriales, las bombas de calor, los congeladores, los deshumificadores, los enfriadores de agua, las máquinas de fabricación de hielo, los paneles de aislamiento y los cobertores de tuberías, que contengan sustancias controladas.

Artículo 6°.- El consumo nacional de las sustancias y productos controlados a que se refiere el artículo anterior deberá ajustarse anualmente a los volúmenes máximos definidos en las metas de reducción progresiva establecidas por el Protocolo de Montreal, hasta lograr su total eliminación, todo ello de acuerdo con los plazos previstos para cada sustancia o producto.

Para tal efecto, desde la entrada en vigencia de esta ley, todas las sustancias y productos controlados quedarán sujetos a las medidas de control y a las restricciones y prohibiciones que establecen sus disposiciones.

Artículo 7°.- Se prohíbe la importación y exportación de sustancias controladas, desde y hacia países que no son Parte del Protocolo de Montreal.

Artículo 8°.- Se prohíbe la importación y exportación de productos, nuevos o usados, que contengan sustancias controladas por el Protocolo de Montreal, contempladas en sus Anexos A, B y Grupo II del Anexo C, desde y hacia países que no son Parte del Protocolo de Montreal.

Artículo 9°.- La importación y exportación de sustancias y productos controlados, desde y hacia países Parte del Protocolo de Montreal, deberán ajustarse a las normas, condiciones, restricciones y plazos previstos en dicho instrumento internacional.

Para tal efecto, mediante uno o más decretos del Ministerio Secretaría General de la Presidencia, que llevarán también la firma de los Ministros de Hacienda, Salud, Relaciones Exteriores, y Economía, Fomento y Reconstrucción, y, cuando corresponda, la del Ministro de Agricultura, se individualizarán las sustancias y productos controlados cuya importación y exportación estarán prohibidas conforme a las estipulaciones del Protocolo de Montreal y establecerán el calendario y plazos para la vigencia de dichas prohibiciones, así como los respectivos volúmenes de importación y exportación anuales para el tiempo intermedio y los criterios para su distribución.

Igual mecanismo se aplicará cuando, en virtud de nuevas decisiones y compromisos adquiridos por Chile para el cumplimiento del Protocolo de Montreal, deban incluirse nuevas sustancias y productos en el régimen de prohibiciones descrito.

Una vez dictados el o los decretos referidos, el Director Nacional de Aduanas, en uso de sus atribuciones, establecerá un sistema de administración de los volúmenes máximos de importación y exportación que en dichos instrumentos se determinen.

Con todo, los decretos que se dicten en virtud de este artículo podrán omitir el establecimiento de volúmenes máximos de importación y exportación anuales, siempre que de la información oficial, validada y proporcionada por los organismos competentes, conste que el consumo interno de la respectiva sustancia o producto controlado es inferior a la meta impuesta por el Protocolo de Montreal, y en tanto dicha circunstancia perdure.

Artículo 10.- Para los efectos de esta ley, serán aplicables las excepciones que el Protocolo de Montreal establece para determinadas sustancias controladas.
Las excepciones aplicables a cada sustancia o producto controlado serán explicitadas en el o en los decretos que se dicten en conformidad al artículo anterior.

Artículo 11.- El Servicio Nacional de Aduanas ejercerá las facultades fiscalizadoras que le otorga la ley para controlar el ingreso y la salida del país de las sustancias y productos controlados, en el momento de cursarse la destinación aduanera y, a posteriori, conforme a las normas establecidas en la Ordenanza de Aduanas y en la ley orgánica del referido Servicio.

Artículo 12.- Sin perjuicio de la fiscalización que compete a la autoridad sanitaria, al Servicio Agrícola y Ganadero y demás organismos competentes, corresponderá al Director Nacional de Aduanas impartir las instrucciones relativas a la forma de acreditar el cumplimiento de los requisitos, exigencias, documentos y visaciones aplicables a las sustancias y productos controlados, para la tramitación de las respectivas destinaciones aduaneras.
En todo caso, para cursar las destinaciones aduaneras de las sustancias y productos controlados aún no prohibidos, de las correspondientes a volúmenes de importación autorizados, o de los exceptuados en conformidad al artículo 10, el Servicio Nacional de Aduanas exigirá un certificado emitido por la autoridad sanitaria respectiva o por el Servicio Agrícola y Ganadero, según corresponda, que señale el lugar autorizado donde se depositarán las respectivas sustancias, la ruta y las condiciones de transporte desde los recintos aduaneros hasta el lugar de depósito indicado, y las modalidades de manipulación de las mismas.
Los certificados a que alude el inciso anterior deberán ser otorgados por el organismo competente dentro del tercer día de requerido y la solicitud sólo podrá denegarse mediante resolución fundada, sin perjuicio de la aplicación de las disposiciones sobre silencio negativo establecidas en el artículo 65 de la ley N° 19.880, sobre Bases de los Procedimientos Administrativos.
Sin perjuicio de lo anterior, será responsabilidad del importador y del exportador, respectivamente, verificar con su proveedor extranjero o nacional la naturaleza del producto o sustancia importado o exportado, para los efectos de dar cumplimiento a la normativa aplicable, correspondiendo al agente de aduanas verificar el cumplimiento de las exigencias o la obtención de las autorizaciones que procedan, conforme a lo dispuesto en el artículo 77 de la Ordenanza de Aduanas.

Artículo 13.- Transcurrido un año desde la fecha en que, de acuerdo con lo previsto en el artículo 9° de esta ley, entre en vigencia la prohibición de importación y exportación de una sustancia o producto controlado, quedará también prohibida la utilización industrial de los mismos.

Artículo 14.- Corresponderá al Ministerio de Salud dictar la reglamentación aplicable a la generación, almacenamiento, transporte, tratamiento o reciclaje de las sustancias y productos controlados, en la que deberán incluirse las normas que permitan una adecuada fiscalización de las actividades anteriores.

Artículo 15.- El reglamento establecerá las demás normas necesarias para la adecuada aplicación de lo previsto en este Título, sin perjuicio de las atribuciones normativas que la ley confiere a los organismos competentes en la materia.

Título III
De las medidas de difusión, evaluación, prevención y protección

Artículo 16.- Para la comercialización y utilización industrial de productos controlados que no estén prohibidos en conformidad a esta ley, en sus etiquetas y publicidad deberá incluirse un aviso destacado que advierta que dicho producto deteriora la capa de ozono.
El contenido, forma, dimensiones y demás características de este aviso serán determinadas por la normativa técnica que para tal efecto dictará el Ministerio de Economía, Fomento y Reconstrucción.
Corresponderá al Servicio Nacional del Consumidor velar por el cumplimiento de la obligación establecida

en este artículo, y su infracción será sancionada conforme a la ley N° 19.496, sobre Protección de los Derechos de los Consumidores.

Artículo 17.- Los efectos científicamente comprobados que produzca la radiación ultravioleta sobre la salud humana serán evaluados periódicamente por el Ministerio de Salud, sin perjuicio de las funciones que la ley asigne a otros organismos para la evaluación de dichos efectos sobre el ganado, especies vegetales cultivadas, flora y fauna y ecosistemas dependientes o relacionados.

Artículo 18.- Los informes meteorológicos emitidos por medios de comunicación social deberán incluir antecedentes acerca de la radiación ultravioleta y sus fracciones, y de los riesgos asociados.

Los organismos públicos y privados que midan radiación ultravioleta lo harán de acuerdo con los estándares internacionales y entregarán la información necesaria a la Dirección Meteorológica de Chile para su difusión. Estos informes deberán expresar el índice de radiación ultravioleta según la tabla que establece para estos efectos la Organización Mundial de la Salud, e indicarán, además, los lugares geográficos en que se requiera de protección especial contra los rayos ultravioleta.

Artículo 19.- Sin perjuicio de las obligaciones establecidas en los artículos 184 del Código del Trabajo y 67 de la ley N° 16.744, los empleadores deberán adoptar las medidas necesarias para proteger eficazmente a los trabajadores cuando puedan estar expuestos a radiación ultravioleta. Para estos efectos, los contratos de trabajo o reglamentos internos de las empresas, según el caso, deberán especificar el uso de los elementos protectores correspondientes, de conformidad con las disposiciones del Reglamento sobre Condiciones Sanitarias y Ambientales Básicas en los Lugares de Trabajo.

Lo dispuesto en el inciso anterior será aplicable a los funcionarios regidos por las leyes N°s. 18.834 y 18.883, en lo que fuere pertinente.

Artículo 20.- Los instrumentos y artefactos que emitan radiación ultravioleta, tales como lámparas o ampolletas, deberán incluir en sus especificaciones técnicas o etiquetas, una advertencia de los riesgos a la salud que su uso puede ocasionar.

El contenido, forma, dimensiones y demás características de esta advertencia serán determinadas por la normativa técnica que para tal efecto dictará el Ministerio de Economía, Fomento y Reconstrucción, en conjunto con el Ministerio de Salud.

Corresponderá al Servicio Nacional del Consumidor velar por el cumplimiento de la obligación establecida en este artículo, y su infracción será sancionada conforme a la ley N° 19.496, sobre Protección de los Derechos de los Consumidores, sin perjuicio de las facultades de la autoridad sanitaria en materia de protección de la salud de las personas.

Artículo 21.- Los bloqueadores, anteojos y otros dispositivos o productos protectores de la quemadura solar, deberán llevar indicaciones que señalen el factor de protección relativo a la equivalencia del tiempo de exposición a la radiación ultravioleta sin protector, indicando su efectividad ante diferentes grados de deterioro de la capa de ozono.

Corresponderá al Servicio Nacional del Consumidor velar por el cumplimiento de la obligación establecida en este artículo, y su infracción será sancionada conforme a la ley N° 19.496, sobre Protección de los Derechos de los Consumidores.

Artículo 22.- Cuando las leyes y reglamentos obliguen a exhibir carteles, avisos o anuncios en playas, balnearios y piscinas, relativos a su aptitud para el baño o la natación, o acerca de su estado de contaminación o condiciones de seguridad, deberá incluirse en aquéllos la siguiente advertencia: "La exposición prolongada a la radiación solar ultravioleta puede producir daños a la salud.".

Título IV
De las infracciones y sanciones

Artículo 23.- El que importare o exportare sustancias o productos controlados infringiendo las disposiciones de esta ley, sus reglamentos o normas técnicas, será sancionado con multa de 2 a 50 unidades tributarias mensuales, cuyo producto ingresará a rentas generales de la Nación.

Las sanciones por las infracciones antes citadas se aplicarán administrativamente por el Servicio Nacional de Aduanas, mediante el procedimiento establecido en el Título II del Libro III de la Ordenanza de Aduanas, pero no regirá a su respecto la rebaja establecida en el artículo 188 de dicho cuerpo normativo.

De las multas aplicadas conforme al inciso anterior se podrá reclamar ante la Junta General de Aduanas, de conformidad con lo dispuesto en el artículo 186 de la Ordenanza de Aduanas.

Con todo, en caso de que las infracciones sean constitutivas de delitos de contrabando u otros previstos en las leyes vigentes, los responsables serán sancionados penalmente conforme a dichas normas legales.

Artículo 24.- Las demás infracciones de las disposiciones de esta ley serán sancionadas con multa, a beneficio fiscal, de 2 hasta 50 unidades tributarias mensuales.

Será competente para conocer de dichas infracciones el juez de policía local correspondiente, sin perjuicio de la competencia que corresponda a los juzgados del trabajo, en su caso.

Artículo 25.- El Director Nacional de Aduanas ordenará, por la vía administrativa y previa coordinación con la autoridad sanitaria o el Servicio Agrícola y Ganadero, según corresponda, la eliminación o disposición final de las sustancias y productos prohibidos, y de aquéllos cuya importación y exportación quede prohibida en virtud de lo dispuesto en esta ley.

Título V
Disposiciones varias

Artículo 26.- No será aplicable la exigencia del certificado previsto en el artículo 12 de esta ley respecto del bromuro de metilo destinado a utilizarse en aplicaciones de cuarentena o de preembarque. En los demás casos, el certificado para dicha sustancia será otorgado por el Servicio Agrícola y Ganadero.

Artículo 27.- Las entidades importadoras, distribuidoras y usuarias de bromuro de metilo tendrán la obligación de declarar al Servicio Agrícola y Ganadero, trimestralmente, las cantidades del producto, adquiridas, almacenadas, distribuidas y utilizadas, por actividad productiva específica.

Artículo 28.- Las disposiciones de esta ley entrarán en vigencia desde la fecha de su publicación.".

Habiéndose cumplido con lo establecido en el N° 1 del artículo 93 de la Constitución Política de la República y por cuanto he tenido a bien aprobarlo y sancionarlo; por tanto promúlguese y llévese a efecto como Ley de la República.

Punta Arenas, 4 de febrero de 2006.- RICARDO LAGOS ESCOBAR, Presidente de la República.- Eduardo Dockendorff Vallejos, Ministro Secretario General de la Presidencia.- Jaime Campos Quiroga, Ministro de Agricultura.- Pedro García Aspillaga, Ministro de Salud.- Nicolás Eyzaguirre Guzmán, Ministro de Hacienda.

Lo que transcribo a Ud. para su conocimiento.- Saluda Atte. a Ud., Edgardo Riveros Marín, Subsecretario General de la Presidencia.

TRIBUNAL CONSTITUCIONAL

Proyecto de ley que establece mecanismos de protección y de evaluación de los efectos producidos por el deterioro de la capa de ozono

El Secretario del Tribunal Constitucional, quien suscribe, certifica que el Honorable Senado envió el proyecto de ley enunciado en el rubro, aprobado por el Congreso Nacional, a fin de que este Tribunal ejerciera el control de constitucionalidad respecto del artículo 24 del mismo, y por sentencia de 31 de enero de 2006, dictada en los autos Rol N° 466, declaró:

1. Que el artículo 24 del proyecto remitido es constitucional.
2. Que el artículo 23 del proyecto remitido es igualmente constitucional.

Santiago, 1° de febrero de 2006.- Rafael Larraín Cruz, Secretario.

Tipo Norma	:Ley 20096
Fecha Publicación	:23-03-2006
Fecha Promulgación	:04-02-2006
Organismo	:MINISTERIO SECRETARÍA GENERAL DE LA PRESIDENCIA
Título	:ESTABLECE MECANISMOS DE CONTROL APLICABLES A LAS SUSTANCIAS AGOTADORAS DE LA CAPA DE OZONO
Tipo Versión	:Única De : 23-03-2006
Inicio Vigencia	:23-03-2006
Id Norma	:248323
URL	:https://www.leychile.cl/N?i=248323&f=2006-03-23&p=

LEY NUM. 20.096

ESTABLECE MECANISMOS DE CONTROL APLICABLES A LAS SUSTANCIAS AGOTADORAS DE LA CAPA DE OZONO

Teniendo presente que el H. Congreso Nacional ha dado su aprobación al siguiente

Proyecto de ley:

"Título I
Disposiciones generales

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Artículo 2°.- Los mecanismos de control y demás medidas que regula esta ley tienen por finalidad la adecuada implementación del Protocolo de Montreal, relativo a las sustancias que agotan la capa de ozono, suscrito y ratificado por Chile y promulgado mediante el decreto supremo N° 238, de 1990, del Ministerio de Relaciones Exteriores, y sus enmiendas posteriores, además de resguardar la salud humana y los ecosistemas que se vean afectados por la radiación ultravioleta.

Artículo 3°.- Conforme a lo previsto en el artículo anterior, los mecanismos de control que establece esta ley permiten registrar y fiscalizar la importación y exportación de sustancias agotadoras de la capa de ozono y de los productos que las utilicen en su funcionamiento, aplicar las restricciones y prohibiciones tanto a dichas operaciones como a la producción nacional de las sustancias indicadas cuando corresponda de conformidad con las estipulaciones del Protocolo de Montreal, y cautelar que la utilización y aplicación de tales sustancias y productos se realice de acuerdo con normas mínimas de seguridad para las personas.

Artículo 4°.- Para el adecuado resguardo de la salud de la población frente a los efectos producidos por el deterioro de la capa de ozono, esta ley establece un conjunto de medidas de difusión, prevención y evaluación tendientes a generar y proporcionar información idónea y oportuna a los sujetos expuestos a riesgo y a estimular conductas seguras frente a éste.

Título II

ASSOCIAÇÃO BRASILEIRA DE COSMETOLOGIA

ANEXO II

Evidências do Dr. Terry Hughes que contra argumentam a credibilidade do estudo publicado em 2016

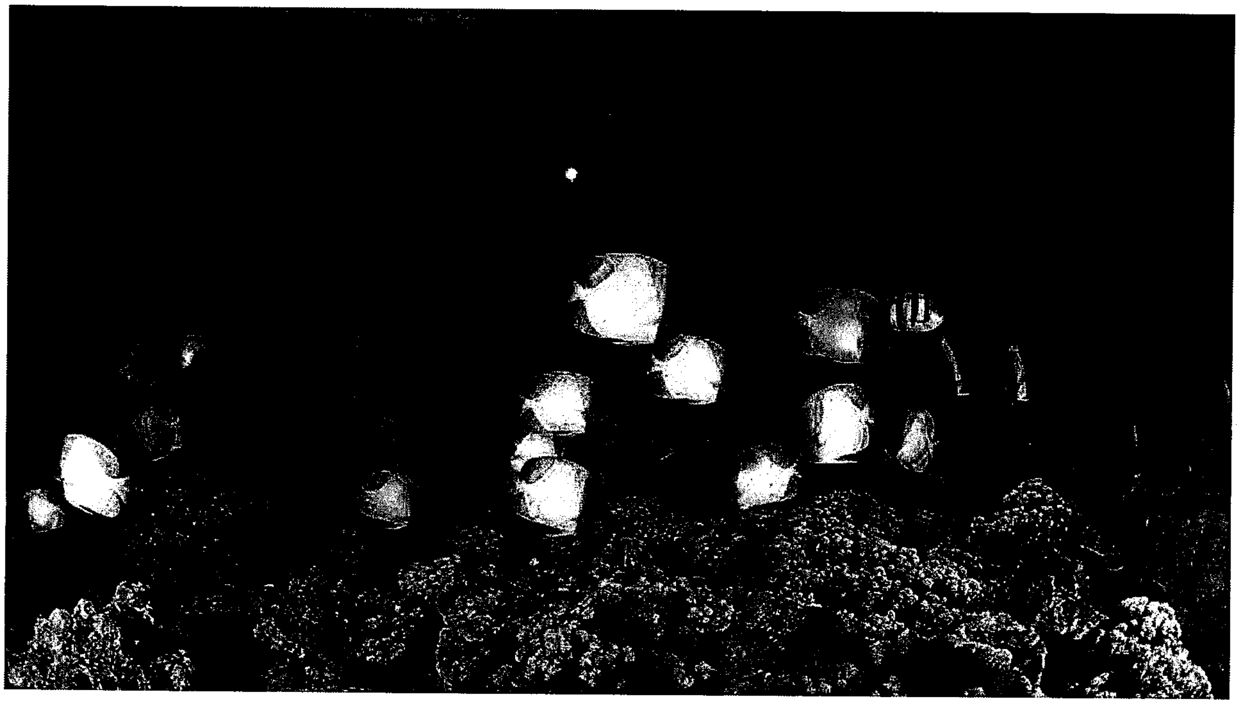
No, your sunscreen isn't killing the world's coral reefs

mashable.com/2015/11/10/sunscreen-killing-coral-reefs/

By Ariel Bogle 2015-11-11 00:40:21 UTC
816

Shares

What's This?



A diver in a reef near Molokini Crater, Maui, Hawaii.

Image: ullstein bild/Getty

By Ariel Bogle2015-11-11 00:40:21 UTC

Swimmers that slather themselves in sunscreen are doing their skin a favour, but it might not be so helpful to any nearby coral reefs. That claim, released in a recent scientific study, sparked global headlines faulting sunscreen for the global decline of these hotbeds of biodiversity.

It's a disturbing idea that something so necessary for protecting humans from skin cancer could be doing so much environmental damage, but what weight should we give this scientific finding?

Not much, it turns out.

See also: New photo shows the expansive dunes of Saturn's strange, hazy moon Titan

The authors of the report, who hail from labs and universities in the U.S. and Israel, found that oxybenzone, an active ingredient in some sunscreens that protects against ultraviolet light, was present in significant quantities around reefs in Hawaii and the Virgin Islands that were favoured by swimmers and divers.

People sunbathe on a beach in Nice, southeastern France, Friday, Sept 18, 2015.

Image: Lionel Cironneau/Associated Press

They determined the chemical has a detrimental affect on the DNA of coral in both its juvenile and adult stages.

The study was published in the journal, *Archives of Environmental Contamination and Toxicology*.

In the lab, the researchers exposed coral to high concentrations of oxybenzone. Not only did it deform coral larvae by "trapping them in their own skeleton," the study found it was also a factor in coral bleaching.

Terry Hughes, director of the Australian Research Council Centre of Excellence for Coral Reef Studies at James Cook University, told *Mashable Australia* he thought the report's findings were inconclusive.

"This particular study was done in a laboratory, so they actually used artificial sea water," he explained. "They put tiny bits of coral into aquaria and then added some chemicals. It's not surprising coral don't like chemicals thrown at them."

Mike van Keulen, director of the Coral Bay Research Station at Murdoch University, agreed that laboratory studies are going to be limited in their scope. However, he thought the study did provide some "concerning" information about the toxicity of some of the compounds contained in sunscreen.

"If we start adding together all these little things, toxins from sunscreen, but also sewage, over-fishing ... they will all together reduce the resilience of coral reefs," van Keulen said, "so they're no longer able to withstand big things like coral bleaching."

Reefs have far bigger threats than sunscreen toxins

In October, the National Oceanic and Atmospheric Administration (NOAA) announced the world's third-ever global coral bleaching event was taking place.

This refers to the phenomena whereby coral turns white after expelling algae in response to higher water temperatures, among other factors, which make the corals more susceptible to bacteria and other sources of stress.

A coral reef that has been bleached.

Image: Catlin Seaview Survey

The bleaching event comes as the world's oceans have heated up to the warmest levels ever recorded since instrument records began in the late 19th century.

Hughes added that the media's extrapolations that sunscreen is threatening the world's coral "are a bit of a stretch."

"The conclusion from the media is sunscreen is killing the world's coral, and that's laughable," he said.

For its part, the report claims that at least 10% of the global reefs are at risk of exposure. "Many reefs are remote, without tourists, and many of them nonetheless are showing impact from climate change ... if you want to study global threats, you have to look on a global scale and they haven't done that," Hughes said of the sunscreen study.

One of the authors of the sunscreen study, Craig A. Downs, executive director of the Haereticus Environmental Laboratory, told *Mashable Australia* in an email he thought the reefs at risk globally from oxybenzone pollution were probably at 30%, but the team went with "the most reasonable conservative number."

"Whatever island/reef system that is populated, and sees intense visitation by 'Westerners' (including Aussies, New Zealanders) as well as by the soaring Chinese tourism phenomenon, you have sunscreen usage, and hence, contamination," he said. "It is not just swimmers, as the source, but also sewage."

Hughes also said the report offered only "limited" data about the concentration of the chemical at tourists sites.

Down acknowledged the Hawaii levels reported in the paper were at the very low end, and numbers used were from "a cursory survey," as the paper states. "At the time, we were looking at environmental microbiology samples... and so had to collect early in the morning BEFORE swimmers of the tourist variety had a chance to get into the water," he wrote.

So, where do the chemicals in sunscreen rank in the taxonomy of threats to global reefs?

"The biggest stresses are climate change, overfishing and pollution, and pollution more generally than sunscreen," Hughes said. "Sunscreen, because of its source, is far less of a problem than run off of pesticides in rivers."

Downs agreed. "My professional opinion is that agricultural run-off and sewage ... are probably responsible for the historical collapse of coral reefs for the past 40 years," he said.

So, your sunscreen could be doing damage, but not at the global scale headlines implied. Plus, sunscreen is vital to lowering your odds of skin cancer.

Next time you go to the beach, consider a sunscreen without all of that oxybenzone, but more importantly, lobby your local politicians for better agricultural practices and action on climate change.

THE CONVERSATION
Academic rigor, journalistic flair

There's insufficient evidence your sunscreen harms coral reefs

February 4, 2019 2.14pm EST

Keep slip slop slapping this summer. DAVE HUNT/AAP

There's insufficient evidence your sunscreen harms coral reefs

February 4, 2019 2.14pm EST

In the face of persistent heatwaves, Australians are reaching for the sunscreen. But you might have heard some mixed messages about its harm to the environment – specifically to coral reefs.

In July 2018, Hawaii passed a law to prohibit the future sale of sunscreens containing benzophene-3 and octinoxate, claiming these two chemicals increase coral bleaching, and have significant harmful impacts on Hawaii's marine environment.

Author

Terry Hughes
Distinguished Professor, James Cook University

Read more: Marine heatwaves are getting hotter, lasting longer and doing more damage

In October 2018, the Republic of Palau followed suit, and banned "reef-toxic" sunscreens. Like most reefs throughout the tropics and subtropics, coral reefs in Hawaii and Palau have already severely bleached multiple times during recent, unusually hot summers, causing extensive loss of corals.

Key West, in Florida, may be the latest area to follow this trend, with a proposed ban to be voted on in early February.

However, medical and skin cancer specialists have warned of the public health risks of a ban on widely used sunscreens, describing the prohibition as risky and unjustified, in part because the few studies that have addressed the environmental impacts of sunscreens experimentally "are not representative of real world conditions".

For example, the way in which coral tissues were exposed to sunscreen in experiments does not mimic the dispersal and dilution of pollutants from a tourist's skin (and other sources) into reef waters and onto corals growing in the wild.

Experiments that expose corals to sunscreen chemicals typically use far higher concentrations than have ever been measured on an actual reef. A recent review of the amount of benzophne-3 in reef waters found that, typically, concentrations are barely detectable – usually, a few parts per trillion. One much higher report of 1.4 parts per million, in the US Virgin Islands, is based on a single water sample.

The environmental concerns over sunscreens on coral reefs are centred overwhelmingly on just two studies. The first, published in 2008, noted that there was no previous scientific evidence for an impact of sunscreens on coral reefs.

This study exposed small fragments of corals (branch tips) to high levels of benzophenone-3 and other chemicals by incubating them for a few days inside plastic bags. The fragments in the bags quickly became diseased with viruses and bleached. The authors concluded "up to 10% of the world reefs are potentially threatened by sunscreen-induced coral bleaching".

Bleaching is a stress response by corals, where they turn pale due to a decline in the symbiotic micro-algae that lives inside their tissues. You can make a coral bleach experimentally by torturing it in any number of ways. However, coral bleaching at a global and regional scale is caused by anthropogenic heating, not sunscreen. We know the footprint of bleaching on the Great Barrier Reef in 1998, 2002, 2016 and 2017 is closely matched to where the water was hottest for longest in each event.

Even the most remote reefs are vulnerable to heat stress. The physiological mechanisms and timescale of thermal bleaching due to global heating is very different from the rapid responses of corals to experimental exposure to high concentrations of sunscreen chemicals.

The second and most-widely cited study of sunscreen toxicity on corals is also laboratory-based. Published in 2016, it focused mainly on the responses of the day-old larvae of one coral species, as well as isolated coral cells. This study did not examine intact coral colonies.

The larvae were placed in 2-3 centilitres of artificial seawater containing a range of concentrations of sunscreen chemicals and a solvent to disperse them. After a few hours, the coral larvae became increasingly pale (bleached) with higher concentrations of oxybenzone.

Read more: Why there's still hope for our endangered coral reefs

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This study also measured the concentration of benzophenone in sea water at six locations in Hawaii. These samples were unreplicated (one per location), and all of them had unmeasureable amounts of sunscreen chemicals. In the US Virgin Islands, the authors found higher concentrations of benzophenone at four out of ten locations, although they did not report results for any blank samples (to control for contamination). The study concluded that oxybenzone threatens the resilience of coral reefs to climate change.

In conclusion, there is actually no direct evidence to demonstrate that bleaching due to global heating is exacerbated by sunscreen pollutants. Similarly, there is no evidence that recovery from thermal bleaching is impaired by sunscreens, or that sunscreens cause coral bleaching in the wild.

Sunscreen **Great Barrier Reef** **Coral** **Coral bleaching**

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ANEXO III

Artigos que evidenciam o aquecimento global como principal causa do branqueamento dos recifes de corais

PLOS | ONE

RESEARCH ARTICLE

A new, high-resolution global mass coral bleaching database

Simon D. Donner[1]*, Gregory J. M. Rickbeil[2], Scott F. Heron[3,4,5]

1 Department of Geography, University of British Columbia, Vancouver, British Columbia, Canada, 2 Integrated Remote Sensing Studio, Faculty of Forestry, University of British Columbia, Vancouver, British Columbia, Canada, 3 Coral Reef Watch, National Oceanic and Atmospheric Administration, Townsville, Queensland, Australia, 4 Global Science and Technology, Inc., Greenbelt, Maryland, United States of America, 5 Physics Department and Marine Geophysical Laboratory, College of Science, Technology and Engineering, James Cook University, Townsville, Queensland, Australia

* simon.donner@ubc.ca

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Abstract

Episodes of mass coral bleaching have been reported in recent decades and have raised concerns about the future of coral reefs on a warming planet. Despite the efforts to enhance and coordinate coral reef monitoring within and across countries, our knowledge of the geographic extent of mass coral bleaching over the past few decades is incomplete. Existing databases, like ReefBase, are limited by the voluntary nature of contributions, geographical biases in data collection, and the variations in the spatial scale of bleaching reports. In this study, we have developed the first-ever gridded, global-scale historical coral bleaching database. First, we conducted a targeted search for bleaching reports not included in ReefBase by personally contacting scientists and divers conducting monitoring in under-reported locations and by extracting data from the literature. This search increased the number of observed bleaching reports by 79%, from 4146 to 7429. Second, we employed spatial interpolation techniques to develop annual 0.04° × 0.04° latitude-longitude global maps of the probability that bleaching occurred for 1985 through 2010. Initial results indicate that the area of coral reefs with a more likely than not (>50%) or likely (>66%) probability of bleaching was eight times higher in the second half of the assessed time period, after the 1997/1998 El Niño. The results also indicate that annual maximum Degree Heating Weeks, a measure of thermal stress, for coral reefs with a high probability of bleaching increased over time. The database will help the scientific community more accurately assess the change in the frequency of mass coral bleaching events, validate methods of predicting mass coral bleaching, and test whether coral reefs are adjusting to rising ocean temperatures.

Introduction

The fate of coral reefs on a warming planet has been the subject of great attention from scientists, governments, and the general public over the past few decades. Prolonged ocean temperatures of only 1–2°C above the range of usual coral experience can lead to the paling of reef-building animals due to a breakdown of the symbiosis with the colourful dinoflagellate

analysis, decision to publish, or preparation of the manuscript.

Competing interests: SF Heron is affiliated with the U.S. Government contractor, Global Science and Technology, Inc.; the authors declare that there are no competing interests and we adhere to PLOS ONE policies on sharing data and materials.

Symbiodinium that reside in coral tissue [1]. Episodes of such mass coral "bleaching" around the world since the early 1980s have led to widespread coral mortality and raised questions about the viability of coral reef ecosystems during a period of rapid climate change [2] [3] [4]. Climate attribution research has found that anthropogenic forcing is likely (>90% chance) to drive recent mass bleaching episodes, including the extensive bleaching across the Eastern Caribbean in 2005 [5] and the northern Great Barrier Reef in 2016 [6]. Modeling studies suggest that projected ocean warming over the next three to four decades may make mass coral bleaching a frequent occurrence on most reefs worldwide, depending on assumptions about coral-symbiont acclimation and adaptation [7] [8] [9] [10].

Despite the overwhelming research attention and concern about mass coral bleaching, our knowledge of the extent of past bleaching episodes is greatly limited by geographical biases in the observational effort and the existing datasets cataloguing those efforts. The widely-used historical bleaching data available from ReefBase (reefbase.org) are limited by the voluntary nature of the submission to the database. Observations in ReefBase are clustered in more developed countries and areas of research interest, like the Caribbean and the Galapagos [11]. The available historical data therefore feature an unknown number of unobserved events or "false negatives." In particular, the lack of data from the Pacific Ocean, home to the majority of the world's coral reefs by area, severely limits the applicability of the data to: (i) global-scale analysis, (ii) enhancing real-time prediction methods, (iii) calibrating models for future prediction, or (iv) testing for acclimation or adaptation over time [11] [12]. Even in cases where bleaching reports are available, the uneven sampling effort creates geographic biases in the number and extent of recorded observations. For example, a 2002 bleaching event in Fiji, home to over 300 islands, has only two point reports in ReefBase, whereas an event that same year in Panama, which has only 10% the reef area of Fiji, has 65 reports. The number or spatial extent of available bleaching reports from ReefBase is therefore not a reliable measure of the change in the frequency of mass coral bleaching over time.

For this study, we developed a two-step process to address the shortcomings of the available global bleaching data. First, we developed a more comprehensive observational database of bleaching reports using targeted outreach to members of the international coral reef monitoring community and by searching the grey and academic literature. Second, we employed indicator kriging to develop annual high-resolution maps of the probability of bleaching occurrence from 1985 through 2010. We then analysed the new datasets to test for changes in the frequency of mass bleaching and the heat stress thresholds at which bleaching tends to occur. The products of this effort will be valuable for describing the extent of past bleaching events, testing bleaching prediction methods, and informing models that project the long-term response of coral reefs to ocean warming.

Materials and methods

Observational bleaching dataset

The new database follows the ReefBase format, including categories for source, country and site names, latitude and longitude of observation, year, month, percent bleached, percent mortality, depth, and survey method (Table 1). The percent bleached (and mortality, where available) is converted into a categorical variable following the same protocol as ReefBase (Table 2). While this simple method of bleaching reporting has many shortcomings, most notably no requirement for data on bleaching by taxa, it allows for consistency in reporting over time and for the inclusion of reports from rapid and low-technology bleaching assessments as well as those conducted by non-scientists.

Table 1. Bleaching database legend.

Category	Description
Country	Follows ReefBase convention
Location	State, region or island
Site_Name	Dive site or local community
Latitude	In decimal degrees
Longitude	In decimal degrees
Date	Date of observation *
Month	Month of observation *
Year	Year of observation
Depth	Depth of observation *
Severity_Code	See Table 2
Percent_Bleached	Percent of coral bleached
Mortality_Code	See Table 2
Percent_Mortality	Percent mortality, as a fraction of coral cover *
Survey_Type	Survey type (e.g., random swim, point intercept transect, etc) *
Source	Initial source of the report (i.e., dataset or group)
Name	Name of contributor of report to database (if relevant)
Citation	Source manuscript or report
Comments	Other comments on the record
Entry_Code	Researcher who entered the data
Database_Code	1 = ReefBase, 2 = New database

*if available

https://doi.org/10.1371/journal.pone.0175490.t001

There were two stages in creating the database. First, the observational records in ReefBase were downloaded (for data through 2010, see "Thermal Stress and Data Analysis") and subjected to a quality control procedure. If sufficient information was available, reports of non-warmwater bleaching (e.g., due to freshwater runoff or tidal exposure) and thermal bleaching caused by local events (warm power plant effluent) were removed [11]. In addition, reports with erroneous coordinates (bleaching reported on land) were corrected where possible using other location information and Google Earth, or otherwise removed.

Second, additional reports were collected from researchers and reef managers through a process of friendly coercion and literature research. This targeted "reef-by-reef" personal approach was used because of the typically low response rate to generic survey requests [13]. Research assistants and the lead author conducted a search of the Coral-List archives (available at http://coral.aoml.noaa.gov/pipermail/coral-list/) and the scholarly and grey literature (using Google Scholar, for publications from 1980 to 2012) for mentions of both "coral" and

Table 2. Bleaching severity categories.

Level	Severity
-1	% unknown
0	No bleaching
1	Mild (1–10% bleached)[1]
2	Moderate (11–50% bleached)
3	Severe (>50% bleached)[1]

[1] Mild and Severe are referred to as Low and High, respectively, in ReefBase

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"bleaching." Authors describing bleaching observations not or only partially recorded in ReefBase were then personally contacted for details on the event as well as any additional bleaching reports from other years or sites in their region of expertise. In addition, researchers and reef managers working in countries that were under-represented in ReefBase, the Coral-List archives, and the literature were personally contacted for missing observations.

For each data source, a personal email requesting data to help fill the specific geographical gap in ReefBase was sent to each contact, followed by a generic description of the database project. The recipients were offered to either share the raw information or to input the bleaching reports(s) directly via a template on our research group's website. Each geographical coordinate with a unique bleaching observation was assigned a unique ID and thus included as an independent record in the database, provided that sufficient details were available (at minimum: the geographical coordinates, year of occurrence, and percent bleaching). Each new record in the database includes the name of the source and/or a literature citation.

The dataset ends in 2010 due to the time lag between bleaching occurrence and the availability of reports, as well as the availability of high-resolution historical sea surface temperature and thermal stress data reconstructed from satellite observations (see "Thermal Stress and Data Analysis").

Spatial modeling of bleaching occurrence

The probability of bleaching occurrence in a given year was spatially modelled across the world's warmwater coral reefs at 0.04° × 0.04° latitude-longitude resolution using indicator kriging [14] [15]. This technique is designed to interpolate probabilities of occurrence of a binary condition, like the presence of a species, or in this case, a bleaching observation. Warmwater coral reef locations were extracted from the Millennium Coral Reef Mapping Project (UNEP-WCMC) [16]; all 0.04° × 0.04° grid cells containing reefs, regardless of attributes, were counted as reef cells in the model.

Bleaching presence in a given year was defined as any grid cell that contained at least one report of severity level 2 or 3 (>10% bleaching). Reports with lower or unknown bleaching severity were excluded because they are likely to represent non-lethal events or mistaken observations. Suggett and Smith [17] note misreading of non-lethal minor bleaching occurrences is a particular problem in voluntary monitoring and citizen science efforts, which were commonly the source of the original ReefBase data.

Pseudo-absences in a given year were defined as any reef cell for which the Degree Heating Week (DHW) values in 0.04° × 0.04° NOAA Coral Reef Watch data for the entire year were zero (see "Thermal Stress and Data Analysis"). The lack of positive DHW values indicates no thermal stress occurred that year. Thermal stress was otherwise not employed in the model. The interpolated bleaching probabilities therefore reflect only the observational data, the geography of the world's coral reefs, and the lack of any thermal stress, not the magnitude of thermal stress or any other physical or biological variables. A subset (14%) of the observed bleaching reports had to be omitted from the indicator kriging procedure because of conflict between the coordinates of the observation, the cells on the coral reef maps, and/or the land mask in the Coral Reef Watch dataset.

For each year and region, empirical semi-variograms were assessed for range, sill, and nugget values after which eight different modeled semi-variograms (Exponential, Spherical, Gaussian, Matern, Stein's Matern, Circular, Linear, Bessel, Pentaspherical) were fit [18]. The model with the lowest Root Mean Squared Error was selected and used to estimate the bleaching probability in each grid cell. In cells with a raw bleaching observation but annual maximum DHW of 0°C-weeks, the estimated bleaching probability will be less than 1; the kriging procedure records both a bleach point and a pseudo-absence point, and the estimated probability for that grid cell, as for all other cells, must be calculated following the selected model. No indicator kriging was carried out if there were no reports that year or all eight of the modeled semi-variograms failed to converge due to the low number of bleaching observations that year. In those cases, the interpolated bleaching probability is zero for all cells, regardless of whether bleaching was observed.

The kriging procedure was carried out separately for the Caribbean, Indian Ocean, the main Pacific Ocean, and the Eastern Pacific Ocean in each year. The Eastern Pacific (e.g., Galapagos and Central America) was treated separately because of the distance from other Pacific coral reefs. To reduce computational requirements, the main Pacific Ocean was split into three sections with 1000 kilometres of overlap between each section; estimated bleaching probabilities were averaged in these overlapping sections to eliminate arbitrary edge effects from splitting the domain.

The resulting 0.04° × 0.04° gridded probability maps are presented here. The maps were also re-projected onto the initial reef polygon map from the Millennium Coral Reef Mapping Project to calculate the area of reefs with different probabilities of bleaching in each year. Regional analysis was conducted using regions defined by Kleypas et al. [19].

Thermal stress data and analysis

To determine which reef locations were exposed to thermal stress and in which years, we used satellite-derived temperature data, following Heron et al. [20] and briefly described here. The Pathfinder version-5.2 dataset [21] is a NOAA Climate Data Record for sea surface temperature. From this, thermal stress for the period 1985–2010 was determined by the DHW metric [22], which combines the magnitude and duration of anomalous warm temperatures. Reef locations were identified as stressed in each year that the DHW value was greater than 0°C-weeks. The annual maximum value is used because the bleaching reports do not consistently contain sufficient information about the timing of bleaching onset and peak in the observational database; for example, 15% of the data in ReefBase do not report the month of observation at all.

Results

Observational database

After quality control procedure and removal of no bleaching reports, there were 4146 independent bleaching reports in the ReefBase data through 2010 (Table 3). The new observational dataset has 7429 reports, an increase of 79% from the ReefBase total. Two-thirds (67%) of the

Table 3. Summary of observational bleaching data.

Observations		Total	Severe	Moderate	Mild	Unknown
ReefBase	All years	4146	1169 (28%)	907 (22%)	1406 (34%)	664 (16%)
	1998	1431 (35%)	690	378	335	28
	2005	533 (13%)	75	175	266	17
New Records	All years	3283	1062 (32%)	1137 (35%)	1001 (30%)	83 (3%)
	1998	42 (1%)	19	12	10	1
	2005	2098 (64%)	729	748	618	3
Total	All years	7429	2231 (30%)	2044 (28%)	2407 (32%)	747 (10%)
	1998	1473 (20%)	709	390	345	29
	2005	2631 (35%)	804	923	884	20

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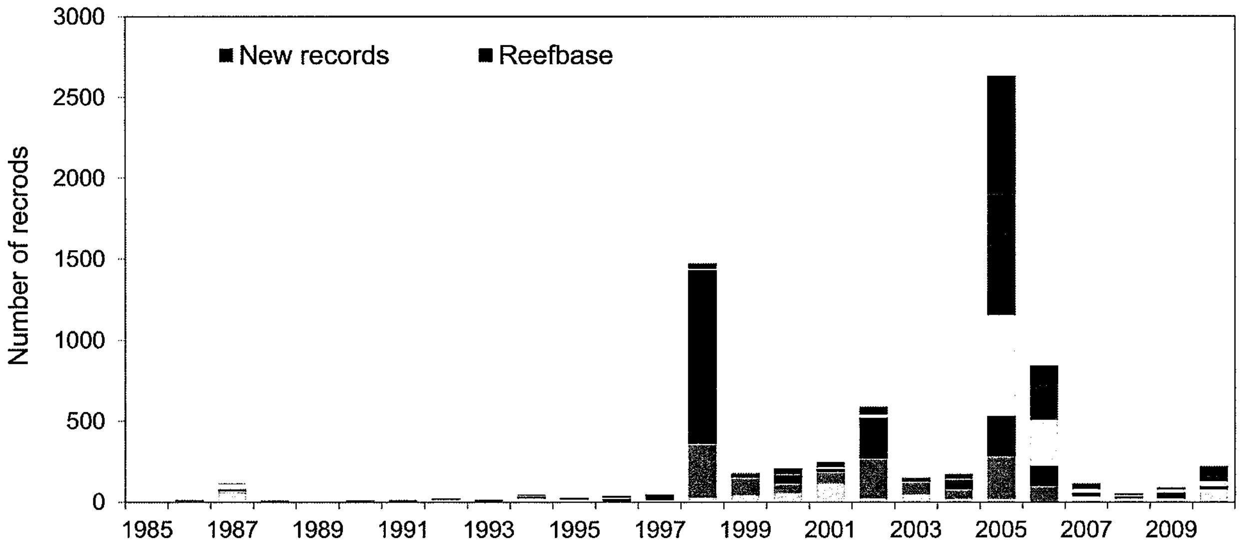

Fig 1. Annual number of bleaching observations for 1985–2010. Blue bars represent original ReefBase reports; orange bars represent new reports. Shading reflects bleaching level, from mild (1–10%) or unknown extent of bleaching (levels 1 and -1 in Table 2, lightest colour) to severe (>50%) bleaching (level 3, darkest colour).

https://doi.org/10.1371/journal.pone.0175490.g001

new reports are bleaching level 2 and 3, in contrast to 50% of the ReefBase reports of this severity. The highest number of new bleaching reports (64%) come from the Caribbean in 2005 where there was extensive bleaching [23] that was not well documented in ReefBase. Due to the additional reports, 2005 emerges as the year with the highest number bleaching observations, rather than 1997/1998 from ReefBase alone (Fig 1). There are also substantial increases in the number of reports from Indo-Pacific countries under-represented in ReefBase. For example, reports from Kenya (22 to 59 reports) and Fiji (56 to 114) are more than doubled in the new database, while reports from Kiribati reports increase from only 2 in ReefBase to 39 in the new database.

The new database shows a dramatic increase in the number of bleaching observations over time. Bleaching reports begin in the 1960s, but no single year has more than 20 observations until 1982, or more than 100 observations until 1987. There are only 12 observations of bleaching at any level before 1980; this increased to 236 during the 1980s, 1874 during the 1990s, and 5094 during the 2000s. If only observations of moderate to severe (level 2 and 3) bleaching are considered, there are just two reports before 1980, 63 during the 1980s, 1232 during the 1990s, and 2863 during the 2000s.

Due to uneven sampling effort and the geography of coral reefs, the number of observations is a potentially misleading measure of the extent of bleaching in a given year. Gridding the data onto the 0.04° × 0.04° resolution indicates that the spatial extent of bleaching observations was highest in 1998, rather than 2005 (Fig 2). Though numerous, the new 2005 reports are clustered in the eastern Caribbean with multiple reports per grid cell. The gridded data suggest that new reports represent a 61% increase in the reported area of cells with bleaching (over ReefBase), with 50% of that increase occurring in 2005, 14% in 2006, and 9% in 2010. Integrating over the entire time period (Fig 3), the largest relative increase in observed bleaching occurred in the Caribbean (333% increase), followed by Micronesia (205%), Western Indian Ocean (172%), Melanesia (164%), Polynesia (129%), and Southeast Asia (122%). The area of

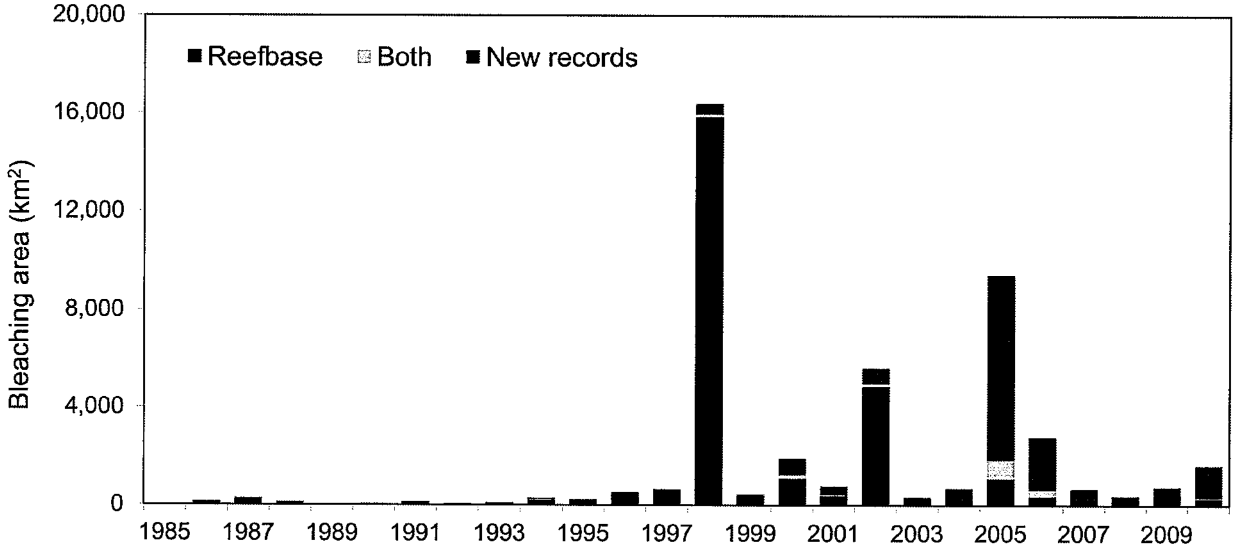

Fig 2. Annual area of moderate and severe (level 2 and 3) bleaching observations for 1985–2010. The area is computed from 0.04° × 0.04° latitude-longitude grid cells containing original ReefBase reports (navy blue), new records (orange), and those in both datasets (grey).

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observed bleaching grid cells in Australia, though only doubling the previous number, increased by over 10 000 km^2.

Interpolated bleaching probabilities

The number of bleaching observations was sufficient to compute interpolated maps of bleaching probabilities for 18 years within 1985 through 2010 (Table 4). In 1985, 1986, and 1989–1994 there were either no bleaching reports (i.e., 1985, 1989) or too few bleaching reports for the modeled semi-variograms to converge in all regions (Fig 1). In eight of 18 years,

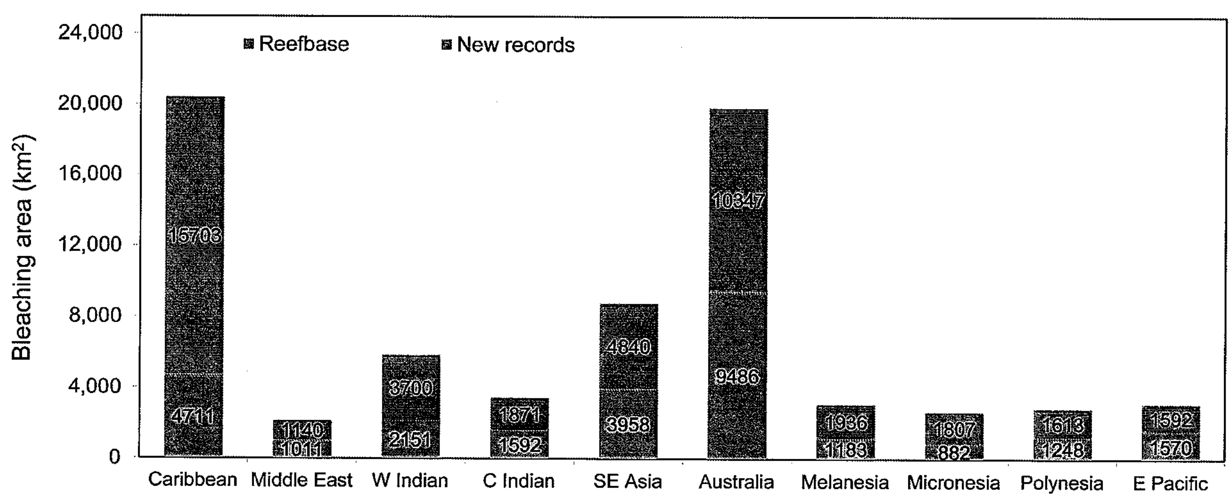

Fig 3. Total area (km^2) of moderate and severe (level 2 and 3) bleaching by region over the 1985–2010 period. The area is computed based on 0.04° × 0.04° latitude-longitude grid cells representing original ReefBase reports (blue) and new reports (orange).

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Table 4. Years for which indicator kriging was conducted.

Year	Caribbean	Indian Ocean	East Pacific	Main Pacific Ocean			Any Regions
				East	Central	West	
1985	-	-	-	-	-	-	-
1986	-	-	-	-	-	-	-
1987	X	-	-	-	-	-	X
1988	X	-	-	-	-	-	X
1989	-	-	-	-	-	-	-
1990	-	-	-	-	-	-	-
1991	-	-	-	-	-	-	-
1992	-	-	-	-	-	-	-
1993	-	-	-	-	-	-	-
1994	-	-	-	-	-	-	-
1995	X	-	-	-	-	-	X
1996	-	X	-	-	-	-	X
1997	-	-	X	-	-	-	X
1998	X	X	X	X	X	X	X
1999	X	-	-	-	-	-	X
2000	-	-	-	X	X	X	X
2001	-	-	-	X	-	X	X
2002	X	X	-	X	X	X	X
2003	X	-	-	-	-	-	X
2004	X	X	-	-	X	-	X
2005	X	X	-	-	-	-	X
2006	X	-	-	-	-	-	X
2007	X	X	-	X	-	-	X
2008	X	-	-	X	-	-	X
2009	X	-	-	X	-	X	X
2010	-	X	-	-	-	X	X

https://doi.org/10.1371/journal.pone.0175490.t004

interpolations could only be performed in one region; only two years (1998 and 2002) had sufficient observations to interpolate within five or six of the regions (Table 4).

In each of these 18 years, indicator kriging expanded the historical representation of the area that likely experienced bleaching. This is demonstrated in maps (Fig 4) for 2005 in northeastern Caribbean, where coral reef monitoring is common and reporting was relatively dense [23], and for 2004 in the central equatorial Pacific around Kiribati and Tuvalu, where coral reef monitoring is rare and reporting was opportunistic [24]. The spatial relationship between the raw observations in these two examples is characterized by their semi-variograms (Fig 4e and 4f), which describe the dissimilarity between values as a function of distance. The best fit model (dashed line) was used to estimate the bleaching probability in each cell in that region and year. In regions and years for which the interpolation did not succeed due to low density of observations, bleaching probabilities were set to zero across the region, which likely results in an underrepresentation of the bleaching probability.

Out of the 18 years in the 1985–2010 period for which indicator kriging could be conducted, 18, 17, and 13 years had cells with bleaching being more likely than not (>50% probability), likely (>66% probability), and very likely (>90% probability), respectively (Fig 5). Projecting the gridded bleaching probabilities onto the global coral reef map shows that the mean fraction of global coral reef area with a more likely than not chance of bleaching in any

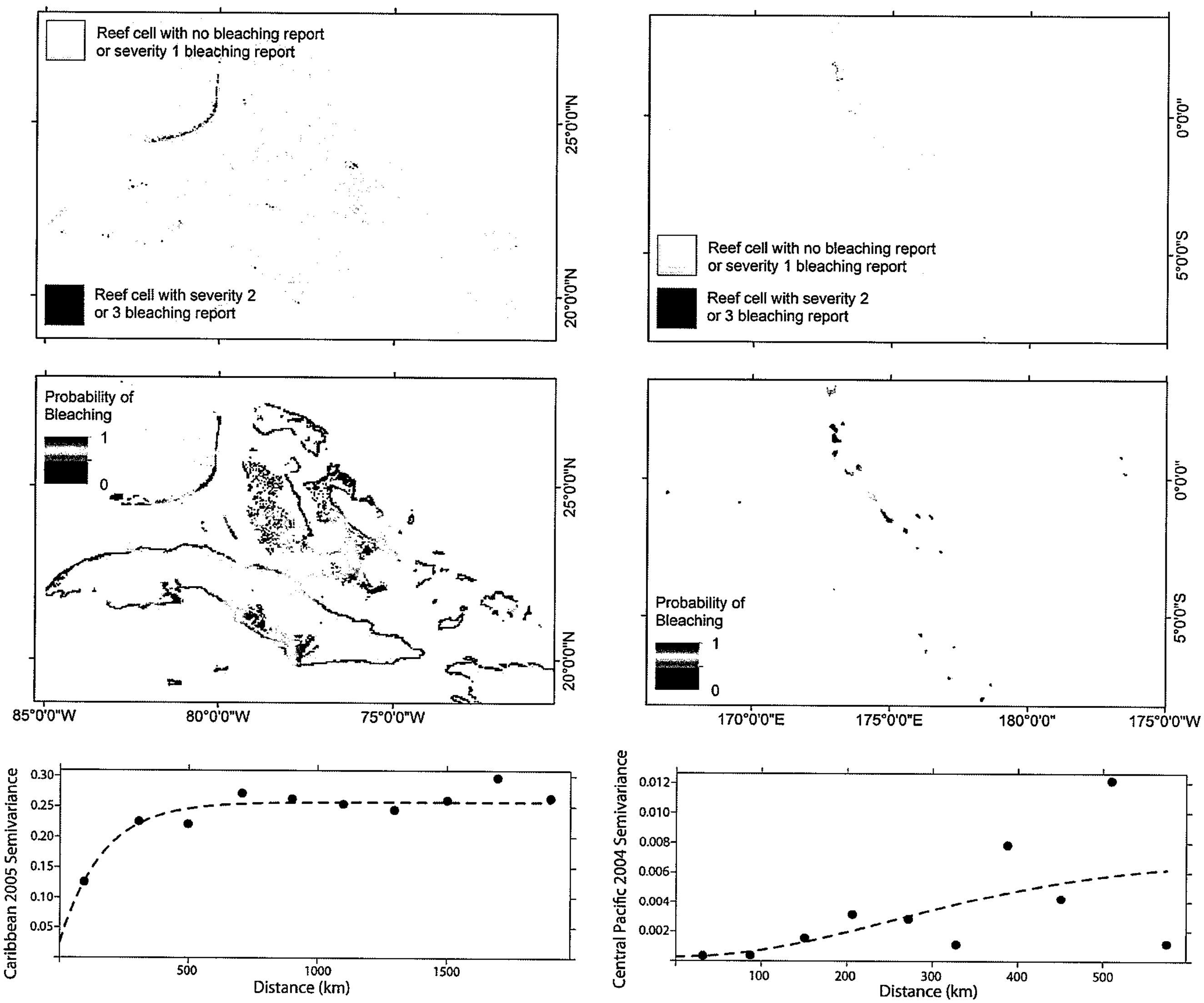

Fig 4. Examples of bleaching observations and probabilities for the Caribbean in 2005 (a,c,e) and central-west equatorial Pacific in 2004 (b,d,f). Top panels (a,b) show the raw observations of moderate and severe bleaching (level 2 and 3) from the database; middle panels (c,d) show the interpolated bleaching probabilities; and bottom panels (e,f) show the semi-variograms for the region and year.

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given year from 1985–2010 is 0.5%. This fractional area of probable bleaching varies from a low of zero in years with no reports or too few reports to perform indicator kriging, to highs of 3.3% in 2005 and 4.2% in 1998.

Regionally, the interpolated probabilities indicate the average relative extent of bleaching from 1985–2010 was greatest in the Eastern Pacific (3.3% of coral reef area per year with a more likely than not probability), the Central Indian Ocean (2.4%), and Caribbean (2.0%), and lowest in Melanesia (0.2%) and the Middle East (0.2%). The most extensive bleaching by region occurred in the Central Indian Ocean in 1998 (66% of reef area with a more likely than not chance of bleaching), followed by the Eastern Pacific Ocean in 1998 (52%), the Caribbean in 2005 (28%), and Micronesia in 2004 (15%).

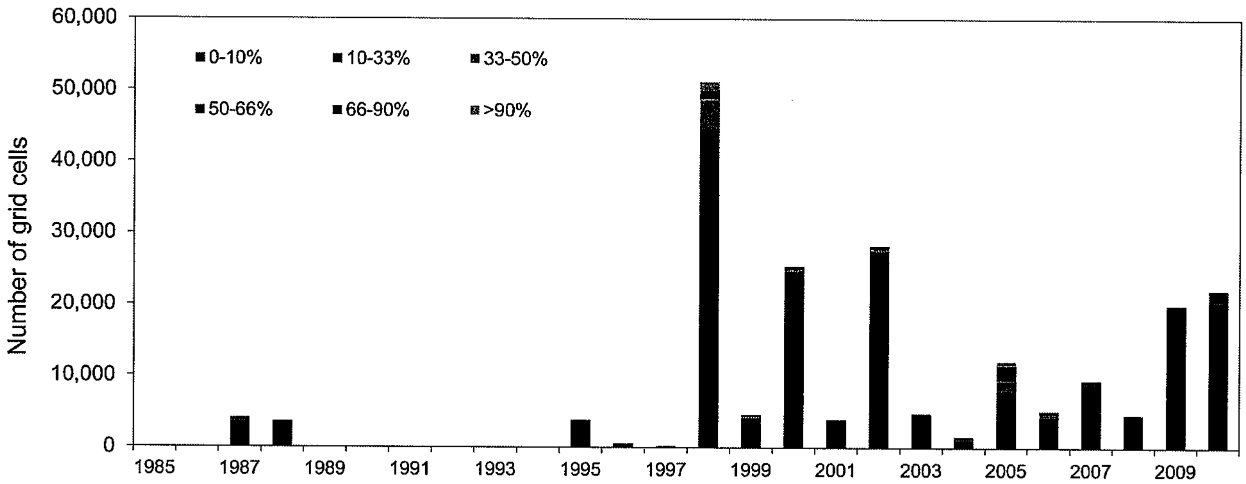

Fig 5. Number of 0.04° × 0.04° latitude-longitude grid cells with different estimated probabilities of bleaching from 1985–2010. Note that the density of bleaching reports was too low in years 1985, 1986, and 1989–94 for the interpolation to succeed.

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Using the available data, there is no trend over time in the number of grid cells or the coral reef area with >50%, >66%, and >90% bleaching probability, or in the mean bleaching probability of all reefs. However, if the 1985–2010 probability database is divided into the 12-year periods before (1985–1996) and after (1999–2010) the 1997/1998 El Niño and worldwide bleaching event, there is a 8-fold, 8-fold, and 3-fold increase in the average area of coral reefs with bleaching probability >50%, >66%, and >90%, respectively, between the earlier and later periods. The increase in the area of reef is significant ($p = 0.05$, t-stat = -2.17, df = 12 for a two-tailed t-test assuming unequal variances) for probability >50%, but not significant for probability >66% ($p = 0.07$, t-stat = -1.95, df = 12) or >90% ($p = 0.3$, tstat = -1.07, df = 15) for which there are fewer years to sample.

Bleaching and thermal stress

To test for a relationship between thermal stress and mass coral bleaching, we compared the DHW value for all reef cells with the DHW of cells with a high probability of bleaching. Over the 1985–2010 period, the reef area-weighted mean and median of the annual maximum DHW of reef cells with more likely than not, likely, or very likely probabilities of bleaching were each significantly higher (two-sided t-test, $p<0.01$) than the mean and median DHW of all reef cells (Table 5). The mean (and median) annual maximum DHW of reef cells that likely and very likely bleached (8.01°C-weeks and 8.10°C-weeks respectively) is similar to the NOAA Coral Reef Watch threshold for Bleaching Alert Level II (8°C-weeks), at which severe

Table 5. Thermal stress for reefs with different bleaching probabilities.

Annual maximum DHW (°C-weeks)	All reefs	>90%	>66%	>66–90%	>50–66%
Area-weighted	1.71	8.16^	8.01*^	7.87*+	6.69*+
Median	<0.01	8.26^	8.10*^	7.92*+	6.49*+

* significantly different (<0.05 level) from probability of >90%

+ significantly different (<0.05 level) from probability of >66%

^ significantly different (<0.05 level) from probability of >66–90%

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bleaching and some mortality is expected. It is important to note, however, that the annual maximum DHW described here refers to the highest value reached during that calendar year, which may be higher than the value at which bleaching began or became severe.

There were also significant differences in the area-weighted mean of annual maximum DHW for coral reefs with different probabilities of bleaching (Table 5). The annual maximum DHW of reefs (area-weighted average 8.16°C-weeks) with a very likely (>90%) probability of bleaching was significantly greater than that of reefs with a likely to very likely (>66–90%) probability of bleaching (7.87°C-weeks; $p<0.001$, t-stat = 16.05, df = 3298) and of reefs with a more likely than not to likely (>50–66%) probability of bleaching (6.69°C-weeks; $p<0.001$, t-stat = 17.66, df = 3733). There was also a significant difference between annual maximum DHW of reefs with a >50–66% bleaching probability with that of all reefs with a >66% bleaching probability ($p<0.001$, t-stat = 8.22, df = 4539), but not with that of reefs with a >66–90% bleaching probability ($p = 0.51$, t-stat = 0.66, df = 5561).

The temporal variation in thermal stress and interpolated bleaching probabilities provide a window into the possible changes in susceptibility of coral reefs to thermal stress over time.

A test of whether the threshold at which bleaching occurs has increased over time (due to adaptation, acclimation, or loss of susceptible taxa) is if the DHW of reefs that experienced bleaching increased faster than that of all reefs, or the surface ocean in general. Annual maximum DHW was averaged across all reef cells for each year, weighted by the coral reef area present in each cell. This area-weighted mean of annual maximum DHW for all reef cells increased significantly ($p<0.01$) over the 26-year period, by 0.08°C-weeks per year (2.14°C-weeks over the entire period; Fig 6a). The total increase was greatest in the Caribbean (4.60°C-weeks), Middle East (3.98°C-weeks), and Melanesia (2.18°C-weeks). There was, however, no significant increase over time in the area-weighted mean of annual maximum DHW of reef cells with more likely than not (Fig 6b), likely, or very likely probability of bleaching.

There were slight differences in the rate of change for DHW of reefs that experienced bleaching with that of all reefs between the 12-year period (1985–1996) before the 1997/1998 El Niño event and that after the event (1999–2000). The mean of annual maximum DHW

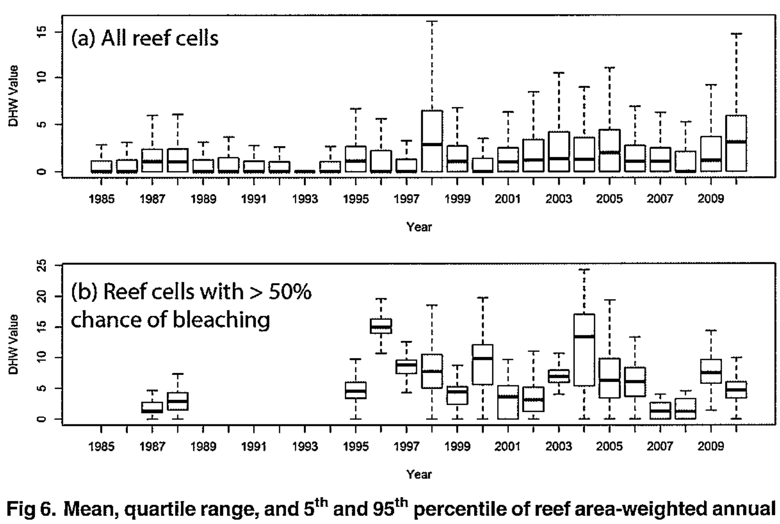

Fig 6. Mean, quartile range, and 5th and 95th percentile of reef area-weighted annual maximum DHW of a) all reef cells and b) reef cells with at least 50% probability of bleaching (more likely than not) from 1985–2010. Note that the density of bleaching reports was too low in years 1985, 1986, and 1989–94 for the interpolation to succeed.

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for all reefs rose by 118%, from 1.02°C-weeks in 1985–1996 to 2.23°C-weeks in 1999–2010 between the two periods. The mean annual maximum DHW for reefs with a likely (>66%) probability of bleaching rose by slightly less, by 103%, from 3.82°C-weeks to 7.77°C-weeks, whereas that of reefs with a very likely (>90%) probability of bleaching increased by slightly more, by 146%, from 3.69°C-weeks to 9.07°C-weeks. The differences between the two periods were all highly significant ($p<0.001$).

Analysis of the trend in DHW at the regional level is limited by the lower number of years for which individual regions have cells reporting non-zero probability of bleaching. In the Caribbean, for which there are 11 years of data, the mean annual maximum DHW of reefs with a very likely probability (>90%) increased by 152%, from 3.08°C-weeks to 7.75°C-weeks, between the 12-year periods before and after the 1997/1998 El Niño. The increase in DHW between the two time periods was 132% and 119% for likely (>66%) and more likely than not (>50%) probability of bleaching respectively. By contrast, the area-weighted DHW of all Caribbean reefs increased nearly four-fold (from 0.89°C-weeks to 3.37°C-weeks) between the two time periods.

Discussion

The expanded global observational bleaching database provides insight into the patterns in mass coral bleaching over time and the relationship between bleaching and thermal stress. It can also be applied to examine the influence of other factors like thermal history [25] [20] and reef resilience [26]. While the ReefBase voluntary bleaching database has been a valuable service for coral reef researchers and managers for many years, the data mining effort undertaken for this study suggests that, without ongoing curation, a voluntary database can suffer from substantial data gaps. The new observational database developed here includes 79% more bleaching records. Notably, two-thirds of the new records are moderate (11–50% coral bleached) or severe (>50% coral bleached) bleaching observations, which more reliably reflect large-scale thermal events than low-intensity observations [17].

Clustering of bleaching reports in areas of high monitoring effort remains an issue in the expanded database. Rasterizing the data partly controls for the uneven sampling effort and provides a consistent measure (area or number of grid cells) of the extent of mass coral bleaching. The difference between the number of reports in a given year (Fig 1) and the number of 0.04° × 0.04° cells with reports in a given year (Fig 2) demonstrates that a straightforward count of the number of bleaching reports is a potentially misleading metric (e.g., contrasting 1998 and 2005).

Expanding and rasterizing the observed bleaching database allowed for spatial interpolation or extrapolation to coral reefs where no monitoring was conducted. The calculated fraction of coral reef area with a more likely than not chance of bleaching ($p>50\%$), estimated by projecting the gridded probability data onto the UNEP-WCMC coral reef map, is generally lower than that of other estimates of the extent of past regional- or global-scale bleaching events. For example, this analysis suggests 4.2% of coral reefs worldwide had a more likely than not chance of bleaching in 1998, whereas the oft-quoted and misquoted 2000 Status of the Coral Reefs of the World Report summary of the 1997–1998 event states that "approximately" 16% of the world's coral reefs not only suffered bleaching but died during the event [27]. Such discrepancies may result for various reasons. Methodological differences exist between the indicator kriging performed here and the less spatially explicit geographical extrapolation employed in past studies. Here, the area of bleaching will be zero in any region and year in which the interpolation did not succeed due to low density of observations. In addition, this study used the newer UNEP-WCMC coral reef map that includes large areas of reef that feature few corals, like the largely sand lagoons of most Pacific atolls; this inflates the global reef area and adds locations that are unlikely to have observed bleaching records to inform the spatial modelling. For these reasons, this study's estimate for 1985–2010 of 0.5% annual frequency of bleaching being more likely than not (p>50%)–implying that, in any given year during that period, 0.5% of the world's coral reefs had a more likely than not chance of bleaching—could be low.

The lack of a significant increasing trend in the extent of bleaching in the interpolated data-set reflects the large year-to-year variability in thermal stress, bleaching extent, and observational effort (relative to the length of the time series), rather than the lack of a change in bleaching extent over past decades. First, an enormous increase in bleaching observations began in the early 1980s; only 12 of the 7436 bleaching reports (0.16%) in the new observational database are from before 1980. The increase is highly unlikely to be from sampling effort alone. Second, given that the canonical or "super" El Niño events which cause surface ocean temperature anomalies and mass coral bleaching in multiple ocean basins only occur roughly once every 20 years [28], a single event like 1997/1998 can obscure a long-term trend in the extent of coral bleaching. If the interpolated bleaching probabilities are examined at decadal time scales, an increase in the extent of bleaching is more readily apparent. The area of reef with a more likely than not (>50%) or likely (>66%) probability of bleaching was eight times higher after than before the 1997/1998 El Niño.

Extension of the observations database and the interpolated bleaching probabilities through the 2014–2016 "global" bleaching event [29,30] may further indicate a decadal-scale increasing trend in the extent of mass coral bleaching. However, it should be noted that although ocean temperatures and bleaching-level thermal stress are projected to continue rising even in an aggressive mitigation scenario [7, 9, 10], it is possible that bleaching observations will not increase in the near future due to the decline of susceptible taxa or populations. Bleaching occurrence is influenced by the composition of the coral and symbiont community. Reefs that experience more recent bleaching may be less likely to experience subsequent moderate to severe bleaching, despite the occurrence of repeat thermal stress, due to loss of coral cover, thermal acclimatization and/or shifts in community composition [31, 32, 33].

The results do show a close historical relationship between the occurrence of thermal stress and a high probability of bleaching, similar to that used by the Coral Reef Watch program in near real-time bleaching prediction. The annual maximum DHW was significantly higher (difference of 1.47°C-weeks) for coral reef cells with a very likely (>90%) probability of bleaching than those with a more likely than not to likely (>50–66%) probability. Most notable, the annual maximum DHW for coral reef cells with a likely or very likely chance of bleaching was approximately equivalent to the Bleaching Alert II threshold (8°C-weeks) used by the Coral Reef Watch program to predict severe bleaching with possible mortality. This correspondence should be viewed with caution because this study employed the maximum DHW value from the calendar year, rather than the DHW at the time of bleaching occurrence because the latter is usually not available in the dataset (e.g., except in the cases of dedicated monitoring programs, observations of bleaching may be weeks or months after the initial occurrence, or not report the specific date or month). Since the annual maximum DHW will often be higher than the value at which bleaching occurs or become severe, the ~8°C-weeks value reported here is likely an overestimate of the mean DHW at the onset of bleaching from 1985–2010.

The results also indicate that annual maximum DHW of coral reefs with a high probability of bleaching increased over time. Since the oceans are warming and thermal stress is increasing, an increase in the annual maximum DHW of coral reefs experiencing bleaching may indicate that temperature extremes have become more intense, but is not in itself evidence of adaptation or acclimation to rising temperatures. However, there is some evidence in the data that the annual maximum DHW of coral reefs with a high probability of bleaching (>90%) increased more rapidly over time than the annual maximum DHW of all coral reefs; if correct, that difference may suggest some adjustment to rising temperatures, whether by acclimation of corals or loss of susceptible species. Notably, the results suggest the reverse in the Caribbean, with annual maximum DHW increasing less rapidly over time in coral reefs with a high probability of bleaching, suggesting no or more limited adjustment to rising temperatures. There has been a marked decline in reef-building corals in the Caribbean [34] and resilience to disturbances, including thermal stress, in the Caribbean is thought to be low [35].

While the interpolated bleaching probabilities provide a means to test for trends in the extent of bleaching over time and how the relationship between thermal stress and bleaching may adjust over time, the accuracy of the interpolated data is still limited by the coverage of the observational database and the quality of the original reports. First, in years and regions with a lack of moderate and severe bleaching reports, whether due to the lack of actual bleaching or a lack of observations, the spatial interpolation was not possible. Second, many of the early reports from ReefBase feature limited information, including unknown causes of bleaching, and unknown extent of bleaching, which potentially introduce errors by being included (or omitted). In addition, some reports had to be excluded from the analysis due to unresolvable conflicts between the coordinates of the reported observation and the land mask for the $0.04^\circ \times 0.04^\circ$ grid. These problems were mitigated somewhat by focusing on the more reliable moderate and severe reports; the trade-off is that fewer records limited the information available for the kriging analysis. Finally, in order to control for differences in sampling and reporting methods, the observational bleaching reports are currently limited to the simple measure of percent coral bleaching (and mortality) used by ReefBase; taxa-level data would help more specifically test the drivers of changes in bleaching occurrences and thresholds over time [36].

Conclusion

The new databases of coral bleaching observations and the probability that bleaching occurred for the 1985–2010 period can support research on the effects of climate change on coral reefs. The databases are available at http://www.simondonner.com/bleachingdatabase as well as via the public data repository figshare ("Coral Bleaching Database V1"). The analysis of the new data demonstrates the increase in coral bleaching over the past three decades, the relationship between coral bleaching and thermal stress at a global scale, and the potential utility of such global databases for validating bleaching prediction methods and testing for changes in bleaching resilience at large-scales. Further work will be necessary to expand the coverage of the observed database, including adding new bleaching observations since 2010 and further back-filling the database with older missing reports, and thus better inform the spatial modeling of bleaching probabilities.

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Author Contributions

Conceptualization: SDD SFH.

Data curation: SDD GJMR.

Formal analysis: SDD GJMR.

Funding acquisition: SDD.

Investigation: SDD GJMR SFH.

Methodology: SDD GJMR.

Project administration: SDD.

Software: SDD GJMR.

Supervision: SDD.

Validation: SDD.

Visualization: SDD GJMR.

Writing – original draft: SDD.

Writing – review & editing: SDD GJMR SFH.

References

1. Brown B. Coral bleaching: causes and consequences. Coral Reefs 16 (Suppl): S129-S138. ResearchGate. 1997 Dec 1; 16(1):S129–38.
2. Donner SD, Skirving WJ, Little CM, Oppenheimer M, Hoegh-Guldberg O. Global assessment of coral bleaching and required rates of adaptation under climate change. Glob Chang Biol. 2005 Dec; 11 (12):2251–65.
3. Hoegh-Guldberg O, Mumby PJ, Hooten AJ, Steneck RS, Greenfield P, Gomez E, et al. Coral reefs under rapid climate change and ocean acidification. Science. 2007 Dec 14; 318(5857):1737–42. https://doi.org/10.1126/science.1152509 PMID: 18079392
4. Pandolfi JM, Connolly SR, Marshall DJ, Cohen AL. Projecting coral reef futures under global warming and ocean acidification. Science. 2011 Jul 22; 333(6041):418–22. https://doi.org/10.1126/science.1204794 PMID: 21778392
5. Donner SD, Knutson TR, Oppenheimer M. Model-based assessment of the role of human-induced climate change in the 2005 Caribbean coral bleaching event. Proceedings of the National Academy of Sciences. 2007; 104(13):5483–5488.
6. King A, Karoly D, Black, M, Hoegh-Guldberg O, Perkins-Kirkpatrick S. Barrier Reef Attribution Study_-Coral Attribution_Data_and_Methods_v3_0.pdf [Internet]. Barrier Reef Attribution Study. [cited 2016 Sep 26]. https://www.climatescience.org.au/sites/default/files/CoralAttribution_Data_and_Methods_v3_0.pdf
7. Donner SD. Coping with Commitment: Projected Thermal Stress on Coral Reefs under Different Future Scenarios. PLoS ONE. 2009 Jun 3; 4(6):e5712. https://doi.org/10.1371/journal.pone.0005712 PMID: 19492060
8. Frieler K, Meinshausen M, Golly A, Mengel M, Lebek K, Donner SD, et al. Limiting global warming to 2°C is unlikely to save most coral reefs. Nature Clim Change. 2013 Feb; 3(2):165–70.
9. van Hooidonk R, Maynard JA, Planes S. Temporary refugia for coral reefs in a warming world. Nature Clim Change. 2013 May; 3(5):508–11.
10. Logan CA, Dunne JP, Eakin CM, Donner SD. Incorporating adaptive responses into future projections of coral bleaching. Glob Change Biol. 2014 Jan 1; 20(1):125–39.
11. Donner SD. An evaluation of the effect of recent temperature variability on the prediction of coral bleaching events. Ecol Appl. 2011; 21(5):1718–1730. PMID: 21830713
12. Logan CA, Dunne JP, Eakin CM, Donner SD. A framework for comparing coral bleaching thresholds. In: Proceedings of the 12th International Coral Reef Symposium (ed Yellowlees D, Hughes TP), pp

10A3 Townsville [Internet]. 2012 [cited 2016 Sep 25]. http://www.icrs2012.com/proceedings/manuscripts/ICRS2012_10A_3.pdf

13. Brick JM, Williams D. Explaining Rising Nonresponse Rates in Cross-Sectional Surveys. The ANNALS of the American Academy of Political and Social Science. 2013 Jan 1; 645(1):36–59.
14. Olea RA. Optimal contour mapping using universal kriging. J Geophys Res. 1974 Feb 10; 79(5):695–702.
15. Solow AR. Mapping by simple indicator kriging. Math Geol. 1986 Apr; 18(3):335–52.
16. UNEP-WCMC, WorldFish Centre, WRI, TNC. Global distribution of warm-water coral reefs, compiled from multiple sources including the Millennium Coral Reef Mapping Project. Version 1.3 [Internet]. 2010 [cited 2016 Sep 25]. http://data.unep-wcmc.org/datasets/1
17. Suggett DJ, Smith DJ. Interpreting the sign of coral bleaching as friend vs. foe. Glob Chang Biol. 2011 Jan; 17(1):45–55.
18. Tsui OW, Coops NC, Wulder MA, Marshall PL. Integrating airborne LiDAR and space-borne radar via multivariate kriging to estimate above-ground biomass. Remote Sensing of Environment. 2013 Dec; 139:340–52.
19. Kleypas JA, Danabasoglu G, Lough JM. Potential role of the ocean thermostat in determining regional differences in coral reef bleaching events. Geophys Res Lett [Internet]. 2008 Feb 9 [cited 2016 Sep 25]; 35(3). Available from: http://doi.wiley.com/10.1029/2007GL032257
20. Heron SF, Maynard J, van Hooidonk R, Eakin CM. Warming Trends and Bleaching Stress of the World's Coral Reefs 1985–2012. Sci. Rep. Forthcoming.
21. Casey KS, Brandon TB, Cornillon P, Evans R. The Past, Present, and Future of the AVHRR Pathfinder SST Program. In: Barale V, Gower JFR, Alberotanza L, editors. Oceanography from Space [Internet]. Dordrecht: Springer Netherlands; 2010 [cited 2016 Sep 25]. p. 273–87. http://www.springerlink.com/index/10.1007/978-90-481-8681-5_16
22. Liu G, Heron S, Eakin C, Muller-Karger F, Vega-Rodriguez M, Guild L, et al. Reef-Scale Thermal Stress Monitoring of Coral Ecosystems: New 5-km Global Products from NOAA Coral Reef Watch. Remote Sens. 2014 Nov 20; 6(11):11579–606.
23. Eakin CM, Morgan JA, Heron SF, Smith TB, Liu G, Alvarez-Filip L, et al. Caribbean Corals in Crisis: Record Thermal Stress, Bleaching, and Mortality in 2005. PLoS ONE. 2010 Nov 15; 5(11):e13969. https://doi.org/10.1371/journal.pone.0013969 PMID: 21125021
24. Donner SD, Kirata T, Vieux C, others. Recovery from the 2004 coral bleaching event in the Gilbert Islands, Kiribati. Atoll Res Bull. 2010; 587:1–25.
25. Thompson DM, van Woesik R. Corals escape bleaching in regions that recently and historically experienced frequent thermal stress. Proceedings of the Royal Society of London B: Biological Sciences. 2009 Aug 22; 276(1669):2893–901.
26. McClanahan TR, Donner SD, Maynard JA, MacNeil MA, Graham NAJ, Maina J, et al. Prioritizing Key Resilience Indicators to Support Coral Reef Management in a Changing Climate. PLoS ONE. 2012 Aug 29; 7(8):e42884. https://doi.org/10.1371/journal.pone.0042884 PMID: 22952618
27. Wilkinson CR, editor. Status of coral reefs of the world: 2000. 363 p.
28. Banholzer S, Donner S. The influence of different El Niño types on global average temperature. Geophys Res Lett. 2014 Mar 28; 41(6):2093–9.
29. Eakin CM, Liu G, Gomez AM, De La Cour JL, Heron SF, Skirving W, et al. Global Coral Bleaching 2014–2017; Status and an Appeal for Observations [Internet]. [cited 2016 Nov 30]. http://coralreefwatch.noaa.gov/satellite/publications/reef-encounter_042016_crw-2014-17_global_bleaching_final.pdf
30. Gomez AM, Eakin CM, De La Cour JL, Liu G, Geiger EF, Heron SF, et al. 2016 ICRS—Abstract [Internet]. [cited 2016 Nov 30]. https://www.sgmeet.com/icrs2016/viewabstract.asp?AbstractID=28759
31. Heron SF, Johnston L, Liu G, Geiger EF, Maynard JA, De La Cour JL, et al. Validation of Reef-Scale Thermal Stress Satellite Products for Coral Bleaching Monitoring. Remote Sens. 2016 Jan 12; 8(1):59.
32. Grottoli AG, Warner ME, Levas SJ, Aschaffenburg MD, Schoepf V, McGinley M, et al. The cumulative impact of annual coral bleaching can turn some coral species winners into losers. Glob Chang Biol. 2014;
33. Guest JR, Baird AH, Maynard JA, Muttaqin E, Edwards AJ et al. (2012) Contrasting patterns of coral bleaching susceptibility in 2010 suggest an adaptive response to thermal stress. PLOS ONE 7: e33353. https://doi.org/10.1371/journal.pone.0033353 PMID: 22428027
34. Perry CT, Steneck RS, Murphy GN, Kench PS, Edinger EN, Smithers SG, et al. Regional-scale dominance of non-framework building corals on Caribbean reefs affects carbonate production and future

reef growth. Glob Chang Biol. 2015 Mar; 21(3):1153–64. https://doi.org/10.1111/gcb.12792 PMID: 25537577

35. Roff G, Mumby PJ. Global disparity in the resilience of coral reefs. Trends Ecol Evol. 2012 Jul; 27 (7):404–13. https://doi.org/10.1016/j.tree.2012.04.007 PMID: 22658876

36. Swain TD, Vega-Perkins JB, Oestreich WK, Triebold C, DuBois E, Henss J, et al. Coral bleaching response index: a new tool to standardize and compare susceptibility to thermal bleaching. Glob Chang Biol. 2016 Jul; 22(7):2475–88. https://doi.org/10.1111/gcb.13276 PMID: 27074334

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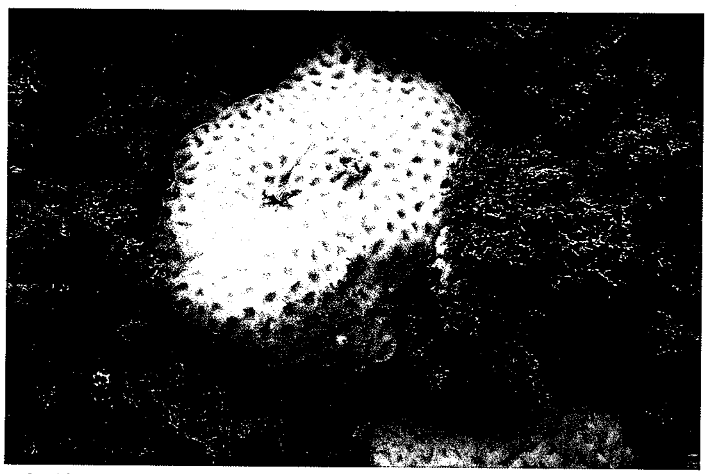
Cientistas detectam imenso branqueamento de corais no sudeste brasileiro

Por Evanildo da Silveira

terça-feira, 16 abril 2019 15:09 1 Comentário



Mussismilia hispida, conhecida como coral-cérebro. Foto: Thomás Banha.

Os corais são como árvores e os recifes que formam como florestas tropicais nos mares. As estruturas de carbonato de cálcio que produzem criam uma grande variedade de habitats para inúmeros outras espécies de animais, entre as quais uma enorme quantidade de peixes. Nada menos que 25% da biodiversidade marinha estão associadas aos recifes. Por isso, é muito preocupante um fenômeno que vem ocorrendo cada vez com mais frequência nessas estruturas em todos os oceanos: o branqueamento de corais. Entre as principais causa disso está o aquecimento global, que eleva a temperatura dos oceanos.

No Brasil, pesquisadores das universidades de São Paulo (USP), Estadual Paulista (Unesp) e Federal da Paraíba (UFPB) detectaram, em fevereiro deste ano, o mais intenso evento de branqueamento de corais já registrado no Atlântico Sul. Ele foi observado na região de Ubatuba, no litoral norte de São Paulo. O mesmo fenômeno, mas com menor gravidade, também foi percebido nas águas do entorno do arquipélago de Alcatrazes, localizado a 35 quilômetros de São Sebastião, na mesma região.

O mais preocupante é que a espécie atingida, a *Mussismilia hispida*, conhecida como coral-cérebro, endêmica do Brasil, é uma das mais resistentes que se conhece. Mesmo assim, 80% das colônias da região estudada branquearam e 2% morreram. "Pode parecer pouco, mas, para aquele local, não é", diz o oceanógrafo Miguel Mies, do Laboratório de Ecologia e Evolução de Mar Profundo (LAMP), do Instituto Oceanográfico da USP (IO), um dos coordenadores do estudo, "No ano que vem deve ser maior, especialmente se as colônias tiverem dificuldades na recuperação."

Segundo Mies, o branqueamento dos corais ocorreu por causa do aquecimento anormal das águas do Atlântico, no sudeste brasileiro. "A temperatura média normal delas é em torno de 27°C", explica. "Mas durante cerca de um mês no início deste ano, entre meados de janeiros e meados de fevereiro, ela ficou acima da média, chegando em alguns dias a 31-32°C. É esta longa exposição dos corais a temperaturas acima da média que leva ao branqueamento deles."

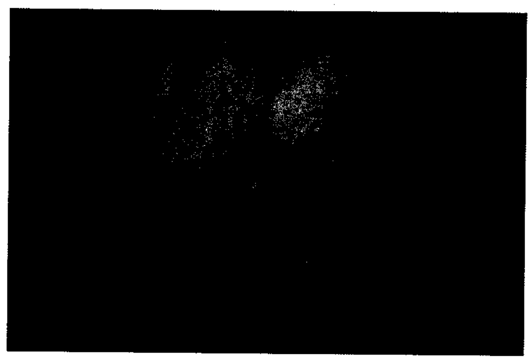


Foto: Thomás Banha.

Em Alcatrazes, o problema foi menor. Apenas cerca de 30% das colônias branquearam, a maioria na faixa dos seis metros de profundidade. "Até o momento temos duas hipóteses principais para esses resultados", diz bióloga Katia Capel, do Centro de Biologia Marinha da USP (CEBIMar-USP), que estudou o fenômeno no arquipélago. "A primeira, é a presença de termoclina (variação brusca de temperatura em uma determinada profundidade), mais constante em Alcatrazes, que atuou como um 'amortecedor' da temperatura, protegendo os corais do branqueamento. "A segunda é que, devido aos esforços para sua preservação, este arquipélago possui um ambiente mais ecologicamente equilibrado, o que, naturalmente, deve aumentar a sua resistência e resiliência a mudanças de clima que estamos presenciando."

Embora o fenômeno seja denominado "branqueamento", este termo, na verdade, não define com precisão o que ocorre com os corais. A primeira vista, a palavra dá a entender que eles ficam brancos ou adquirem essa cor. O que acontece de fato, no entanto, é que, nesse caso, os corais ficam com seus esqueletos expostos, que são brancos naturalmente e recobertos por uma camada de tecido translúcido. A cor deles é dada por microalgas fotossintetizantes, chamadas zooxantelas.

Katia explica que grande parte dos corais de água rasa vivem em associação simbiótica com essas microalgas. Por meio da fotossíntese, elas produzem grande parte da energia necessária aos seus hospedeiros "Esta associação auxilia na nutrição deles, pois as zooxantelas endosimbiontes, em troca de 'abrigo' e subprodutos do metabolismo do coral, podem chegar a suprir grande parte das carências energéticas do animal", diz.

Marcelo Soares, da Universidade Federal do Ceará (UFC), que estuda o fenômeno na costa do Nordeste, explica que as zooxantelas fornecem alimento para o coral, funcionando como pequenas fábricas de produção de comida, que usam a luz do sol, carbono e nutrientes. "Essas microalgas também fornecem a coloração dos corais", acrescenta. "Quando elas saem do coral, eles perdem uma fonte importante de nutrição e também sua cor."

Diversas situações de estresse podem fazer com que essa relação simbiótica seja quebrada, sendo o branqueamento o resultado mais visível da expulsão das microalgas.

"Diversas situações de estresse podem fazer com que essa relação simbiótica seja quebrada, sendo o branqueamento o resultado mais visível da expulsão das microalgas. Entre elas, está o aumento da temperatura da água."

temperatura da água. "Quando as zooxantelas são expostas ao estresse térmico, elas produzem espécies reativas de oxigênio, que são nocivas aos corais", explica Mies. "Por conta disso, eles as expulsam de seus tecidos, deixando seu esqueleto branco exposto. Como essa relação simbiótica é essencial para os animais, muitas vezes o branqueamento leva à morte."

De acordo com Katia, apesar de ser uma resposta específica para cada espécie de coral e seus respectivos simbiontes, devido a pouca capacidade deles em suprir suas carências energéticas sem o auxílio das microalgas por períodos prolongados, dependendo do tempo em que a anomalia térmica permanece, os corais morrem por inanição ou doenças relacionadas a ela. Mas, se o período for curto, eles conseguem se recuperar.

O problema é que essas anomalias estão cada vez mais frequentes e durando mais tempo, aumentando o número de casos de branqueamento em massa. "No Brasil existe pouca documentação, mas dezenas de eventos já foram documentados", conta Mies. "No mundo, são incontáveis. No mínimo muitas centenas. O mais grave é que estamos vivenciando eventos globais, nos quais a maioria dos recifes do mundo inteiro branqueia ao mesmo tempo. O primeiro foi em 1998, o segundo em 2009, o terceiro em 2014 e estamos entrando no quarto."

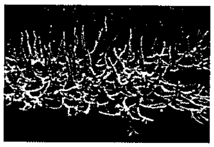
Foto: Thomás Banha.

Para Soares, o branqueamento é um problema grave, que responde por parte dos danos ambientais dos recifes. "Em todo o mundo, passando pela Austrália (grande barreira de corais), Caribe, África e Brasil, os recifes tem a cada ano experimentado temperaturas altas nos mares", explica. "Isto cria um estresse após outro, o que dificulta que as colônias possam se recuperar. Em 15 a 20 anos, se o controle das emissões de carbono não for feito, perderemos cerca de 80% deles. Fora o aquecimento global, temos pesca excessiva, plásticos, poluição e o turismo descontrolado que também os estão degradando."

Mies, por sua vez, alerta para os prejuízos que advêm da morte dos corais. "O desaparecimento deles significa perda de habitats e, consequentemente, de biodiversidade", alerta. "Além do disso, recifes são economicamente importantes, pois produzem alimento para países costeiros, particularmente para aqueles de porte pequeno, que não possuem gado. Eles também são atrações turísticas, muito relevantes para o PIB de muitas nações dependente dessa atividade; fonte de compostos para indústria farmacêutica; e importantes para a aquariofilia. Perdê-los significa prejudicar esses países e atividades econômicas, além, é claro, da biodiversidade do planeta."

Leia Também

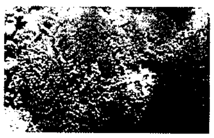
Branqueamento mata 70% do maior recife de coral do JapÃ£o



A mortandade dos corais ocorreu na lagoa de Sekisei, em Okinawa. Autoridades japonesas afirmam que o cenÃ¡rio chegou ao ponto de extrema gravidade

((o)) ((o))eco 1

Os corais mais ameaÃ§ados do planeta



EspÃ©cies ainda pouco conhecidas estÃ£o sumindo. Pesquisadores se reÃºnem em Londres e lanÃ§am iniciativa de conservaÃ§Ã£o.

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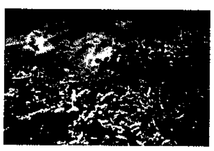
Peixes de corais sofrem de â€œsÃndrome de Doryâ€□



Estudo revela o efeito nefasto de pequenas quantidades de petrÃ³leo no sistema nervoso de espÃ©cies que vivem em corais â€" e da ameaÃ§a a todo o ecossistema

((o)) ((o))eco 1

mudanças climáticas | recifes de corais

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Carlos Silva · *2 semanas atrás* 0

Situação crítica que estamos vivendo atualmente e ao invés de tomar atitude com relação a este problemas, estamos, na verdade, estimulando-o cada vez mais. Triste fim para estas espécies e triste realidade para nós humanos que, mesmo sobrevivendo, vamos ter de conviver com o fato de que não fizemos nada a respeito...

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ELSEVIER

Review Article

Climate change, global warming and coral reefs: Modelling the effects of temperature

M. James C. Crabbe*

Luton Institute for Research in the Applied Natural Sciences, Faculty of Creative Arts, Technology and Science, University of Bedfordshire, Park Square, Luton LU1 3JU, UK

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ABSTRACT

Climate change and global warming have severe consequences for the survival of scleractinian (reef-building) corals and their associated ecosystems. This review summarizes recent literature on the influence of temperature on coral growth, coral bleaching, and modelling the effects of high temperature on corals. Satellite-based sea surface temperature (SST) and coral bleaching information available on the internet is an important tool in monitoring and modelling coral responses to temperature. Within the narrow temperature range for coral growth, corals can respond to rate of temperature change as well as to temperature *per se*. We need to continue to develop models of how non-steady-state processes such as global warming and climate change will affect coral reefs.

Contents

1. Introduction

Coral reefs, found predominantly between the tropics of Capricorn and Cancer, provide an environment in which one third of all marine fish species and many thousands of other species are found, and from which 6 million tons of fish are caught annually. This not only provides an income to national and international fishing fleets, but also for local communities, which in addition rely on the local fish stocks to provide nutritional sustenance. The reefs also act as barriers to wave action and storms by reducing the incident wave energy through wave reflection, dissipation and shoaling, protecting the land and an estimated half a billion people who live within 100 km of reefs.

The growth and subsistence of corals depend on many variables, including temperature, irradiance, calcium carbonate saturation, turbidity, sedimentation, salinity, pH, and nutrients. These variables influence the physiological processes of photosynthesis and calcification as well as coral survival, and as a result coral reefs occur only in select areas of the world's oceans. Meteorological processes can alter these variables, and Fig. 1 summarizes their influences on global and synoptic scales on coral requirements for growth and survival (Walker, 2005; Crabbe et al., 2008a). Coral reefs are cur-

* Tel.: +44 1582 489265; fax: +44 1582 489212.
E-mail address: James.Crabbe@beds.ac.uk.

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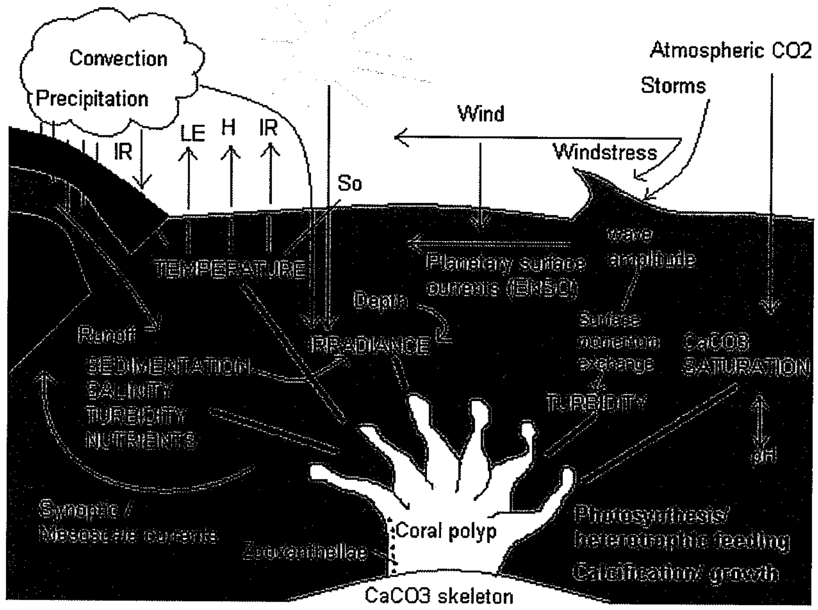

Fig. 1. Schematic diagram summarizing key meteorological processes and coral requirements controlling calcification, photosynthesis, and survival. Adapted from Crabbe et al. (2008a) and Crabbe et al. (2008b).

rently under severe threat from climate change (Lough, 2008), as well as from many other anthropogenic influences, such as pollution and overfishing (Mumby et al., 2007; Crabbe et al., 2008b).

This review will concentrate on the effects of temperature on modern scleractinian (reef-building) corals, and the recent insights that modelling can provide to increase our understanding of coral ecology and survival in a period of climate change.

2. The Influence Of Temperature On Coral Growth

Many studies have examined the impact of air temperature variations on coral growth rates. In a study of the correlation between air temperature and growth rates of coral from a colony of *Porites lutea* in the Great Barrier Reef in the district of Haapiti, Australia (Bessat and Buiges, 2001), measurements were taken from coral cores. For the period from 1958 to 1990, linear regression gave a correlation between air temperature 25 km from where the core was taken and coral skeletal density of $r = 0.37$; for the same period, the correlation between air temperature and annual calcification rate was lower at $r = 0.28$. These results indicated that a 1 °C rise in temperature would lead to an increase in the density rate of about 10.5% and an increase in the calcification rate of about 4.5%. Coral calcification rates and extension rates have been highly correlated with sea surface temperatures (SSTs) and to a lesser extent with incoming solar radiation (Nie et al., 1997; Lough and Barnes, 2000). In juvenile corals, temperature causes a transition between isometric and allometric growth scaling in warmer versus cooler years, respectively (Edmunds, 2006; Edmunds, 2008).

Interestingly, on the Great Barrier Reef (GBR), calcification rates in massive *Porites* colonies declined by approximately 21% in two regions 450 km apart. This was a function primarily of a decrease in linear extension (16%) with a smaller decline in skeletal density (6%) (Cooper et al., 2008) and contrasts with previous studies on the environmental controls on growth of massive *Porites* on the GBR. In a study on reefs of East Africa (McClanahan et al., 2007) it appeared that it was not just the high stability of tropical environments that creates high biological diversity but also large temperature fluctuations that prepares the corals for the unexpected and this may allow them to persist in what is becoming an increasingly hostile environment.

Growth rates also depend upon minimum seasonal temperatures. Changes in average winter air temperature at the flower garden banks in the Gulf of Mexico were found to correspond to changes in *Montastea annularis* growth rates (Slowey and Crowley, 1995). Interdecadal changes in the growth rate of the corals corresponded to changes in average minimum winter season air temperatures at New Orleans. Slowey and Crowley (1995) acknowledged that the correspondence between the changes in the two were not one to one because the influence of air temperature on water temperature depends on a number of meteorological and oceanographic factors. The minimum temperatures over the Gulf of Mexico can be caused by the passage of fronts bringing cold dry air from Canada, and probably this process is primarily responsible for stressing corals at the flower gardens and reducing their winter growth rate. There was a major shift towards colder winters during the 1950s and this coincided with the decline of coral growth at the flower gardens.

3. Coral Bleaching

Most of the pigmentation within corals is within the symbiotic algal cells—the zooxanthellae. Coral bleaching is caused by corals losing their zooxanthellae. Thermal bleaching occurs when the coral is exposed to prolonged above-normal (or below-normal) temperatures, resulting in additional energy demands on the coral, depleted reserves, and reduced biomass (Muller-Parker and D'Elia, 1997). The effect of high temperatures can be aggravated by high levels of irradiance (Gleason and Wellington, 1993), although high UV radiation is not a primary factor in causing mass bleaching (Hoegh-Guldberg, 1999). Coral reefs within or near the western Pacific warm pool (WPWP) have had fewer reported bleaching events relative to reefs in other regions. Analysis of SST data indicate that the warmest parts of the WPWP have warmed less than elsewhere in the tropical oceans, which supports the existence of thermostat mechanisms that act to depress warming beyond certain temperature thresholds (Kleypas et al., 2008).

Corals can die as a result of bleaching, though they may partially or fully recover from bleaching events (Lough, 2000). Bleaching causes a decrease in the growth rate of corals, and the time taken for a coral to recover from a bleaching event may be several years or decades. If the frequency of bleaching increases, then the capacity for coral reefs to recover is diminished (Done, 1999). This has been observed during a number of 'natural' events, e.g., 1983–1984 (Glynn, 1990), 1997–1998 (Goreau et al., 2000; Glynn et al., 2001) and 2005 (Wilkinson and Souter, 2008). Experimental studies show that thermal history, in addition to light history, can influence the response of reef-building corals to thermal stress, and therefore, have implications for the modeling of bleaching events (Middlebrook et al., 2008). Significant levels of mortality can occur in a bleaching event before any chance for subsequent recombination of the host-symbiont unit (Jones, 2008). To better understand factors affecting the potential evolution of bleaching resistance in corals in response to increased average sea temperatures, a mathematical model of coevolutionary interactions between partners in a coral-algae mutualistic symbiosis has been developed (Day et al., 2008). This showed that traits in mutualistic symbioses, such as thermal tolerance in corals, are potentially subject to novel kinds of evolutionary constraints and that these constraints are mediated by ecological dynamics. The nature of interspecific control of bleaching resistance and the mode of sexual reproduction interacted to strongly influence the rate of spread of resistance alleles.

4. Modelling The Effects Of High Temperature On Corals

The frequency that corals will be bleached in the future has been estimated by using projections of future sea surface temperatures from four different general circulation models (GCMs) forced by the IPCC IS92a emission scenario (Hoegh-Guldberg, 1999). The SST projections were combined with thermal thresholds for corals, derived by using the Integrated Global Ocean Services System (IGOSS) dataset provided by the Joint World and Scientific Meteorological Organization (WMO) and United Nations Educational, Scientific and Cultural Organization (UNESCO), Joint Intergovernmental Oceanographic Commission's (JCOMM) Technical Commission for Oceanography and Marine Meteorology, and from literature and Internet reports of bleaching events. All SST projections indicated that the frequency of bleaching events is set to rise rapidly, with the highest rates in the Caribbean, Southeast Asia, and Great Barrier Reef, and the lowest rates in the central Pacific. The frequency of bleaching events was predicted to become annual in most oceans by 2040, and the Caribbean and Southeast Asia are projected to reach this point by 2020, triggered by seasonal changes in seawater temperature rather than by El Niño events.

The geographical patterns and the timing of probable repeat occurrences of coral mortality in the Indian Ocean have been estimated (Sheppard, 2003). Forecast sea surface temperatures at 33 sites in the Indian Ocean were blended onto historical sea surface temperatures. The forecast temperatures were estimated by using the IS92a scheme, which follows a median path. These studies indicate a 50% probability of SSTs being warm enough by 2030 for the occurrence of coral bleaching events at Comoros and Chagos in the Indian Ocean, and by 2070 in the Saudi Arabian Gulf.

In order to predict imminent rises in SSTs, the U.S. National Oceanic and Atmospheric Administration's Coral Reef Watch (NOAA CRW) develops and operationally produces satellite-based coral bleaching nowcasts and alerts available on the Internet (Liu et al., 2006). These products are based on nighttime-only Advanced Very High Resolution Radiometer (AVHRR) sea surface temperatures from operational NOAA polar-orbiting satellites, and, for example,

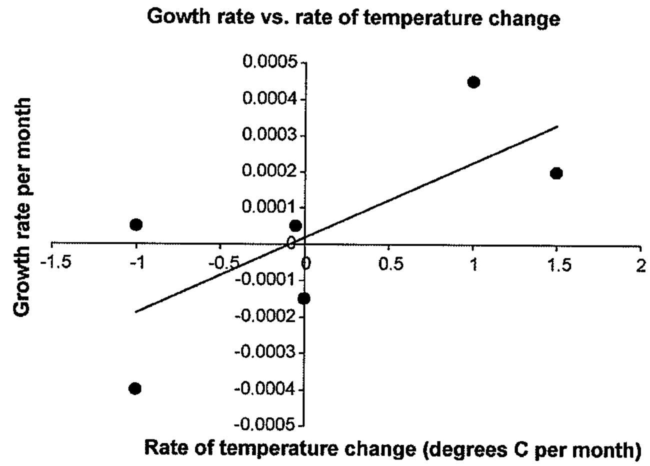

Fig. 2. Influence of the rate of change of temperature on the growth rate of an *Acropora palmata* coral colony from Curaçao (Bak, 1976). $R^2 = 0.53$. For details see the text.

provided alerts for the 2005 Caribbean mass-bleaching event, indicating that average ocean temperatures during July–October 2005 for the Caribbean exceeded temperatures seen at any time during the past 154 years (NOAA, 2008). Similar systems are in use for the Great Barrier Reef (Maynard et al., 2008).

Modelling of growth rates (by weight; Bak, 1976) of the branching coral *Acropora palmata* with temperature on a Curaçao coral reef, using a smoothing spline to produce a nonparametric fit to the data, suggested that the 30-day averaged maximum daily temperature could explain about 3% of the variability in the time-dependent growth rate (Crabbe et al., 2008a). Interestingly, the temperature correlation was negative, suggesting that during the measurement period, temperatures rose to higher than optimum temperatures for growth, thus inhibiting coral growth, but were not sufficiently high to cause bleaching of this species. Thus what would normally be a positive correlation became a slight but significant negative correlation.

For *Acropora palmata* colonies on fringing reefs off the north coast of Jamaica, over the period 2002–2007, the rate of growth of *Acropora palmata* was largely proportional to *rate of change of SST*, with $R^2 = 0.935$ (Crabbe, 2007). If we now model the growth rate data of *Acropora palmata* from Curaçao (Bak, 1976) with rate of change of temperature (Fig. 2), then $R^2 = 0.53$, rather than the small negative correlation if only temperature, rather than rate of change of temperature, is taken into account. These modelling studies suggest that within the narrow temperature range for coral growth, corals respond to rate of temperature change as well as to temperature *per se*.

5. Conclusion

Climate processes and extremes can influence the physiological processes responsible for the growth of coral reef colonies. Coral growth takes place within narrow limits of temperature, irradiance, salinity, pH, and turbidity, all variables that are influenced by climate and weather. In a number of empirical models for coral growth, small changes in temperature and rates of temperature change can significantly influence coral colony growth rates. We need to continue to develop models of how non-steady-state processes such as global warming and climate change will effect coral reefs, and on whether corals or their symbiont algae will evolve to keep pace with the climate and environmental changes.

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I thank the Earthwatch Institute for funding for the coral measurements made on the reefs of Jamaica, Professor Rolf Bak for providing some essential data from his study of coral growth in Curaçao, Emma Walker (University of Reading) and Professor David Stephenson (University of Exeter) for helpful conversations, and Dr. Albert Maris of the Antilles meteorological service for meteorological data for the period that coral growth was being measured on Curaçao reefs.

References

Bak, R.P.M., 1976. The growth of coral colonies and the importance of crustose correline algae and burrowing sponges in relation with carbonate accumulation. Netherlands Journal of Sea Research 10, 285–337.

Bessat, F., Buiges, D., 2001. Two centuries of variation in coral growth in a massive *Porites* colony from Moorea (French Polynesia): a response of ocean-atmosphere variability from south central Pacific. Palaeogeography, Palaeoclimatology, Palaeoecology 175, 381–392.

Cooper, T.F., De 'Ath, G., Fabricius, K.E., Lough, J.M., 2008. Declining coral calcification in massive *Porites* in two nearshore regions of the northern Great Barrier Reef. Global Change Biology 14, 529–538.

Crabbe, M.J.C., 2007. Global warming and coral reefs: modelling the effect of temperature on *Acropora palmata* colony growth. Computational Biology and Chemistry 31, 294–297.

Crabbe, M.J.C., Walker, E.L.L., Stephenson, D.B., 2008a. The impact of weather and climate extremes on coral growth. In: Diaz, H., Murnane, R. (Eds.), Climate Extremes and Society. Cambridge University Press, Cambridge, UK, pp. 165–188.

Crabbe, M.J.C., Martinez, E., Garcia, C., Chub, J., Castro, L., Guy, J., 2008b. Growth modelling indicates hurricanes and severe storms are linked to low coral recruitment in the Caribbean. Marine Environmental Research 65, 364–368.

Day, T., Nagel, L., Van Oppen, M.J.H., Caley, M.J., 2008. Factors affecting the evolution of bleaching resistance in corals. American Naturalist 171, E72–E88.

Done, T.J., 1999. Coral communities adaptability to environmental change at the scales of regions, reefs and reef zones. American Zoologist 39, 66–79.

Edmunds, P.J., 2006. Temperature-mediated transitions between isometry and allometry in a colonial modular invertebrate. Proceedings of The Royal Society B 273, 2275–2281.

Edmunds, P.J., 2008. The effects of temperature on the growth of juvenile scleractinian corals. Marine Biology 154, 153–162.

Gleason, M.G., Wellington, G.M., 1993. Ultraviolet radiation and coral bleaching. Nature 365, 836–838.

Glynn, P.W., 1990. Coral mortality and disturbances to coral reefs in the tropical eastern Pacific. In: Glynn, P.W. (Ed.), Global Ecological Consequences of the 1982-83 El Niño-Southern Oscillation. Elsevier Press, Amsterdam, pp. 55–126.

Glynn, P.W., Maté, J.L., Baker, A.C., Calderón, M.O., 2001. Coral bleaching and mortality in Panamá and Ecuador during the 1997–1998 El Niño-Southern Oscillation event: spatial/temporal patterns and comparisons with the 1982–1983 event. Bulletin of Marine Science 69, 79–109.

Goreau, T., McClanahan, T., Hayes, R., Strong, A.E., 2000. Conservation of coral reefs after the 1998 global bleaching event. Conservation Biology 14 (1), 5–15.

Hoegh-Guldberg, O., 1999. Climate change, coral bleaching and the future of the world's coral reefs. Marine Freshwater Research 50, 839–866.

Jones, R.J., 2008. Coral bleaching, bleaching-induced mortality, and the adaptive significance of the bleaching response. Marine Biology 154, 65–80.

Kleypas, J.A., Danabasoglu, G., Lough, J.M., 2008. Potential role of the ocean thermostat in determining regional differences in coral reef bleaching events. Geophysical Research Letters 35, L03613.

Liu, G., Strong, A.E., Skirving, W.J., Arzayus, L.F., 2006. Overview of NOAA coral reef watch program's near-real-time satellite global coral bleaching monitoring activities. In: Proceedings of the 10th International Coral Reef Symposium, Okinawa, pp. 1783–1793.

Lough, J.M., 2000. Unprecedented thermal stress to coral reefs? Geophysical Research Letters 27, 3901–3904.

Lough, J.M., 2008. 10th anniversary review: a changing climate for coral reefs. Journal of Environmental Monitoring 10, 21–29.

Lough, J.M., Barnes, D.J., 2000. Environmental controls on growth of the massive coral *Porites*. Journal of Experimental Marine Biology 245, 225–243.

McClanahan, T.R., Ateweberhan, M., Muhando, C., Maina, J., Mohammed, S.M., 2007. Effects of climate and seawater temperature variation on coral bleaching and mortality. Ecological Monographs 74, 503–525.

Maynard, J.A., Turner, P.J., Anthony, K.R.N., Baird, A.H., Berkelmans, R., Eakin, C.M., Johnson, J., Marshall, P.A., Packer, G.R., Rea, A., Willis, B.L., 2008. ReefTemp: an interactive monitoring system for coral bleaching using high-resolution SST and improved stress predictors. Geophysical Research Letters 35, L05603.

Middlebrook, R., Hoegh-Guldberg, O., Leggat, W., 2008. The effect of thermal history on the susceptibility of reef-building corals to thermal stress. Journal of Experimental Biology 211, 1050–1056.

Muller-Parker, G., D'Elia, C.F., 1997. Interactions between corals and their symbiotic alga. In: Birkeland, C. (Ed.), Life and Death of Coral Reefs. Chapman & Hall, New York, pp. 96–112.

Mumby, P.J., Hastings, A., Edwards, H.J., 2007. Thresholds and the resilience of Caribbean coral reefs. Nature 450, 98–101.

Nie, B., Chen, T., Liang, M., Wang, Y., Zhong, J., Zhu, Y., 1997. Relationship between coral growth rate and sea surface temperature in the northern part of the South China Sea during the past 100 years. Science in China (series D) 40, 173–182.

NOAA, 2008. Earth System Research Laboratory, NOAA Extended Reconstructed Sea Surface Temperature (SST) V2, http://www.cdc.noaa.gov/cdc/data.noaa.ersst.html.

Sheppard, C.R.C., 2003. Predicted recurrences of mass coral mortality in the Indian Ocean. Nature 425, 294–297.

Slowey, N.C., Crowley, T.J., 1995. Interdecadal variability of northern hemisphere circulation recorded by Gulf of Mexico corals. Geophysical Research Letters 22, 2345–2348.

Walker, E.L.L., 2005. The role of weather and climate processes in coral growth. M.Sc. thesis, University of Reading.

Wilkinson, C., Souter, D., 2008. Status of Caribbean Coral Reefs after Bleaching and Hurricanes in 2005. Global Coral Reef Monitoring Network, and Reef and Rainforest Research Centre, Townsville, Australia.

LETTERS
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nature climate change

Ecological memory modifies the cumulative impact of recurrent climate extremes

Terry P. Hughes[1,7*], James T. Kerry[1,7], Sean R. Connolly[1,2,7], Andrew H. Baird[1], C. Mark Eakin[3], Scott F. Heron[3,4], Andrew S. Hoey[1], Mia O. Hoogenboom[1,2], Mizue Jacobson[1,2], Gang Liu[3,5], Morgan S. Pratchett[1], William Skirving[3,5] and Gergely Torda[1,6]

Climate change is radically altering the frequency, intensity and spatial scale of severe weather events, such as heatwaves, droughts, floods and fires[1]. As the time interval shrinks between recurrent shocks[2–5], the responses of ecosystems to each new disturbance are increasingly likely to be contingent on the history of other recent extreme events. Ecological memory—defined as the ability of the past to influence the present trajectory of ecosystems[6,7]—is also critically important for understanding how species assemblages are responding to rapid changes in disturbance regimes due to anthropogenic climate change[2,3,6–8]. Here, we show the emergence of ecological memory during unprecedented back-to-back mass bleaching of corals along the 2,300 km length of the Great Barrier Reef in 2016, and again in 2017, whereby the impacts of the second severe heatwave, and its geographic footprint, were contingent on the first. Our results underscore the need to understand the strengthening interactions among sequences of climate-driven events, and highlight the accelerating and cumulative impacts of novel disturbance regimes on vulnerable ecosystems.

Changes through time are fundamental to the study of ecology and evolution, yet our understanding of the contemporary condition of ecosystems often discounts the role of non-equilibrial dynamics and history[6,9]. Emerging theoretical frameworks and models point to the important effects of time lags and memory, as the enduring influences of past experiences and changing conditions unfold over time[7]. For example, the responses of ecosystems during ecological succession, and the evolution of life history traits, are key legacy effects of the history of recurrent disturbances[2]. On most coral reefs, for instance, where recurrent tropical cyclones have historically been the most significant external disturbance[10], regional- and global-scale bleaching of corals has become a major additional agent of mortality of reef-building corals in recent decades[5,11]. Here, we document how ecological memory of severe coral bleaching on the Great Barrier Reef in 2016[12] subsequently transformed the response of corals to heat stress during a second marine heatwave in 2017. We show further that the geographic pattern of heat exposure in 2016 had a lingering impact on the spatial footprint of bleaching along the 2,300 km length of the world's largest reef system during the subsequent heatwave one year later—history has a geographic signal. Our results demonstrate the need to understand the combined, interactive effects of sequences of recurrent climate-related disturbances at a hierarchy of spatial scales, and the critical role of recent history for predicting ecological outcomes in an era of rapid global change.

The response of corals to heat stress during the second of two unprecedented back-to-back bleaching events on the Great Barrier Reef was markedly different from the first. Heat stress—measured from satellites as degree heating weeks (DHW; °C-weeks)—was greater in 2017 on 79.9% of individual reefs ($n = 3,863$ reefs; Fig. 1a and Supplementary Fig. 1), yet despite the higher and/or longer-lasting summer sea surface temperatures, the surviving corals were more resistant in 2017 to a recurrence of bleaching compared with the previous year (Fig. 1b and Supplementary Fig. 2). Specifically, in 2016, an exposure of 4–5 °C-weeks elicited a 50% probability of severe bleaching (affecting >30% of corals), but in 2017 the same 50% response occurred at a much higher level of heat exposure of 8–9 °C-weeks. In comparison, an exposure of 8–9 °C-weeks in 2016 was associated with a >90% probability of severe bleaching (Fig. 1b). Furthermore, the bleaching response curves in 2017 (in response to the severity of the second heatwave) were contingent on the history of heat exposure in 2016, with the shift being progressively greater depending on the severity of heat stress in the first event (Fig. 1c). For example, reefs exposed to 9 °C-weeks in 2017 had only a 14% probability of re-bleaching if they had experienced 9 °C-weeks in 2016, compared with almost 100% for reefs that were exposed to 0 or 3 °C-weeks in 2016 (Fig. 1c).

In 2016, the most intense heat exposure and bleaching occurred in the northern third of the Great Barrier Reef (Supplementary Video 1), whereas in 2017 the central region was the most severely affected (Supplementary Fig. 3). Consequently, the back-to-back bleaching has cumulatively extended along close to two-thirds of the Great Barrier Reef, while the southernmost region escaped with little or no bleaching in both episodes. Of the 606 individual reefs that were surveyed in both bleaching events, 22.3% bleached severely twice, 21.8% bleached severely in 2016 but not 2017, 9.2% bleached severely in 2017 but not 2016, and 46.7% (overwhelmingly in the south, and on offshore far northern reefs) escaped severe bleaching in both years (Supplementary Fig. 3b). The back-to-back heatwaves bring the total number of mass bleaching events on the Great Barrier Reef to four over the past two decades (in 1998, 2002, 2016 and 2017). Of the 171 reefs that have been assessed by aerial surveys during all 4 events, only 7% have escaped bleaching entirely since 1998, and 61% have been severely bleached (>30% of colo-

[1]Australian Research Council Centre of Excellence for Coral Reef Studies, James Cook University, Townsville, Queensland, Australia. [2]College of Science and Engineering, James Cook University, Townsville, Queensland, Australia. [3]Coral Reef Watch, US National Oceanic and Atmospheric Administration, College Park, MD, USA. [4]Marine Geophysical Laboratory, Physics Department, James Cook University, Townsville, Queensland, Australia. [5]Global Science and Technology, Greenbelt, MD, USA. [6]Australian Institute of Marine Science, Townsville, Queensland, Australia. [7]These authors contributed equally: Terry P. Hughes, James T. Kerry, Sean R. Connolly. *e-mail: terry.hughes@jcu.edu.au

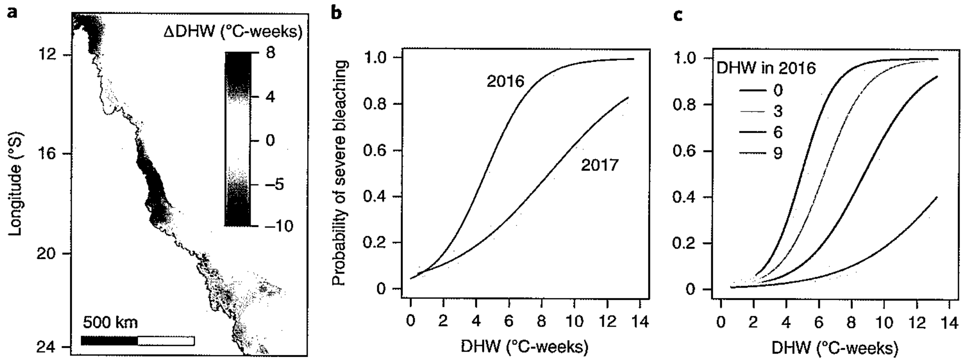

Fig. 1 | The bleaching response of corals on the Great Barrier Reef was diminished in a second summer heatwave, despite higher exposure to heat stress. **a**, Change in cumulative heat exposure on the Great Barrier Reef, measured on 3,863 individual reefs by satellites as DHW, in 2017 compared with 2016. Red indicates greater exposure in 2017, while blue indicates less. **b**, Bleaching response curves, with 95% confidence limits (shading), in two consecutive years. The *x* axis shows the heat exposure in 2016 (red) and 2017 (blue). The *y* axis is the probability of severe bleaching (affecting >30% of corals) calculated from aerial bleaching scores ($n = 1{,}135$ reefs in 2016, and 742 in 2017). **c**, Bleaching response curves in 2017, explained by DHW in 2017 and its interaction with DHW in 2016, for reefs with 4 different levels of heat exposure: 0, 3, 6 and 9 °C-weeks in 2016.

nies affected) at least once. So far, the cumulative footprint of severe bleaching extends throughout most of the northern and central regions, and along the 2,300 km coastline of the Great Barrier Reef (Supplementary Fig. 4).

The severity of bleaching in different regions along the Great Barrier Reef in 2017 was contingent on the geographic pattern of heat exposure and bleaching in 2016, revealing the emergence of a spatial pattern of ecological memory (Fig. 2). We used the bleaching threshold fitted from the 2016 event (red curve in Fig. 1b) to predict the expected 2017 bleaching from the DHW exposure in the second year, then mapped the location of reefs that were predicted to not bleach severely in 2017 but actually did, or that were expected to bleach but did not. This analysis reveals strikingly different outcomes in 2017 for the northern, central and southern regions of the reef (Fig. 2), depending on the severity of heat exposure in both 2016 and 2017.

The northern region bleached much less in 2017 compared with 2016, even on individual reefs that had the same severe 8–13 °C-week exposure in both summers (Supplementary Fig. 3). The prediction error distribution in a model that predicted the 2017 bleaching event based on the heat stress experienced in 2017, but using the fitted bleaching response curve from 2016, is strongly skewed in the northern Great Barrier Reef (Fig. 2a), because of the erroneous prediction of a high probability of bleaching that did not actually occur. Reefs exhibiting this apparent resistance to bleaching in 2017 (coloured blue in Fig. 2b) were widely distributed throughout the region, across the full spectrum of environmental conditions, from nearshore to the outer edge of the continental shelf, and spanning a latitudinal extent of close to 700 km. A plausible mechanism for less bleaching in the second event is the observed mass mortality of heat-sensitive coral species caused by the unprecedented intensity of heat stress in 2016 (Fig. 3a and Supplementary Video 2), which sharply increased the proportion of more resistant, heat-tolerant colonies in 2017[11]. The hardier corals that were bleached relatively mildly in 2016 subsequently regained their colour during the ensuing winter, then bleached moderately again when heat stress recurred in 2017 (Fig. 3a).

In the central region, heat exposure and the severity of bleaching were both sharply higher in the second year (Fig. 1a and Supplementary Fig. 3). However, a model predicting the level of bleaching in 2017, based on the fitted 2016 bleaching threshold, showed that the observed bleaching in the central region during the second event was indistinguishable from the amount expected, in stark contrast with the strong historical pattern further north (Fig. 2a). Consequently, the distribution of prediction errors was symmetrical for the central region (Fig. 2a), indicating that the bleaching responses to heat exposure in 2017 were very similar to the responses in 2016. In 2016, the central region experienced relatively moderate warming and bleaching, and in contrast with the northern Great Barrier Reef, only a small loss of <10% of corals occurred[12]. Therefore, central populations of heat-susceptible corals remained intact and vulnerable in 2017 (Fig. 1a and Supplementary Fig. 3). Any acclimation that may have occurred in central populations, in response to moderate heat exposure in 2016, was apparently swamped by the extreme marine heatwave in the following year (Supplementary Fig. 3a).

In the southern Great Barrier Reef, less bleaching than predicted occurred in 2017 despite the corals being exposed to higher heat stress during the second year (Figs. 1,2b and 3b). Consequently, the predicted error distribution was asymmetrical, and intermediate between the central and northern regions (Fig. 2a). In 2016, reefs that were exposed to 4 °C-weeks, on average, had a 50% chance of bleaching severely (Fig. 1b). In 2017, 24.9% of the reefs we resampled in the southern region ($n = 346$) experienced >4 °C-weeks, yet only 9.5% bleached, consistent with a shift in the response curve (Fig. 1b). Although the historical effect was weaker compared with the north (Fig. 2), it is plausible that the earlier experience of low levels of heat stress in 2016 improved the chances of corals escaping a bleaching response in 2017 throughout the southern region. The historical effect we observed (Fig. 2) is consistent with a variety of potential mechanisms for acclimation and adaptation of corals and their symbionts to recurrent heat stress events[13–15].

The spatial correspondence between heat exposure (DHW) and patterns of bleaching on individual reefs along and across the Great Barrier Reef (Supplementary Fig. 3) was weaker in 2017 than in 2016 because of the confounding effect of the ecological memory of heating, bleaching and mortality one year earlier. Severe bleaching in 2016 was predicted correctly for 83% of reefs by a generalized linear model (GLM), based on satellite-derived DHW at a resolution of 5 km. However, in 2017, DHW explained the occurrence of severe bleaching in only 69% of cases, consistent with the divergent responses to heat stress of reefs in the central versus northern and southern regions (Fig. 2a). A key finding is that the model fit for 2017 was substantially improved by incorporating DHW scores for 2016 as well as 2017, from 69 to 82% (for 606 reefs that were assessed in both years), indicating that bleaching

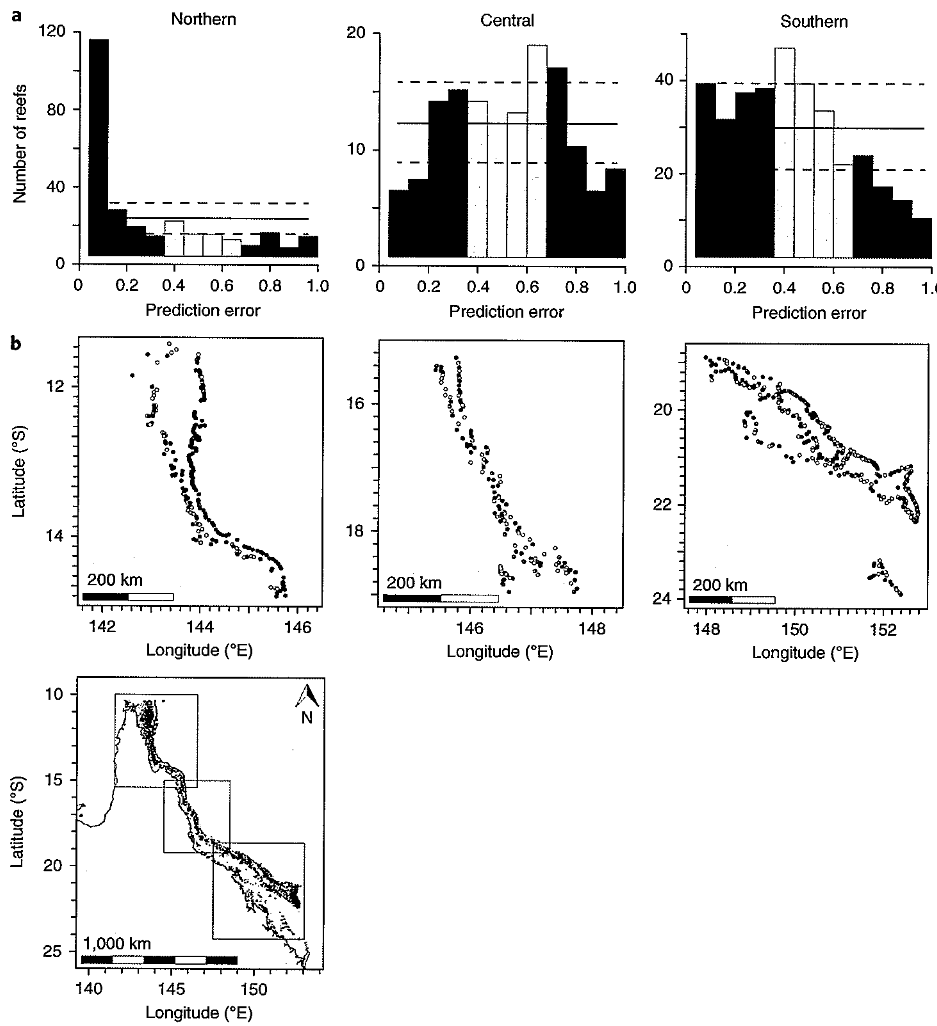

Fig. 2 | Ecological memory of the 2016 bleaching event unfolds differently in the northern, central and southern Great Barrier Reef. a. Histograms of standardized errors in predicting the 2017 bleaching event based on the 2016 response curve, in northern, central and southern regions of the Great Barrier Reef. A reef erroneously predicted to bleach with a high probability has a value close to 0, and a reef erroneously predicted as very unlikely to bleach has a value close to 1. The prediction errors are colour coded as blue (0, 0.333), gold (0.333, 0.667) and red (0.667, 1). The null expectation is for a uniform distribution of standardized residuals (solid horizontal line) and 95% confidence intervals on this null expectation are depicted with dashed horizontal lines. **b**. Maps of standardized model prediction errors showing the locations of reefs ($n=742$) and the degree to which the 2016 bleaching model (red curve in Fig. 1b) overestimated actual 2017 bleaching (blue reefs), correctly estimated 2017 bleaching (gold) and underestimated 2017 bleaching (red). The boundaries of the northern, central and southern regions are indicated in the larger-scale map.

in 2017 was influenced by the ecological memory of heat exposure 1 year earlier. The remaining unexplained variation (18%) is likely to be attributable to measurement errors in the satellite DHW metric and the bleaching scores, and to variation in the light, cloud cover, wind, rainfall and hydrodynamic conditions experienced by individual reefs.

In summary, the outcome of the global heatwave on the Great Barrier Reef in 2017 depended not only on the heat stress of that year, but was also contingent on the history of heat exposure and the physiological and ecological responses experienced one year earlier. We show that recurrent bleaching in 2017 was less than expected for a given level of heat stress for hundreds of reefs, depending on the nature of experiences in the recent past, and that history consequently had a discernible geographic footprint (Fig. 2). Potential mechanisms for generating large-scale contingencies from multiple events include acclimatization[16,17], a re-assortment of symbiotic zooxanthellae, bacteria or other symbionts[18,19], increased vulnerability in corals injured or weakened by previous disturbances[20–22], and/or a shift in species composition due to differential survival before a subsequent event[11,12,23,24].

The unprecedented back-to-back bleaching of corals on the Great Barrier Reef, predominantly in the north in 2016, followed by the central region in 2017 (Supplementary Fig. 3b), creates a new set of legacies that will unfold in coming decades. For example, the recovery of corals is likely to be slow because of the unprecedented loss of adult brood stock and the presence of many millions of dead, unstable coral skeletons that are poor substrates for the persistence of new recruits (Fig. 3a). In the longer term, the ecological resilience of coral reefs to global warming will be challenged by the growing misalignment between coral life-histories (an evolutionary legacy strongly influenced by the return times of cyclones (Fig. 3c)) and the emergence of a radically different disturbance regime that now includes frequent, regional-scale mass bleaching events (Supplementary Fig. 3). Furthermore, based on

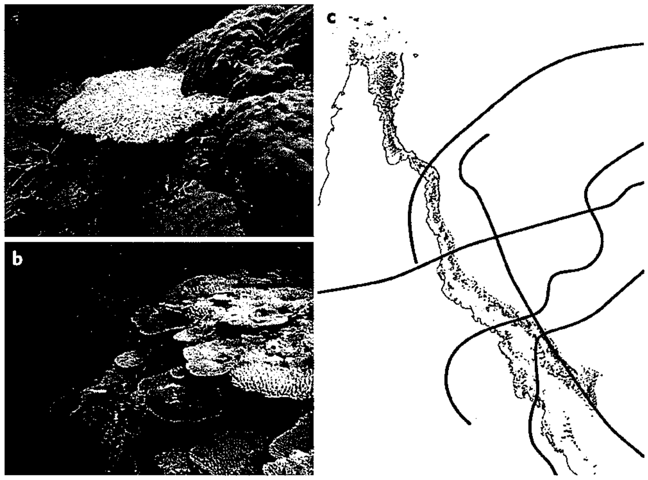

Fig. 3 | Legacy effects of multiple disturbance. a, Disproportionate loss of abundant, susceptible tabular and branching *Acropora* corals on northern reefs in 2016, compared with more resistant mound-shaped *Porites*, increased community resistance to recurrent bleaching in 2017. **b**, Corals in the southern Great Barrier Reef remained unbleached and dominated by *Acropora* in 2017, despite higher levels of heat exposure than in 2016. **c**, Map of the Great Barrier Reef showing the tracks of 5 severe tropical cyclones that peaked at either category 4 or 5 in the past decade (2008-2017). Coral life-histories are an evolutionary legacy of the history of recurrent cyclones. Contemporary mass-bleaching events, including the unprecedented back-to-back events in 2016 and 2017, represent a radical shift in historical disturbance regimes, causing a misalignment between the frequency of disturbances and the capacity of corals to recover. Photo credits: **a**, J.T.K.; **b**, G.T.

our investigation of recurrent heatwaves and coral bleaching in 2016 and 2017, we conclude that it is no longer feasible to understand fully the consequence of an individual climate-driven event in isolation from other disturbances that occur before and afterwards. Rather, because of the increasing frequency of climate-driven disturbances[4,5], it is imperative now more than ever to scrutinize sequences of multiple disturbance events to reveal the complex role of ecological memory, and its geographical extent.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, statements of data availability and associated accession codes are available at https://doi.org/10.1038/s41558-018-0351-2.

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References

1. AghaKouchak, A. et al. How do natural hazards cascade to cause disasters? *Nature* **561**, 458–460 (2018).
2. Johnstone, J. F. et al. Changing disturbance regimes, ecological memory, and forest resilience. *Front. Ecol. Environ.* **14**, 369–378 (2016).
3. Turner, M. G. Disturbance and landscape dynamics in a changing world. *Ecology* **91**, 2833–2849 (2010).
4. Allen, M. et al. *Global Warming of 1.5°C* (IPCC, 2018); http://www.ipcc.ch/report/sr15
5. Hughes, T. P. et al. Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. *Science* **359**, 80–83 (2018).
6. Peterson, G. D. Contagious disturbance, ecological memory, and the emergence of landscape pattern. *Ecosystems* **5**, 329–338 (2002).
7. Ogle, K. et al. Quantifying ecological memory in plant and ecosystem processes. *Ecol. Lett.* **18**, 221–235 (2015).
8. Seidl, R. et al. Spatial variability in tree regeneration after wildfire delays and dampens future bark beetle outbreaks. *Proc. Natl Acad. Sci. USA* **113**, 13075–13080 (2016).
9. Hughes, T. P. et al. Living dangerously on borrowed time during unrecognized regime shifts. *Trends Ecol. Evol.* **28**, 149–155 (2013).
10. Puotinen, M. L. Tropical cyclones in the Great Barrier Reef region, 1910–1999: a first step towards characterising the disturbance regime. *Aust. Geogr. Stud.* **42**, 378–392 (2004).
11. Baker, A. C., Glynn, P. W. & Riegl, B. Climate change and coral reef bleaching: an ecological assessment of long-term impacts, recovery trends and future outlook. *Estuar. Coast. Shelf Sci.* **80**, 435–471 (2008).
12. Hughes, T. P. et al. Global warming transforms coral reef assemblages. *Nature* **556**, 492–496 (2018).
13. Ainsworth, T. D. et al. Climate change disables coral bleaching protection on the Great Barrier Reef. *Science* **352**, 338–342 (2016).
14. Thomas, L. & Palumbi, S. R. The genomics of recovery from coral bleaching. *Proc. R. Soc. B* **284**, 20171790 (2017).
15. Torda, G. et al. Rapid adaptive responses to climate change in corals. *Nat. Clim. Change* **7**, 627–636 (2017).
16. Guest, J. R. et al. Contrasting patterns of coral bleaching susceptibility in 2010 suggest an adaptive response to thermal stress. *PLoS ONE* **7**, e33353 (2012).
17. Riegl, B. et al. Demographic mechanisms of reef coral species winnowing from communities under increased environmental stress. *Front. Mar. Sci.* https://doi.org/10.3389/fmars.2017.00344 (2017).
18. Bourne, D., Iida, Y., Uthicke, S. & Smith-Keune, C. Changes in coral-associated microbial communities during a bleaching event. *ISME J.* **2**, 350–363 (2008).
19. Cunning, R., Silverstein, R. N. & Baker, A. C. Symbiont shuffling linked to differential photochemical dynamics of *Symbiodinium* in three Caribbean reef corals. *Coral Reefs* **37**, 145–152 (2017).
20. Muller, E. M., Rogers, C. S., Spitzack, A. S. & Van Woesik, R. Bleaching increases likelihood of disease on *Acropora palmata* (Lamarck) in Hawksnest Bay, St. John, US Virgin Islands. *Coral Reefs* **27**, 191–195 (2008).
21. Miller, J. et al. Coral disease following massive bleaching in 2005 causes 60% decline in coral cover on reefs in the US Virgin Islands. *Coral Reefs* **28**, 925–937 (2009).
22. Williams, D. E., Miller, M. W., Bright, A. J., Pausch, R. E. & Valdivia, A. Thermal stress exposure, bleaching response, and mortality in the threatened coral *Acropora palmata*. *Bull. Mar. Poll.* **124**, 189–197 (2017).
23. Pratchett, M. S., McCowan, D., Maynard, J. A. & Heron, S. F. Changes in bleaching susceptibility among corals subject to ocean warming and recurrent bleaching in Moorea, French Polynesia. *PLoS ONE* **8**, e70443 (2013).
24. McClanahan, T. R. Changes in coral sensitivity to thermal anomalies. *Mar. Ecol. Prog. Ser.* **570**, 71–85 (2017).

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Author contributions

The study was conceptualized and led by T.P.H., who also wrote the first draft of the paper. All authors contributed to writing subsequent drafts. J.T.K. coordinated data compilation, analysis and graphics. J.T.K. and T.P.H. conducted the aerial bleaching surveys in 2016 and 2017. Underwater assessments and ground-truthing of aerial scores were performed by A.H.B., A.S.H., M.O.H., M.S.P. and G.T. S.F.H., C.M.E., G.L. and W.S. provided satellite data on heat stress. S.R.C. and M.J. contributed statistical and modelling expertise.

Competing interests

The authors declare no competing interests.

Additional information

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Methods

We measured the bleaching responses of corals exposed to a broad spectrum of heat exposures in each of two consecutive marine heatwaves, throughout the Great Barrier Reef in the summers of 2016 and 2017. Mass bleaching is a stress response by corals following their exposure to marine heatwaves, disrupting their symbiotic relationship with zooxanthellae, causing a loss of colour. We conducted aerial surveys of individual reefs ($n = 1,135$ reefs in 2016, and 742 in 2017, of which 606 were common to both years) at an elevation of approximately 150 m, using light fixed-wing aircraft and a helicopter. The reefs extended throughout the Great Barrier Reef, from the coast to the edge of the continental shelf up to 250 km offshore, and along 14° of latitude[25]. We followed the same methodology used earlier in aerial assessments of bleaching in 1998 and 2002[26], in which each reef was assigned by visual assessment to one of 5 categories of bleaching severity: (0) <1% of corals bleached; (1) 1–10%; (2) 10–30%; (3) 30–60%; and (4) >60% of corals bleached. We confirmed the accuracy of the aerial scores by underwater ground-truthing in 2016 on 104 reefs along the Great Barrier Reef that exhibited the full spectrum of bleaching[25]. The aerial bleaching scores for each year are shown in Supplementary Fig. 3b as heat maps (stretch type: histogram equalize) using inverse distance weighting (power: 2, cell size: 1,000, search radius: variable, 100 points) in ArcGIS 10.2.1.

Maximum accumulated heat exposure throughout the Great Barrier Reef in 2016 and 2017 was quantified at 5 km resolution, using the NOAA Coral Reef Watch version 3 DHW metric (Supplementary Figs. 1 and 3a), which incorporated both the temperature anomaly above the long-term summer maximum, and the duration[27]. DHW is the most accurate metric currently available for predicting large-scale bleaching[25,28] and subsequent mortality[12]. Geographic patterns of maximum DHW values are presented in Supplementary Fig. 3a as a heat map of the Great Barrier Reef for each year (stretch type: histogram equalize) using inverse distance weighting (power: 2, cell size: 1,000, search radius: variable, 100 points) in ArcMap 10.2.1. The difference between the cumulative heat exposure in both years is shown in Fig. 1a, indicating that sea surface temperatures in 2017 were generally hotter and/or longer lasting. Widespread bleaching began 2–3 weeks earlier in 2017 than in 2016, in mid-February, consistent with the earlier onset of heat stress[28]. A significant weather event also occurred in each summer: severe tropical cyclone Winston crossed Fiji on 20 February 2016, before moving to the southern Great Barrier Reef as a rain depression with persistent cloud cover, reducing sea temperatures in late February and early March, and curtailing bleaching in the south. In the following summer, severe tropical cyclone Debbie crossed the southern Great Barrier Reef at approximately 20° S on 27–28 March 2017. However, the resulting wind, cloud and rain was 4–6 weeks too late and too far south to moderate the second bout of severe bleaching. Cyclone Debbie is the southernmost cyclone trajectory in Fig. 3c.

We used the aerial bleaching scores in each year to test for a shift in the bleaching response of corals to heat exposure in 2016 versus 2017 (Fig. 1b). We fit a GLM with binomial error structure, using DHW as the explanatory variable and the level of bleaching as the binomial response (that is, whether a reef was severely bleached (aerial score categories 3 and 4) or not (categories 0–2)). Coral assemblages with bleaching scores of category 2 or lower generally regained their colour following each bleaching event, whereas corals in category 3, and especially category 4, had high levels of mortality[12]. Categories 0–2 versus 3–4 provided a viable split of the data: in 2016, 55% of surveyed reefs ($n = 1,135$) had a bleaching score of 3–4, compared with 33% in 2017 ($n = 742$) (Supplementary Fig. 2). Alternative binning splits of bleaching scores (0 versus 1–4, 0–1 versus 2–4 and 0–3 versus 4) yielded similar results, despite more uneven splits of the data (that is, the severity of bleaching was significantly correlated with DHW and the threshold shifted upwards in 2017 (as in Fig. 1b)).

To evaluate the goodness of fit of the models to the data, we compared the observed residuals with the quantiles of a null distribution of residuals generated by simulation from the fitted models[29]. Because this approach compares observed versus expected quantiles, the null expectation is for a uniform distribution of residual quantiles (standardized residuals)[28]. Inspection of the standardized residuals from our GLMs supported this null expectation (one-sample Kolmogorov–Smirnov test: $D = 0.041$, $P = 0.17$ for the 2017 model; and $D = 0.019$, $P = 0.81$ for the 2016 model). In our analyses, a standardized residual value close to 0 indicates that the model predicted severe bleaching in 2017 with a high probability, while this did not actually occur. Conversely, a standardized residual near 1 indicates that severe bleaching occurred even though the model fit implied such bleaching to be highly unlikely.

To further investigate the deviation of the pattern of bleaching responses to heat exposure in 2017 from 2016, we mapped the extent to which the model that was fitted to the 2016 data could predict actual occurrences of severe bleaching in 2017. Here, we used the 2016 bleaching response curve (shown in red in Fig. 1b) to predict bleaching in 2017 given the observed DHW exposure for 742 reefs surveyed for bleaching in 2017. We generated predicted quantiles for this 2017-from-2016 prediction model, and we used them to produce 'standardized prediction error' values in the same way that we generated standardized residuals for our other models. We termed these standardized prediction errors, rather than standardized residuals, because they represent genuine out-of-sample prediction (using a model calibrated from 2016 data to predict bleaching in 2017). We mapped geographical variation in the prediction errors (Fig. 2) for each of three regions distinguished by differences in their history of heat exposure: the northern region (from approximately 10–15° S) that experienced the most extreme heat exposure in 2016; the central region (15–19° S) that was moderately exposed in 2016 compared with extreme heat stress in 2017; and the south (19–24° S), where minor bleaching occurred in both years. In addition, we investigated how the footprints of heat exposure in the previous year affected the bleaching responses in 2017. We fitted the GLM model with binomial error structure as we did with the 2017 data (blue line in Fig. 1b), but with the addition of an interaction term between DHW values from 2016 and 2017 (Fig. 1c, which shows specific DHW values in 2016 of 0, 3, 6 and 9 °C-weeks). In this model, we omitted a fixed effect of 2016 DHW, to ensure that all thresholds had the same intercept at 0 °C-weeks.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

Source data are available online at the Tropical Data Hub (https://tropicaldatahub.org/).

References

25. Hughes, T. P. et al. Global warming and recurrent mass bleaching of corals. *Nature* **543**, 373–377 (2017).
26. Berkelmans, R., De'ath, G., Kininmonth, S. & Skirving, W. J. Comparison of the 1998 and 2002 coral bleaching events on the Great Barrier Reef: spatial correlation, patterns, and predictions. *Coral Reefs* **23**, 74–83 (2004).
27. Liu, G. et al. NOAA Coral Reef Watch's 5 km Satellite Coral Bleaching Heat Stress Monitoring product suite version 3 and Four-Month Outlook version 4. *Reef Encounter* **32**, 39–45 (2017).
28. *Coral Reef Watch Satellite Monitoring and Modeled Outlooks* (NOAA, 2018); https://coralreefwatch.noaa.gov/satellite/index.php
29. Hartig, F. *DHARMa: Residual Diagnostics for Hierarchical (Multi-Level/Mixed) Regression Models* R package version 0.1.5 (R Foundation for Statistical Computing, 2017); https://CRAN.R-project.org/package=DHARMa

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☐	☒	Estimates of effect sizes (e.g. Cohen's *d*, Pearson's *r*), indicating how they were calculated
☒	☐	Clearly defined error bars *State explicitly what error bars represent (e.g. SD, SE, CI)*

Our web collection on statistics for biologists may be useful.

Software and code

icy information about availability of computer code

Data collection	n/a
Data analysis	R code for statistical analysis (version R3.5.1). ArcGIS (ArcMap 10.2.1) for graphical interpolation of data

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors/reviewers upon request. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Research guidelines for submitting code & software for further information.

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Policy information about availability of data

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Source data are available online at the Tropical Data Hub, https://tropicaldatahub.org/.

Field-specific reporting

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☐ Life sciences ☐ Behavioural & social sciences ☒ Ecological, evolutionary & environmental sciences

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Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	Reefs were surveyed from the air, during two bleaching events throughout the Great Barrier Reef
Research sample	1135 reefs in 2016, 742 in 2017. 606 common in both years
Sampling strategy	Reefs were selected at random along the length of the Great Barrier Reef
Data collection	Collected and recorded during aerial survey (TPH and JTK)
Timing and spatial scale	Eight days of aerial surveys during the peak of the bleaching events. March - April 2016. March - April 2017
Data exclusions	No data were excluded
Reproducibility	n/a
Randomization	Reefs were selected at random along the length of the Great Barrier Reef
Blinding	n/a

Did the study involve field work? ☒ Yes ☐ No

Field work, collection and transport

Field conditions	Low tide and low wind conditions, during the peak of the bleaching
Location	Great Barrier Reef along 14 degrees of latitude
Access and import/export	n/a
Disturbance	n/a

Reporting for specific materials, systems and methods

Materials & experimental systems

n/a	Involved in the study	
☒	☐	Unique biological materials
☒	☐	Antibodies
☒	☐	Eukaryotic cell lines
☒	☐	Palaeontology
☒	☐	Animals and other organisms
☒	☐	Human research participants

Methods

n/a	Involved in the study	
☒	☐	ChIP-seq
☒	☐	Flow cytometry
☒	☐	MRI-based neuroimaging

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LETTER

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Global warming transforms coral reef assemblages

Terry P. Hughes[1]*, James T. Kerry[1], Andrew H. Baird[1], Sean R. Connolly[1,2], Andreas Dietzel[1], C. Mark Eakin[3], Scott F. Heron[3,4,5], Andrew S. Hoey[1], Mia O. Hoogenboom[1,2], Gang Liu[3,4], Michael J. McWilliam[1], Rachel J. Pears[6], Morgan S. Pratchett[1], William J. Skirving[3,4], Jessica S. Stella[6] & Gergely Torda[1,7]

Global warming is rapidly emerging as a universal threat to ecological integrity and function, highlighting the urgent need for a better understanding of the impact of heat exposure on the resilience of ecosystems and the people who depend on them[1]. Here we show that in the aftermath of the record-breaking marine heatwave on the Great Barrier Reef in 2016[2], corals began to die immediately on reefs where the accumulated heat exposure exceeded a critical threshold of degree heating weeks, which was 3–4 °C-weeks. After eight months, an exposure of 6 °C-weeks or more drove an unprecedented, regional-scale shift in the composition of coral assemblages, reflecting markedly divergent responses to heat stress by different taxa. Fast-growing staghorn and tabular corals suffered a catastrophic die-off, transforming the three-dimensionality and ecological functioning of 29% of the 3,863 reefs comprising the world's largest coral reef system. Our study bridges the gap between the theory and practice of assessing the risk of ecosystem collapse, under the emerging framework for the International Union for Conservation of Nature (IUCN) Red List of Ecosystems[3], by rigorously defining both the initial and collapsed states, identifying the major driver of change, and establishing quantitative collapse thresholds. The increasing prevalence of post-bleaching mass mortality of corals represents a radical shift in the disturbance regimes of tropical reefs, both adding to and far exceeding the influence of recurrent cyclones and other local pulse events, presenting a fundamental challenge to the long-term future of these iconic ecosystems.

Extreme weather events due to anthropogenic global warming are rapidly emerging as major contemporary threats to almost all ecosystems[1]. On coral reefs, severe heatwaves trigger episodes of mass bleaching[4–7], which occur when the relationship between corals and their photosynthetic symbionts (zooxanthellae, *Symbiodinium* spp.) breaks down, turning the coral pale. Bleached corals are physiologically damaged and nutritionally compromised, and they can die if the bleaching is severe and the recovery time of their symbionts is prolonged[8,9]. However, the relationship between heat exposure, bleaching and the initial and longer term mortality of different taxa is not well understood or quantified. Although the concept of winners versus losers has been widely applied to describe inter-specific differences in the degree of bleaching[10–14], predicting the definitive losers, namely those corals that fail to regain their colour and ultimately die following heat stress, is key to understanding how climate change affects biodiversity, species composition and ecosystem function. To date, no study has, to our knowledge, examined the quantitative relationship between a broad range of heat exposures and the response of coral assemblages. Establishing the shape of this response curve is essential for identifying the critical levels of heat exposure that trigger bleaching and mass mortality, and for predicting the amount of heat exposure that could drive a transformation in species composition and the widespread collapse of ecological functions. Here, we examine geographical patterns of heat exposure and the resultant mortality of coral assemblages along the 2,300 km length of the Great Barrier Reef, following the record-breaking marine heatwave of 2016[2]. We show that taxonomic patterns of bleaching did not predict the identity of the corals that ultimately died, that many corals succumbed immediately from heat stress, and that others died more slowly following the depletion of their zooxanthellae. The die-off of corals drove a radical shift in the composition and functional traits of coral assemblages on hundreds of individual reefs, transforming large swaths of the Great Barrier Reef from mature and diverse assemblages to a highly altered, degraded system.

The 2016 bleaching event triggered an unprecedented loss of corals on the northern third of the Great Barrier Reef, and to a lesser extent, the central third, with almost no heat-stress mortality occurring further south (Fig. 1a and Extended Data Figs. 1–3). The geographical footprint and intensity of the coral die-off (Fig. 1a) closely matched the observed north–south pattern in accumulated heat (Fig. 1b), measured as satellite-derived degree heating weeks (DHW in °C-weeks), a commonly used measurement that incorporates both the duration and intensity of heat stress[15,16]. The 5-km-resolution DHW values (Fig. 1b) were significantly correlated with independently estimated losses of corals (Fig. 1a; $r^2 = 0.50$, $P < 0.001$, $n = 1{,}156$ reefs). In the northern, 700-km-long section of the Great Barrier Reef (from 9.5–14.5 °S), in which the heat exposure was the most extreme, 50.3% of the coral cover on reef crests was lost within eight months (Fig. 1b). More broadly, throughout the entire Great Barrier Reef, including the southern third, in which the heat exposure was minimal (Fig. 1b), the cover of corals declined by 30.0% between March and November 2016. In comparison, the massive loss of corals from the 2016 marine heatwave was an order of magnitude greater and more widespread than the patchier, localized damage that typically occurs on reef sites within the track of a severe tropical cyclone[17].

At the scale of individual reefs, the severity of coral mortality was also highly correlated with the amount of bleaching, and with the level of heat exposure (Fig. 2). Initially, at the peak of temperature extremes in March 2016, many millions of corals died quickly in the northern third of the Great Barrier Reef over a period of only 2–3 weeks (Fig. 2a). These widespread losses were not due to the attrition of corals that slowly starved because they failed to regain their symbionts[9]. Rather, temperature-sensitive species of corals began to die almost immediately in locations that were exposed to heat stress of more than 3–4 °C-weeks (Figs. 1b, 2a). The amount of initial mortality increased steadily with increasing heat exposure ($r^2 = 0.50$, $P < 0.001$, $n = 63$ reefs); on reefs which were exposed to less than 4 °C-weeks, fewer than 5% of the corals died, whereas an initial median loss of 15.6% of corals was recorded on reefs with 4–8 °C-weeks exposure, and a median loss of 27.0% of corals at locations that experienced 8 °C-weeks or more (Fig. 2a). Across the entire Great Barrier Reef, 34.8% of individual reefs experienced at least 4 °C-weeks, and 20.7% of reefs were exposed to 8 °C-weeks or more of accumulated heat stress in 2016 (Fig. 1b). The amount of initial mortality at the peak of summer varied strikingly among different groups of corals (Extended Data Fig. 4a).

[1]Australian Research Council Centre of Excellence for Coral Reef Studies, James Cook University, Townsville, Queensland, Australia. [2]College of Science and Engineering, James Cook University, Townsville, Queensland, Australia. [3]Coral Reef Watch, US National Oceanic and Atmospheric Administration, College Park, MD, USA. [4]Global Science & Technology, Inc., Greenbelt, MD, USA. [5]Marine Geophysical Laboratory, Physics Department, James Cook University, Townsville, Queensland, Australia. [6]Great Barrier Reef Marine Park Authority, Townsville, Queensland, Australia. [7]Australian Institute of Marine Science, Townsville, Queensland, Australia. *e-mail: terry.hughes@jcu.edu.au

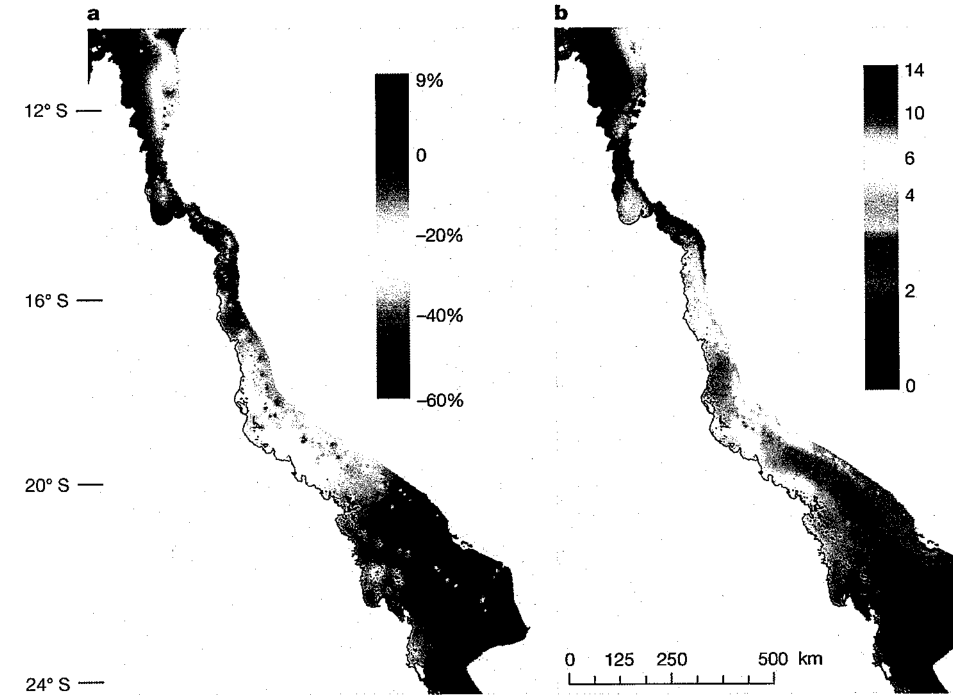

Fig. 1 | Large-scale spatial patterns in change in coral cover and in heat exposure on the Great Barrier Reef, Australia. **a**, Change in coral cover between March and November 2016. **b**, Heat exposure, measured in DHW (in °C-weeks) in the summer of 2016. Map template is provided by Geoscience Australia (© Commonwealth of Australia (Geoscience Australia) 2018).

During the ensuing Austral winter, the bleached corals in the northern and central Great Barrier Reef either slowly regained their colour and survived or they continued to die at unprecedented levels. Less than 1% of surviving colonies remained bleached after eight months. The severity of the longer term loss of corals, measured in situ as the decline in coral cover between March and November, was accurately predicted by the percentage of corals that were initially bleached (Fig. 2b; $r^2 = 0.51$, $P < 0.001$, $n = 63$ reefs). Specifically, reefs that experienced less than 25% bleaching in March typically had almost no loss of cover after eight months (Fig. 2b). By contrast, above this threshold, the loss of coral cover increased progressively, indicating that fewer of the bleached corals survived. Furthermore, the longer term loss of coral cover also intensified with increasing levels of heat exposure (DHW) experienced by each reef ($r^2 = 0.44$, $P < 0.001$, $n = 63$ reefs; Fig. 2c). Consequently, we recorded almost no loss of coral cover for reefs exposed to 0–3 °C-weeks, compared to a 40% decline at 4 °C-weeks, 66% for 8 °C-weeks, and extreme declines of > 80% for exposures of 9 °C-weeks or more. The nonlinear responses to heat exposure varied significantly among coral taxa (Extended Data Figs. 5, 6), illustrating a spectrum of survivorship among winners versus losers, driving a radical shift in species composition.

Post-bleaching mortality has disproportionately transformed the assemblage structure and functional diversity of corals on reefs that experienced high levels of bleaching (affecting more than 60% of colonies), as illustrated by a non-metric multi-dimensional scaling (nMDS) analysis (Fig. 3). The abundances of all categories of corals

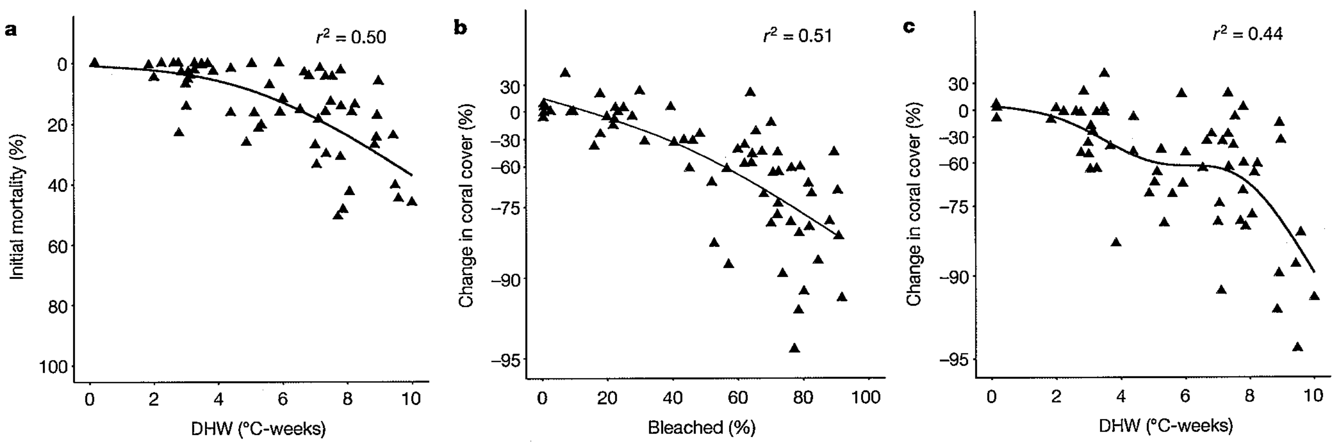

Fig. 2 | The initial and longer term response of coral assemblages to heat exposure. Regression curves were fitted using generalized additive models, with 95% confidence limits (ribbons). Data points represent individual reefs. **a**, Initial coral mortality measured at the peak of bleaching ($n = 63$ reefs), versus the heat exposure each reef experienced (satellite-based DHW (in °C-weeks)). **b**, Longer term change in coral cover ($\log_{10}$) between March and November 2016 on 63 individual reefs, versus the initial amount of bleaching recorded underwater. **c**, Longer term change in coral cover ($\log_{10}$) between March and November 2016, versus heat exposure (DHW) on the same individual reefs.

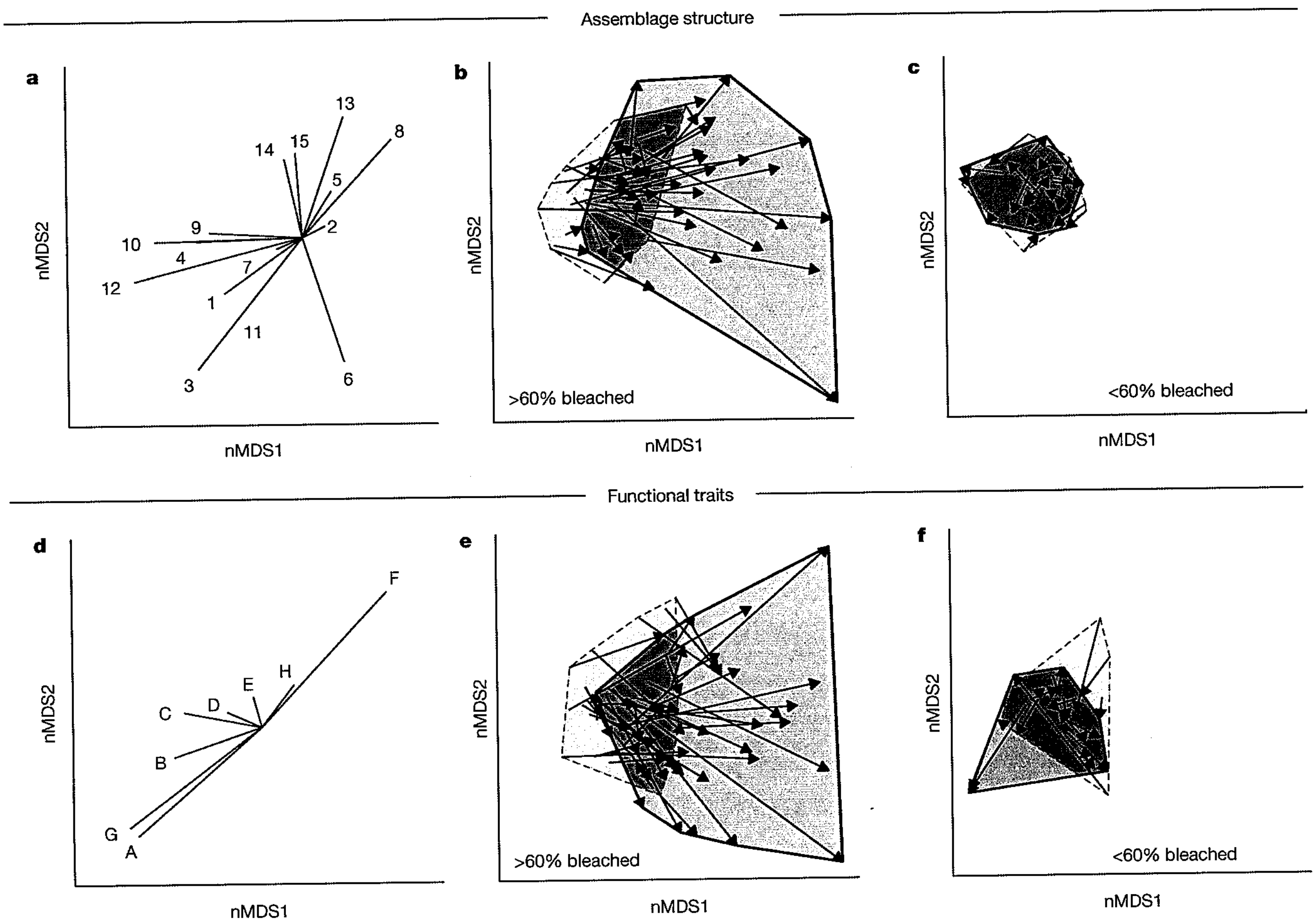

Fig. 3 | Changes in assemblage structure and functional traits of corals following mass bleaching. a–c, nMDS analyses of shifts in coral assemblages between March and November 2016. **a**, Fifteen nMDS vectors indicate the responses of individual taxa: 1, other *Acropora*; 2, favids; 3, *Isopora*; 4, *Montipora*; 5, Mussidae; 6, other *Pocillopora*; 7, *Pocillopora damicornis*; 8, Poritidae; 9, *Seriatopora hystrix*; 10, staghorn coral (*Acropora* spp.); 11, *Stylophora pistillata*; 12, tabular coral (*Acropora* spp.); 13, soft corals; 14, other scleractinia; 15, other sessile fauna (see Methods). **b**, The grey polygon bounds the ordination space occupied by coral assemblages on each reef in March. Red arrows connect the before–after pairs of data points for each location to show changes in composition on severely bleached reefs (> 60% of colonies bleached, $n = 43$ reefs) after eight months (in November), bounded by the red polygon. **c**, Blue arrows connect the before–after pairs of data points for each location on reefs ($n = 20$) that were moderately (< 60% bleached), bounded by the grey (March) and blue polygons (November). **d–f**, nMDS analyses of shifts in assemblage trait composition between March and November 2016 at the same locations. **d**, The eight vectors indicate the absolute contribution of traits to coral assemblages: A, surface area to volume ratio; B, growth rate; C, colony size; D, skeletal density; E, colony height; F, corallite width; G, interstitial space size; H, reproductive mode (see Methods and Extended Data Table 1). **e**, The shift in abundance-weighted trait space coordinates for coral assemblages over eight months for reefs with > 60% bleaching. **f**, The shift in abundance-weighted trait space coordinates for coral assemblages on reefs with < 60% bleaching.

decreased to varying degrees on these heavily bleached reefs, shown by the orientation of the nMDS vectors (Fig. 3a) and the directional shift in the before–after assemblages (Fig. 3b). Tabular and staghorn *Acropora*, *Seriatopora hystrix* and *Stylophora pistillata*—fast-growing, three-dimensional species that dominate many shallow Indo-Pacific reefs—all declined by > 75% (Extended Data Fig. 4b). In contrast to the radical shifts on heavily bleached reefs, assemblages changed very little between March and November on reefs that experienced moderate (30–60%) or minor (0–30%) bleaching (Fig. 3c).

The response of coral assemblages on reefs exposed to a broad range of heat stress, ranging from 0 to 10 °C-weeks, was strikingly nonlinear (Fig. 4). The changes in assemblage structure after eight months (measured as the Euclidean distance between before and after compositions on each reef; Fig. 3b, c) were small on reefs that were exposed to less than 6 °C-weeks, whereas reefs subjected to more than 6 °C-weeks lost over 50% of their corals (Fig. 2c) and shifted markedly in composition (Fig. 4). Satellite-derived DHW data indicate that 28.6% of the 3,863 reefs comprising the Great Barrier Reef experienced thermal exposures of more than 6 °C-weeks during the 2016 bleaching event, and 20.7% (800 reefs) were exposed to more than 8 °C-weeks (Fig. 1). Individual reefs with this severity of heat exposure have undergone an unprecedented ecological collapse, extending southwards from Papua New Guinea for up to 1,000 km (Fig. 1). Reefs that were exposed to less than 6 °C-weeks were located predominantly in the southern half of the Great Barrier Reef, and in a narrow northern patch at the outer edge of the continental shelf where temperature anomalies in 2016 above the local long-term summer maximum were small (Fig. 1b).

The abrupt, regional-scale shift in coral assemblages has also radically reduced the abundance and diversity of species traits that facilitate key ecological functions (Fig. 3d, e and Extended Data Tables 1, 2). A before–after analysis of the multi-dimensional trait space of coral assemblages, weighted by the absolute abundance of taxa contributing to each trait, reveals a transformation in the functional-trait composition of assemblages on heavily bleached reefs (affecting over 60% of colonies) in the eight-month period after March 2016 (Fig. 3e). In most cases, reefs shifted away from the dominance of fast-growing, branching and tabular species that are important providers of three-dimensional habitat, to a depauperate assemblage dominated by taxa

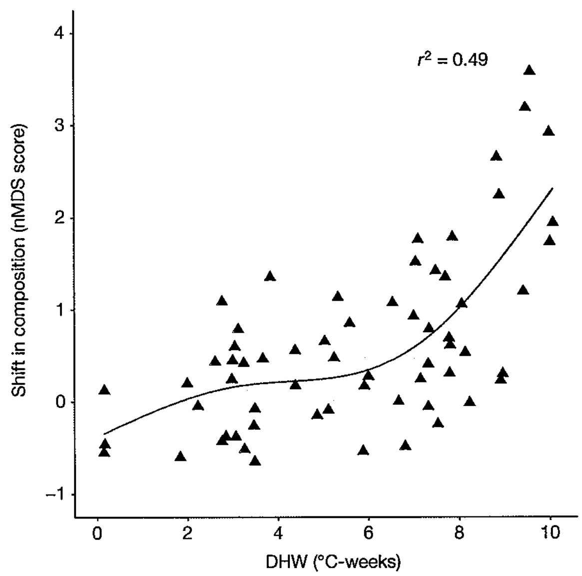

Fig. 4 | Change in coral assemblages in response to heat exposure. The regression curve is fitted using a generalized additive model, with 95% confidence limits. Each data point represents the shift in composition ($n = 63$ reefs), based on the Euclidean distance in a non-metric multi-dimensional scaling analysis of assemblages on individual reefs sampled at the peak of bleaching and eight months later. Heat exposure for each reef was measured as satellite-derived DHW (in °C-weeks).

with simpler morphological characteristics and slower growth rates. By contrast, on less-bleached reefs the weighted abundances of functionally important traits typically showed small gains (Fig. 3f).

In conclusion, our analyses show that acute heat stress from global warming is a potent driver of a 1,000 km-scale transformation of coral assemblages, affecting even the most remote and well-protected reefs within an iconic World Heritage Area. Forecasts of coral bleaching made continuously by the US National Oceanic and Atmospheric Administration are accompanied with guidance that a DHW exposure of 4 °C-weeks is expected to cause significant bleaching, and 8 °C-weeks may also result in mortality of corals[15,16,18]. Similarly, a model for predicting the locations of resilient reefs on the Great Barrier Reef assumed that coral mortality starts to occur only once thermal exposure exceeds 6 °C-weeks[19]. However, we show that substantial mortality occurred on the Great Barrier Reef in 2016 well below 6 °C-weeks, beginning instead at 3–4 °C-weeks, and with typical losses exceeding 50% at 4–5 °C-weeks (Fig. 2c). Furthermore, the threshold that we have identified for the breakdown of assemblage structure, approximately 6 °C-weeks (Fig. 4), was transgressed in 2016 throughout most of the northern, as well as much of the central, region of the Great Barrier Reef (Fig. 1). The prospects for a full recovery to the pre-bleaching coral assemblages are poor, for several reasons. First, many of the surviving coral colonies continue to die slowly even after recovery of their algal symbionts, because they have lost extensive patches of tissue, are injured and fragmented, and because corals weakened by bleaching are susceptible to subsequent outbreaks of disease[20,21]. Second, the replacement of dead corals by larval recruitment and subsequent colony growth will take at least a decade even for fast-growing, highly fecund corals, such as species of *Acropora*, *Pocillopora*, *Seriatopora* and *Stylophora*[22,23]. The success of future recruitment will depend on an adequate supply of larvae from lightly bleached locations, the rapid break down of many millions of dead coral skeletons to provide a more enduring and stable substrate for settling larvae and the availability of suitable settlement cues and conditions for survival of juvenile corals[24]. Third, for longer-lived, slow-growing species, the trajectory of replacement of dead corals on heavily damaged reefs will be far more protracted, almost certainly decades longer than the return-times of future bleaching events. The recurrence of mass bleaching during the recovery period will be critical, in view of the global rise in the frequency of bleaching events[4–6].

The 2015–2016 global bleaching event is a watershed for the Great Barrier Reef, and for many other severely affected reefs elsewhere in the Indo-Pacific Ocean[4]. Furthermore, the Great Barrier Reef experienced severe bleaching again in early 2017, causing additional extensive damage[25,26]. The most likely scenario, therefore, is that coral reefs throughout the tropics will continue to degrade over the current century until climate change stabilizes[7,27], allowing remnant populations to reorganize into novel, heat-tolerant reef assemblages. The 2016 marine heatwave has triggered the initial phase of that transition on the northern, most-pristine region of the Great Barrier Reef (Figs. 1, 4), changing it forever as the intensity of global warming continues to escalate. The large-scale loss of functionally diverse corals is a harbinger of further radical shifts in the condition and dynamics of all ecosystems, reinforcing the need for risk assessment of ecosystem collapse[3], especially if global action on climate change fails to limit warming to 1.5–2 °C above the pre-industrial base-line.

Online content

Any Methods, including any statements of data availability and Nature Research reporting summaries, along with any additional references and Source Data files, are available in the online version of the paper at https://doi.org/10.1038/s41586-018-0041-2.

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1. IPCC. *Climate Change 2014: Impacts, Adaptation, and Vulnerability* (eds Field, C. B. et al.) (Cambridge Univ., Cambridge, 2014).
2. Australian Bureau of Meteorology. 2016 marine heatwave on the Great Barrier Reef. http://www.bom.gov.au/environment/doc/marine-heatwave-2016.pdf (2016).
3. Bland, L. M. et al. Developing a standardized definition of ecosystem collapse for risk assessment. *Front. Ecol. Environ.* **16**, 29–36 (2018).
4. Hughes, T. P. et al. Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. *Science* **359**, 80–83 (2018).
5. Heron, S. F., Maynard, J. A., van Hooidonk, R. & Eakin, C. M. Warming trends and bleaching stress of the World's coral reefs 1985–2012. *Sci. Rep.* **6**, 38402 (2016).
6. Donner, S. D., Rickbeil, G. J. M. & Heron, S. F. A new, high-resolution global mass coral bleaching database. *PLoS ONE* **12**, e0175490 (2017).
7. Hughes, T. P. et al. Coral reefs in the Anthropocene. *Nature* **546**, 82–90 (2017).
8. Baird, A. H. & Marshall, P. A. Mortality, growth and reproduction in scleractinian corals following bleaching on the Great Barrier Reef. *Mar. Ecol. Prog. Ser.* **237**, 133–141 (2002).
9. Baker, A. C., Glynn, P. W. & Riegl, B. Climate change and coral reef bleaching: an ecological assessment of long-term impacts, recovery trends and future outlook. *Estuar. Coast. Shelf Sci.* **80**, 435–471 (2008).
10. Marshall, P. A. & Baird, A. H. Bleaching of corals on the Great Barrier Reef: differential susceptibilities among taxa. *Coral Reefs* **19**, 155–163 (2000).
11. Loya, Y. et al. Coral bleaching: the winners and the losers. *Ecol. Lett.* **4**, 122–131 (2001).
12. Hughes, T. P. et al. Climate change, human impacts, and the resilience of coral reefs. *Science* **301**, 929–933 (2003).
13. Swain, T. D. et al. Coral bleaching response index: a new tool to standardize and compare susceptibility to thermal bleaching. *Glob. Change Biol.* **22**, 2475–2488 (2016).
14. Hughes, T. P. et al. Global warming and recurrent mass bleaching of corals. *Nature* **543**, 373–377 (2017).
15. Eakin, C. M. et al. Caribbean corals in crisis: record thermal stress, bleaching, and mortality in 2005. *PLoS ONE* **5**, e13969 (2010).
16. Liu, G. et al. Reef-scale thermal stress monitoring of coral ecosystems: new 5-km global products from NOAA Coral Reef Watch. *Remote Sens.* **6**, 11579–11606 (2014).
17. Beeden, R. et al. Impacts and recovery from severe tropical cyclone Yasi on the Great Barrier Reef. *PLoS ONE* **10**, e0121272 (2015).
18. Kayanne, H. Validation of degree heating weeks as a coral bleaching index in the northwestern Pacific. *Coral Reefs* **36**, 63–70 (2017).
19. Hock, K. et al. Connectivity and systemic resilience of the Great Barrier Reef. *PLoS Biol.* **15**, e2003355 (2017).
20. Muller, E. M. et al. Bleaching increases likelihood of disease on *Acropora palmata* (Lamarck) in Hawksnest Bay, St. John, US Virgin Islands. *Coral Reefs* **27**, 191–195 (2008).
21. Miller, J. et al. Coral disease following massive bleaching in 2005 causes 60% decline in coral cover on reefs in the US Virgin Islands. *Coral Reefs* **28**, 925–937 (2009).
22. Kayanne, H., Harii, S., Ide, Y. & Akimoto, F. Recovery of coral populations after the 1998 bleaching on Shiraho Reef, in the southern Ryukyus, NW Pacific. *Mar. Ecol. Prog. Ser.* **239**, 93–103 (2002).

23. Gilmour, J. P., Smith, L. D., Heyward, A. J., Baird, A. H. & Pratchett, M. S. Recovery of an isolated coral reef system following severe disturbance. *Science* **340**, 69–71 (2013).
24. Webster, N. S., Soo, R., Cobb, R. & Negri, A. P. Elevated seawater temperature causes a microbial shift on crustose coralline algae with implications for the recruitment of coral larvae. *ISME J.* **5**, 759–770 (2011).
25. Hughes, T. P. & Kerry, J. T. Back-to-back bleaching has now hit two-thirds of the Great Barrier Reef. *The Conversation* https://theconversation.com/back-to-back-bleaching-has-now-hit-two-thirds-of-the-great-barrier-reef-76092 (2017).
26. Great Barrier Reef Marine Park Authority. Final report: 2016 coral bleaching event on the Great Barrier Reef. http://elibrary.gbrmpa.gov.au/jspui/bitstream/11017/3206/1/Final-report-2016-coral-bleaching-GBR.pdf (2017).
27. Hartmann, D. L. et al. in *Climate Change 2013: The Physical Science Basis*. (eds Stocker, T.F. et al.) 159–254 (IPCC, Cambridge Univ. Press, Cambridge, 2013).

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Author contributions The study was conceptualized by T.P.H., who also wrote the first draft of the paper. All authors contributed to writing subsequent drafts. J.T.K. coordinated data compilation, analyses and graphics. Aerial bleaching surveys were conducted by T.P.H. and J.T.K. Underwater bleaching and mortality censuses were undertaken by A.H.B., A.D., A.S.H., M.O.H., M.J.M., R.J.P., M.S.P., J.S.S. and G.T. C.M.E., S.F.H., G.L. and W.J.S. provided satellite data on heat stress. M.J.M. undertook the functional trait analysis and S.R.C. provided statistical advice and modelled loss of coral cover among different taxa.

Competing interests The authors declare no competing interests.

Additional information

Extended data is available for this paper at https://doi.org/10.1038/s41586-018-0041-2.
Supplementary information is available for this paper at https://doi.org/10.1038/s41586-018-0041-2.
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METHODS

Initial mortality and heat stress. We used aerial surveys, conducted in March–April 2016, to measure the geographical extent and severity of bleaching on the Great Barrier Reef, and subsequently converted the bleaching scores into mortality estimates (Fig. 1a) using a calibration curve based on underwater measurements of coral losses (Extended Data Fig. 1). The aerial surveys were conducted throughout the Great Barrier Reef Marine Park and the Torres Strait between Australia and Papua New Guinea, from the coast of Queensland to the outermost reefs, and along the entire Reef from latitudes 9.5 °S to 23.5 °S. Each of 1,156 individual reefs was scored into one of five bleaching categories: 0, less than 1% of corals bleached; 1, 1–10%; 2, 10–30%; 3, 30–60%; 4, more than 60% of corals bleached. The accuracy of the aerial scores was ground-truthed by measuring the extent of bleaching underwater on 104 reefs, also during March–April 2016[14,28].

We assessed underwater the initial mortality of different taxa due to heat stress, at the same time as the aerial surveys, on 63 reefs that spanned the full spectrum of heat exposures and bleaching. On each reef, the extent of bleaching and mortality on individual coral colonies was measured at two sites using five $10 \times 1\,m^2$ belt transects placed on the reef crest at a depth of 2 m. We identified each colony (at the species or genus level) and recorded a categorical bleaching score for each one ($n = 58{,}414$ colonies): 1, no bleaching; 2, pale; 3, 1–50% bleached; 4, 51–99% bleached; 5, 100% bleached; 6, recently dead. The dead colonies, which had suffered whole-colony mortality, were white with fully intact fine-scale skeletal features, typically still had patches of rotting coral tissue and were experiencing the initial week or two of colonization by filamentous algae, features which distinguished them from corals that had died earlier. The timing of our initial underwater censuses, at the peak of the bleaching in March–April 2016, was critical for identifying corals that were dying directly from heat stress, and for measuring the baseline composition of the assemblages.

Heat stress on the Great Barrier Reef in 2016 was quantified at 5-km resolution, using the NOAA Coral Reef Watch version 3 DHW metric[16]. DHW values are presented in Fig. 1b as a heat map (stretch type: histogram equalize) using inverse distance weighting (power: 2, cell size: 1000, search radius: variable, 100 points) in ArcMap 10.2.1.

Longer term mortality. To measure longer term coral loss (decrease in coral cover after eight months) and its relationship to the level of bleaching and heat exposure, we also conducted detailed before–after assessments of taxon-specific abundances by re-visiting the 63 reefs. We measured abundances in March–April and eight months later at the same locations in October–November, allowing us to compare changes in coral cover for 15 ecologically and taxonomically distinct components of benthic assemblages, on reefs exposed to a broad spectrum of heat stress. These measurements were conducted at the same two geo-referenced sites per reef, on reef crests at a depth of 2 m, using five 10-m long line-intercept transects per site. There were no cyclones or flood events on the Great Barrier Reef during the March–November period (Austral winter) in 2016. Unbleached reefs typically showed small increases in cover due to growth, which we included in the regression analyses. Analysis of change in coral cover was undertaken using the $\log_{10}$-transformed ratio of final to initial cover. To improve readability of Fig. 2 and Extended Data Fig. 1, changes in coral cover are presented as percentages calculated from the log-scale.

We compared the initial and final composition of corals using a non-metric multi-dimensional scaling (nMDS) analysis based on a Bray–Curtis similarity matrix of square-root transformed data, and quantified the shift over time using the Euclidean distance between before–after assemblages at each location. We then estimated the relationship between the shift in composition at each reef versus the level of heat exposure experienced there (Fig. 4). To include all species, the majority of which are too rare to analyse individually, we pooled them into 15 ecologically cohesive groups depending on their morphology, life history and taxonomy. Three of the fifteen groups are ubiquitous species or species complexes: *Pocillopora damicornis*, *Seriatopora hystrix* and *Stylophora pistillata*. In each of the multi-species groups, the dominant species or genera on reef crests were: other *Acropora* (*A. gemmifera*, *A. humilis*, *A. loripes*, *A. nasuta*, *A. secale*, *A. tenuis* and *A. valida*); favids (that is, species and genera from the formerly recognized family Faviidae: *Cyphastrea*, *Favia*, *Favites*, *Goniastrea*, *Leptastrea*, *Montastrea* and *Platygyra*); Mussidae (*Lobophyllia* and *Symphyllia*); *Isopora* (*I. palifera* and *I. cuneata*); other *Pocillopora* (*P. meandrina* and *P. verrucosa*); other sessile animals (sponges, tunicates, molluscs); *Porites* (*P. annae* and *P. lobata*); *Montipora* (*M. foliosa*, *M. grisea*, *M. hispida*, *M. montasteriata* and *M. tuberculosa*); staghorn *Acropora* (*A. florida*, *A. intermedia*, *A. microphthalma*, *A. muricata* and *A. robusta*); soft corals (alcyonaceans and zooanthids); tabular *Acropora* (*A. cytherea*, *A. hyacinthus* and *A. anthocercis*).

We calculated longer term mortality for all species combined at the scale of the entire Great Barrier Reef in three ways, all of which yielded consistent results. The first approach, which provided the best spatial resolution (Fig. 1a), was based on a comparison of the observed loss of total coral cover on 63 reefs that extend along the entire Great Barrier Reef measured underwater between March and November, with aerial bleaching scores of the same locations in March–April (Extended Data Fig. 1). This calibration allowed us to convert the aerial scores of bleaching that we recorded for 1,156 reefs into mortality estimates for each of the five aerial score categories, and to map the geographic footprint of losses of corals throughout the Great Barrier Reef (Fig. 1a). The spatial patterns of coral decline (Fig. 1a) are presented as a heat map of the calibrated scores (stretch type: histogram equalize) using inverse distance weighting (power: 2, cell size: 1000, search radius: variable, 100 points) in ArcMap 10.2.1.

The second methodology for estimating large-scale mortality is independent of aerial surveys of bleaching, and based on the loss of total coral cover on 110 reefs (Extended Data Fig. 2), including the 63 reefs that were re-censused for change in composition. The median cover on these reefs declined between March and November from 34% to 20% (Extended Data Fig. 3). For method two, the observed loss of coral cover was averaged for replicate reefs surveyed within each of eight sectors of the Great Barrier Reef Marine Park and the Torres Strait), corrected for differences in reef area for each sector based on GIS data provided by the Great Barrier Reef Marine Park Authority, and then summed to calculate the total loss. For method three, we used the fitted relationship between satellite-derived DHW and observed change in cover (Fig. 2c) to score the losses or gains on all 3,863 individual reefs comprising the Great Barrier Reef, and averaged the total. These two alternative approaches for estimating large-scale loss of cover, both based on before–after underwater surveys (Extended Data Figs. 2 and 3) yielded consistent results with Fig. 1a—a 29.0% and 27.7% decline, respectively, after eight months.

Differential mortality among coral taxa. To estimate how exposure to heat (measured as DHW) affects loss of cover differentially among taxa, we used a linear mixed effects model. The fixed effect was DHW and we allowed for a random effect of taxonomic grouping on both the intercept and slope of the relationship between coral cover change and DHW. We excluded from the analysis observations with zero initial coral cover of a particular taxonomic group. Change in coral cover was transformed before analysis by calculating the $log\left(\frac{C_f+\epsilon}{C_i+\epsilon}\right)$ where C_f and C_i were the final and initial coral cover, respectively, and ϵ was the minimum observed value of coral cover. The estimated random effect on intercepts was approximately zero, so we eliminated it from our final model. Thus, in the final model, there was a common intercept, but differences between taxa in sensitivity to DHW (that is, there was a random effect of taxonomic group on the slope). To illustrate these differences, Extended Data Fig. 5 plots the estimated slope of the coral cover response variable for each taxon versus DHW as the overall mean effect of DHW plus the taxon-specific random effect. Conditional standard errors plotted in Extended Data Fig. 5 are the standard errors on each random effect.

Shifts in functional traits. To calculate how differential mortality affected the mix of traits in the coral assemblages, we scored eight traits for 12 of the 15 functional groupings (excluding soft corals, other Scleractinia, and other sessile fauna, Extended Data Tables 1, 2). We chose traits that are likely to influence ecosystem functions. For example, corals with fast growth rates and high skeletal density strongly influence calcification, colony shape affects photosynthesis and the provision of three-dimensional habitat, and the size of corallites is a measure of heterotrophy. The traits were scored using the Coral Trait Database[29], with the exception of colony size, which we measured directly for each group on reef crests using the geometric mean of intercept lengths for each taxon from our initial transects. For multi-species groups, the traits were generally identical for all species, except for *Montipora* and *Porites*, for which we used the mean score across the reef crest species that we encountered. To measure the depletion of traits based on changes in absolute abundances between March and November (Fig. 3e, f), we used a community weighted mean (CWM) analysis of each trait:

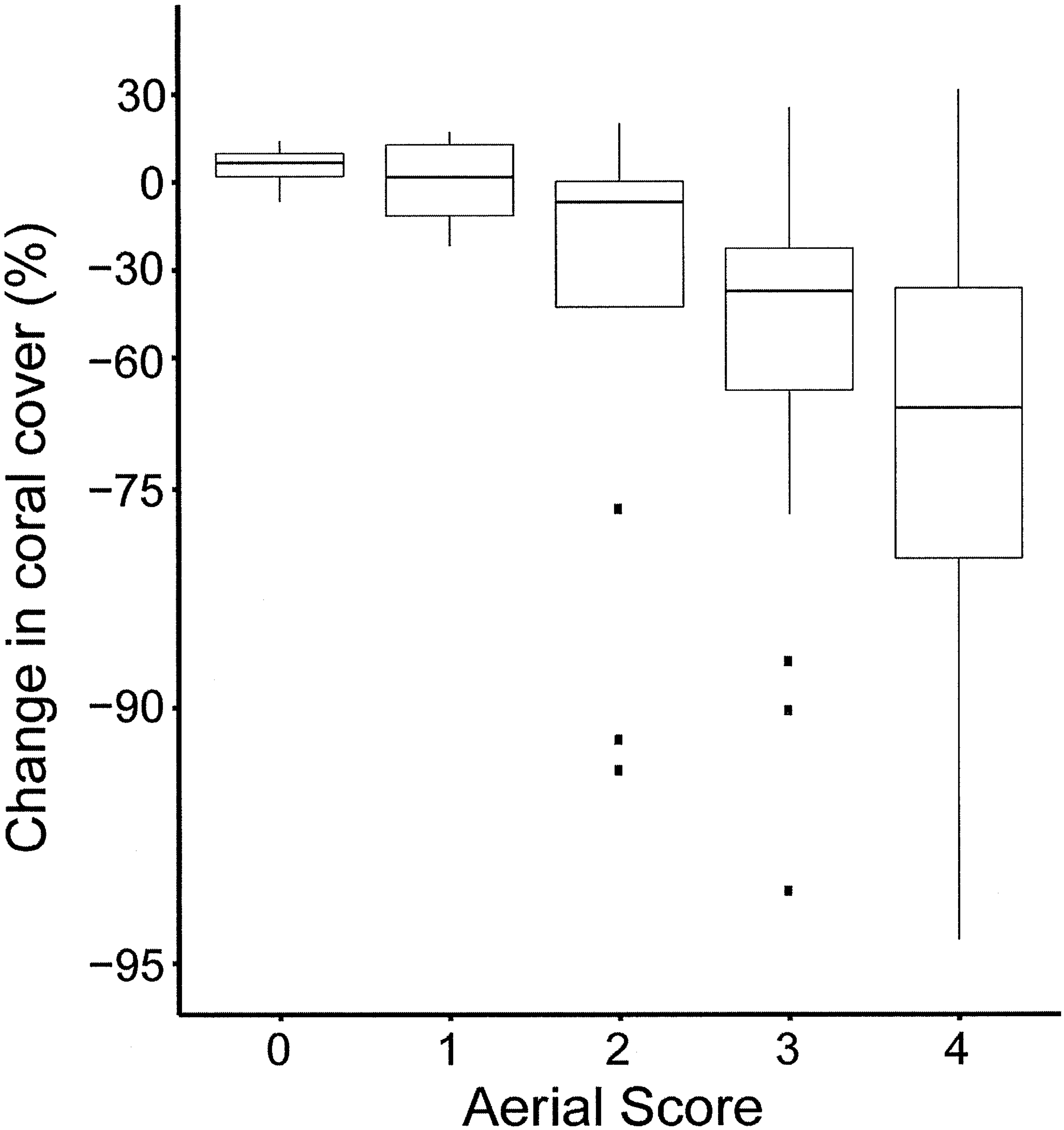
$$\mathrm{CWM} = \sum_{i=1}^{n} a_i \mathrm{trait}_i$$

where a_i is the abundance of coral taxa i and trait_i is the trait value of coral taxa i. This metric provides a trait value for each reef weighted by the total abundance of each taxa. To visualize the overall shift in functional composition, we used a nMDS analysis based on a Bray–Curtis dissimilarity matrix of square-root transformed data for each trait community weighted mean, creating a multi-dimensional trait space in which reefs are positioned according to the value and abundance of critical traits.

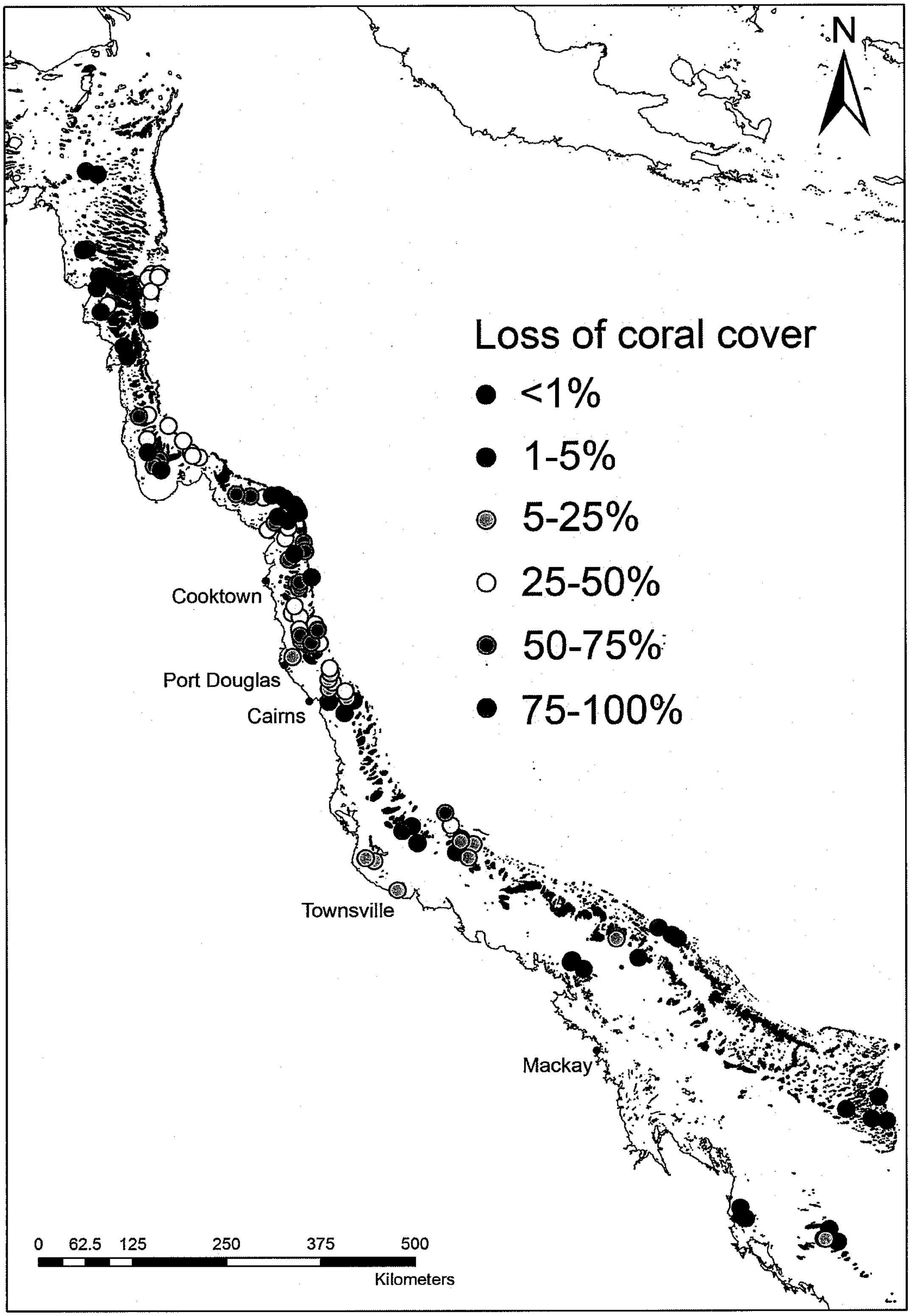
Reporting summary. Further information on experimental design is available in the Nature Research Reporting Summary linked to this paper.

Data availability. All heat exposure data used in this study are publicly available from the US National Oceanic and Atmospheric Administration. Source data for coral bleaching, mortality and abundances are available online at the Tropical Data Hub: https://doi.org/10.4225/28/5a725ee7548a7.

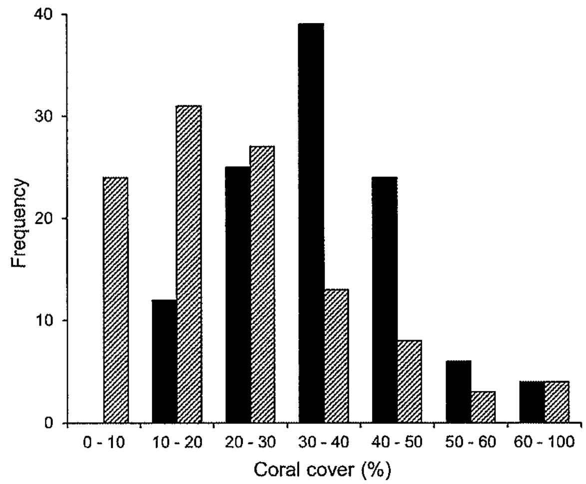
28. Hughes, T. P., Kerry, J. T. & Simpson, T. Large-scale bleaching of corals on the Great Barrier Reef. *Ecology* **99**, 501 (2017).
29. Madin, J. S. et al. The Coral Trait Database, a curated database of trait information for coral species from the global oceans. *Sci. Data* **3**, 160017 (2016).



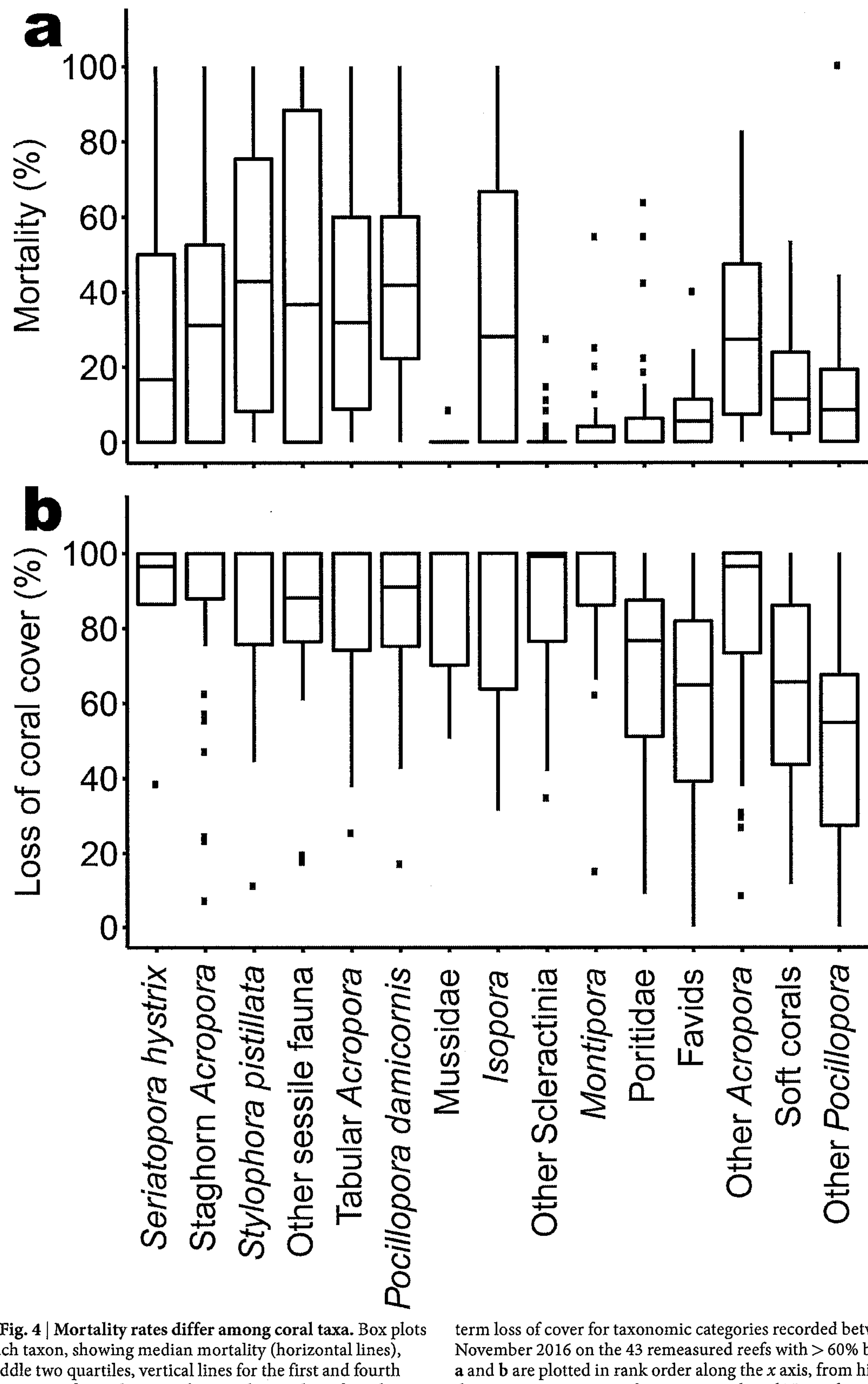
Extended Data Fig. 1 | Relationship between aerial bleaching scores and change in coral cover. Aerial scores of bleaching on the *x* axis are: 0 (< 1% of colonies bleached), 1 (1–10%), 2 (10–30%), 3 (30–60%) and 4 (60–100%). Change in coral cover on the *y* axis was measured in situ between March and November 2016 on 98 reefs that were also scored from the air. Box plots are shown for each aerial category, showing median values (horizontal lines), boxes for values in the 25th–75th percentiles, vertical lines for values less than the 25th percentile and greater than the 75th, and data points for outliers. Medians were used when calibrating change in cover for each aerial category (see Fig. 1a).



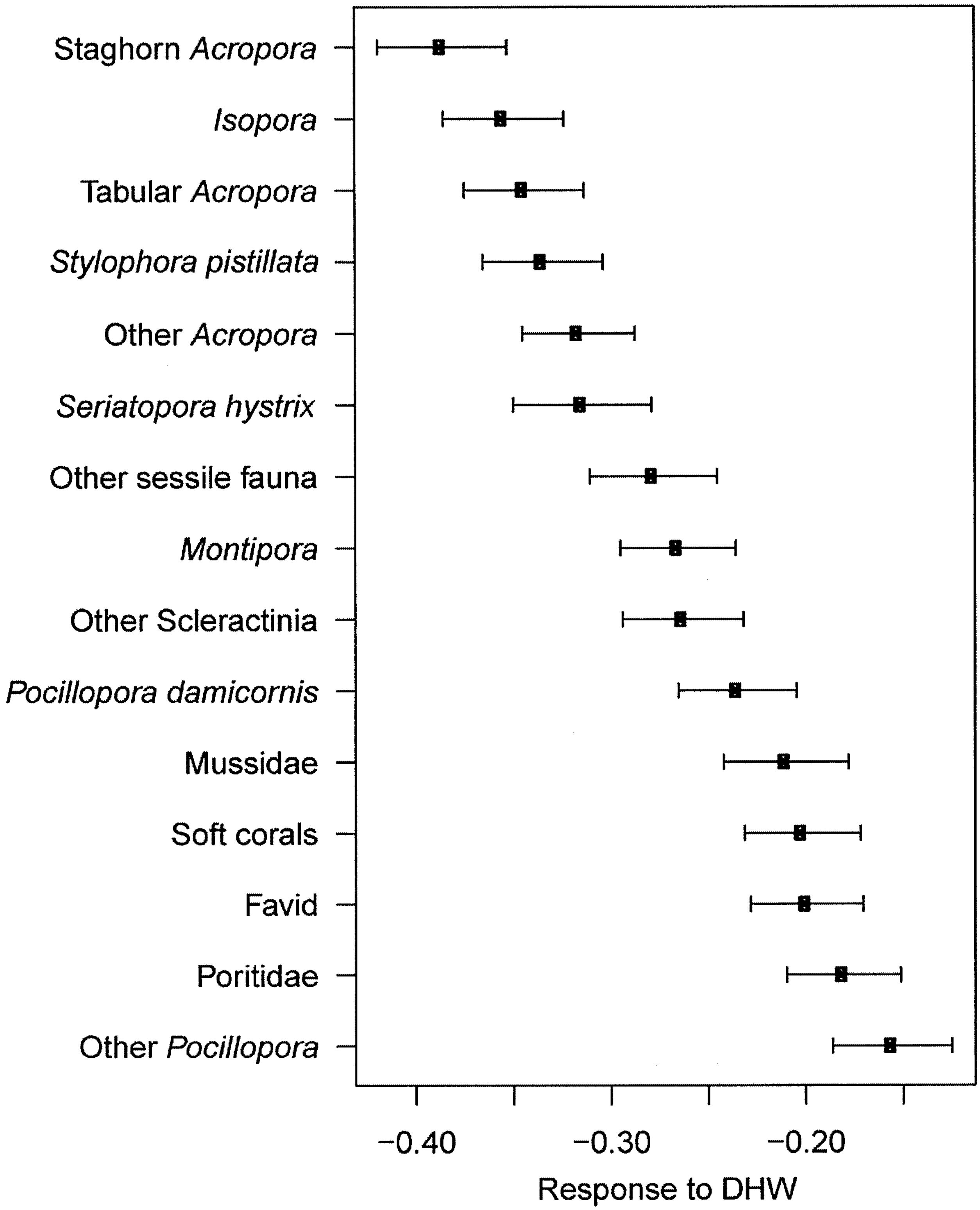
Extended Data Fig. 2 | Loss of coral cover along the Great Barrier Reef in 2016. Losses, measured on 110 reefs between March and November 2016, range from 0 (dark green) to 100% (1–5% (green), 5–25% (light green), 25–50% (yellow), 50–75% (orange) and 75–100% (red)). Map template is provided by Geoscience Australia (Commonwealth of Australia (Geoscience Australia) 2018).



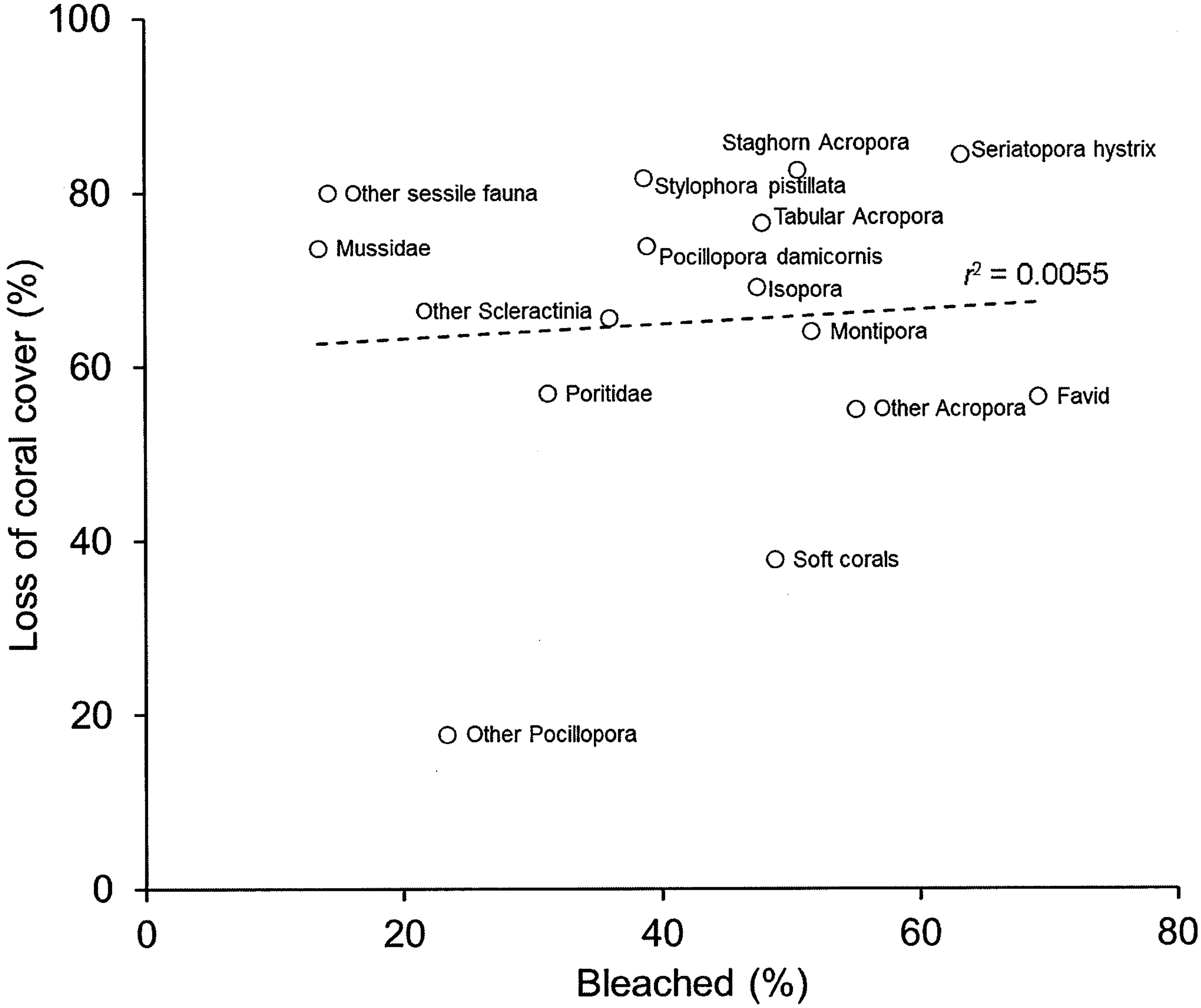
Extended Data Fig. 3 | Shifts in coral cover following coral bleaching. The frequency distribution of coral cover on 110 reefs, measured in March 2016 (solid bars) and again in November 2016 (hashed bars). Reef locations are shown in Extended Data Fig. 2.



Extended Data Fig. 4 | Mortality rates differ among coral taxa. Box plots are shown for each taxon, showing median mortality (horizontal lines), boxes for the middle two quartiles, vertical lines for the first and fourth quartiles, and data points for outliers. **a**, The initial mortality of corals recorded on belt transects on 43 reefs with > 60% bleaching. **b**, Longer term loss of cover for taxonomic categories recorded between March and November 2016 on the 43 remeasured reefs with > 60% bleaching. Taxa in **a** and **b** are plotted in rank order along the *x* axis, from highest to lowest decreases in mean cover between March and November 2016.



Extended Data Fig. 5 | Differential sensitivity of coral taxa to temperature stress. Sensitivity is estimated from the loss of cover on 63 reefs for different groups of corals between March and November 2016, as a function of heat exposure (DHW). The horizontal axis is the slope of the relationship between the log-ratio of final and initial coral cover (response variable) and DHW (explanatory variable). Values plotted for each taxonomic grouping (ordered from most sensitive to least sensitive) are random effects estimates, with conditional standard errors.



Extended Data Fig. 6 | Bleaching extent is unrelated to mortality. The regression shows the relationship between the levels of bleaching by individual coral taxa on severely bleached reefs (where > 60% of all colonies were affected, $n = 43$ reefs), and their subsequent loss of cover eight months later. The non-significant correlation indicates that the winners–losers spectrum of bleaching among taxa is a poor predictor of which ones ultimately die.

Extended Data Table 1 | Eight traits of coral species and their key functional roles

Trait	Trait scores	Reef function
Growth rate	In mm/year: 0-10 (1), 10-20 (2), 20-40 (3), 40-60 (4), >60 (5).	Carbonate framework accretion; reef regeneration
Skeletal density	In g/cm^3: <1 (1), 1-1.4 (2), 1.4-1.7 (3), 1.7-2 (4), >2 (5)	Carbonate framework accretion
Corallite width	In mm: <1 (1), 1-2 (2), 2-5 (3), 5-15 (4) ; <15 (5)	Filter feeding; nutrient capture
Interstitial space size	(1-5) Based on morphological categories.	Habitat provision
Colony height	(1-5) Based on morphological categories.	Carbonate framework accretion; habitat provision
Surface area to volume ratio	(1-5) Based on morphological categories	Primary productivity; nutrient cycling
Colony size	Rank (1-12) measured from reef crest transects	Carbonate framework accretion; habitat provision
Reproductive mode	Brooders (1), Mixed (2), Spawners (3)	Reef connectivity and regeneration

Extended Data Table 2 | Trait scores for each of 12 groups of corals

Taxon	Corallite size	Growth rate	Colony size	Skeletal density	Colony height	Tissue area	Interstitial space size	Reproductive mode
Bushy *Acropora*	2	3	7	3	3	5	3	Spawner
Favids	4	1	4	3	2	1	1	Spawner
Isopora	2	2	10	3	2	2	1	Brooder
Montipora	2	3	9	5	1	1	1	Spawner
Mussidae	5	1	3	2	2	1	1	Spawner
Other *Pocillopora*	1	3	8	3	3	4	3	Spawner
Pocillopora damicornis	1	3	2	4	2	4	3	Brooder
Poritidae	2	2	6	2	4	1	1	Mix
Seriatopora hystrix	1	3	1	5	2	3	3	Brooder
Staghorn *Acropora*	2	5	11	4	5	3	5	Spawner
Stylophora pistillata	2	3	5	4	2	3	3	Brooder
Tabular *Acropora*	2	4	12	4	3	5	5	Spawner

Spawners release eggs and sperm that fertilize externally, whereas brooders release internally fertilized planulae larvae.

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☐ Initial submission ☐ Revised version ☒ Final submission

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Experimental design

1. Sample size

Describe how sample size was determined.

No statistical methods were used to predetermine sample size of experimental treatments - the study was observational (non-manipulative). For aerial scoring of bleaching, a sample size of 1,156 reefs was sufficient to map bleaching throughout the Great Barrier Reef, and to demonstrate a statistically significant correlation ($p < 0.001$) with a satellite-based measures of heat exposure on each reef. For underwater observations, a sample size of 63 reefs was sufficient to demonstrate relationships between heat exposure, bleaching and mortality (all with $p < 0.001$)

2. Data exclusions

Describe any data exclusions.

No data were excluded

3. Replication

Describe whether the experimental findings were reliably reproduced.

The study is observational rather than experimental. See #1 for justification of sample sizes.

4. Randomization

Describe how samples/organisms/participants were allocated into experimental groups.

There were no experimental treatments. Therefore, reefs were selected randomly from throughout the Great Barrier Reef to assess their condition.

5. Blinding

Describe whether the investigators were blinded to group allocation during data collection and/or analysis.

There were no experimental treatments. Therefore, investigators were not blinded to allocation during experiments and outcome assessment.

Note: all studies involving animals and/or human research participants must disclose whether blinding and randomization were used.

6. Statistical parameters

For all figures and tables that use statistical methods, confirm that the following items are present in relevant figure legends (or in the Methods section if additional space is needed).

n/a	Confirmed	
☐	☒	The exact sample size (*n*) for each experimental group/condition, given as a discrete number and unit of measurement (animals, litters, cultures, etc.)
☐	☒	A description of how samples were collected, noting whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
☒	☐	A statement indicating how many times each experiment was replicated
☐	☒	The statistical test(s) used and whether they are one- or two-sided (note: only common tests should be described solely by name; more complex techniques should be described in the Methods section)
☐	☒	A description of any assumptions or corrections, such as an adjustment for multiple comparisons
☐	☒	The test results (e.g. *P* values) given as exact values whenever possible and with confidence intervals noted
☐	☒	A clear description of statistics including central tendency (e.g. median, mean) and variation (e.g. standard deviation, interquartile range)
☐	☒	Clearly defined error bars

See the web collection on statistics for biologists for further resources and guidance.

Software

Policy information about availability of computer code

7. Software

Describe the software used to analyze the data in this study.	R coding for statistical analysis. ArcGIS (ArcMap) for graphical interpolation of data

For manuscripts utilizing custom algorithms or software that are central to the paper but not yet described in the published literature, software must be made available to editors and reviewers upon request. We strongly encourage code deposition in a community repository (e.g. GitHub). *Nature Methods* guidance for providing algorithms and software for publication provides further information on this topic.

Materials and reagents

Policy information about availability of materials

8. Materials availability

Indicate whether there are restrictions on availability of unique materials or if these materials are only available for distribution by a for-profit company.	No unique materials were used

9. Antibodies

Describe the antibodies used and how they were validated for use in the system under study (i.e. assay and species).	No antibodies were used

10. Eukaryotic cell lines

a. State the source of each eukaryotic cell line used.	No cell lines were used
b. Describe the method of cell line authentication used.	No cell lines were used
c. Report whether the cell lines were tested for mycoplasma contamination.	No cell lines were used
d. If any of the cell lines used are listed in the database of commonly misidentified cell lines maintained by ICLAC, provide a scientific rationale for their use.	No cell lines were used

Animals and human research participants

Policy information about studies involving animals; when reporting animal research, follow the ARRIVE guidelines

11. Description of research animals

Provide details on animals and/or animal-derived materials used in the study.	No animals were used

Policy information about studies involving human research participants

12. Description of human research participants

Describe the covariate-relevant population characteristics of the human research participants.	Study did not involve human research participants

PeerJ

Patterns of bleaching and mortality following widespread warming events in 2014 and 2015 at the Hanauma Bay Nature Preserve, Hawai'i

Ku'ulei S. Rodgers*, Keisha D. Bahr*, Paul L. Jokiel† and Angela Richards Donà*

Hawai'i Institute of Marine Biology, University of Hawai'i, Kāne'ohe, HI, United States of America
* These authors contributed equally to this work.
† Deceased.

ABSTRACT

Drastic increases in global carbon emissions in the past century have led to elevated sea surface temperatures that negatively affect coral reef organisms. Worldwide coral bleaching-related mortality is increasing and data has shown even isolated and protected reefs are vulnerable to the effects of global climate change. In 2014 and 2015, coral reefs in the main Hawaiian Islands (MHI) suffered up to 90% bleaching, with higher than 50% subsequent mortality in some areas. The location and severity of bleaching and mortality was strongly influenced by the spatial and temporal patterns of elevated seawater temperatures. The main objective of this research was to understand the spatial extent of bleaching mortality in Hanauma Bay Nature Preserve (HBNP), O'ahu, Hawai'i to gain a baseline understanding of the physical processes that influence localized bleaching dynamics. Surveys at HBNP in October 2015 and January 2016 revealed extensive bleaching (47%) and high levels of coral mortality (9.8%). Bleaching was highly variable among the four HBNP sectors and ranged from a low of ~31% in the central bay at Channel (CH) to a high of 57% in the area most frequented by visitors (Keyhole; KH). The highest levels of bleaching occurred in two sectors with different circulation patterns: KH experienced comparatively low circulation velocity and a low temperature increase while Witches Brew (WB) and Backdoors (BD) experienced higher circulation velocity and higher temperature increase. Cumulative mortality was highest at WB (5.0%) and at BD (2.9%) although WB circulation velocity is significantly higher. HBNP is minimally impacted by local factors that can lead to decline such as high fishing pressure or sedimentation although human use is high. Despite the lack of these influences, high coral mortality occurred. Visitor impacts are strikingly different in the two sectors that experienced the highest mortality evidenced by the differences in coral cover associated with visitor use however, coral mortality was similar. These results suggest that elevated temperature was more influential in coral bleaching and the associated mortality than high circulation or visitor use.

Subjects Conservation Biology, Ecology, Environmental Sciences, Marine Biology
Keywords Coral bleaching, Global climate change, Marine protected area, Elevated seawater temperature, Marine life conservation district, Currents, Hanauma Bay

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Corresponding author
Angela Richards Donà,
angelard@hawaii.edu

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Additional Information and Declarations can be found on page 11

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INTRODUCTION

Global sea surface temperatures (SSTs) have increased an average 0.9 °C in the past century due to an increase in anthropogenic atmospheric gases resulting mainly from fossil fuel burning (*Sabine et al., 2004*). The greatest increases of 0.06–0.11 °C decade^{-1} have occurred since 1970 (*EPA, 2016*) and have resulted in mass coral bleaching events worldwide. Scientific documentation of these events began nearly a decade later (*Jaap, 1979*). Since then, large-scale bleaching has occurred worldwide with increasing frequency and severity, and is projected to continue (*Hoeke et al., 2011*; *Mora et al., 2014*; *Bahr, Jokiel & Rodgers, 2015*). Nearly half of the corals in the western Indian Ocean were lost following widespread bleaching in 1998. By 2005, SSTs in the Caribbean had surpassed any previously reported temperatures and caused unprecedented coral mortality (*Eakin, Lough & Heron, 2009*). The year 2014 marked the beginning of the longest global bleaching event on record, which currently continues and has affected more reefs than any previous worldwide bleaching event (*Eakin et al., 2014*). Australia's Great Barrier Reef (GBR) recently experienced catastrophic bleaching and mortality with over 90% of its 2,300 km reef tract affected (*ARC, 2016*). The pristine reefs of the northern GBR were thought to be resistant to bleaching due to their remote location and low fishing and tourism pressure, however, over 99% of these reefs were observed bleached along a 1,000 km stretch (*Normile, 2016*). On Kiritimati atoll, over 80% mortality occurred during a record 15 months with SSTs above local bleaching thresholds. By November 2016, up to 90% of corals were dead (*Baum Lab, 2016*). This devastating loss of coral occurred on the relatively undisturbed reefs in the southeastern part of the atoll as well as in the degraded northwest (*Sandin et al., 2008*; *Watson, Claar & Baum, 2016*). The full extent of worldwide coral mortality has not yet been quantified, however, NOAA climate models predict another year of warming for the GBR, Kiritimati, and other Pacific Islands, particularly in the southern hemisphere (*NOAA Coral Reef Watch, 2017*). The negative influence of prolonged elevated seawater temperature on coral reefs is not selective and appears to affect protected, pristine, and degraded reefs, equally.

Coral reefs of the Hawaiian Islands have not been exempt, experiencing extensive bleaching in recent years. Significant heating in the offshore waters statewide (+1.15° over the past 58 years) has led to an increase in frequency of coral bleaching events (*Jokiel & Brown, 2004*; *Bahr, Jokiel & Rodgers, 2015*). The bleaching events that affected the Hawaiian Islands in 1996, 2002, and 2004 were relatively short in duration and thus coral recovery was high (*Jokiel & Brown, 2004*). Conversely, Hawaiian reefs experienced unsurpassed bleaching on a statewide scale during the multi-year bleaching events in 2014 and 2015 (*Bahr, Jokiel & Rodgers, 2015*).

The Hanauma Bay Nature Preserve (HBNP), a 40 ha fully protected Marine Life Conservation District (MLCD) established in 1967, is the most popular snorkeling location in the Hawaiian Islands with close to one million visitors annually (Fig. 1). The Coral Reef Assessment and Monitoring Program (CRAMP) began surveys here in 2000 and has shown a significant decline in shallow water coral cover with the majority of the decrease occurring after 2002 (*Brown et al., 2004*; *Rodgers et al., 2015*). The recent and predicted bleaching (*Jokiel & Brown, 2004*; *Hoeke et al., 2011*; *Eakin et al., 2014*) poses an imminent

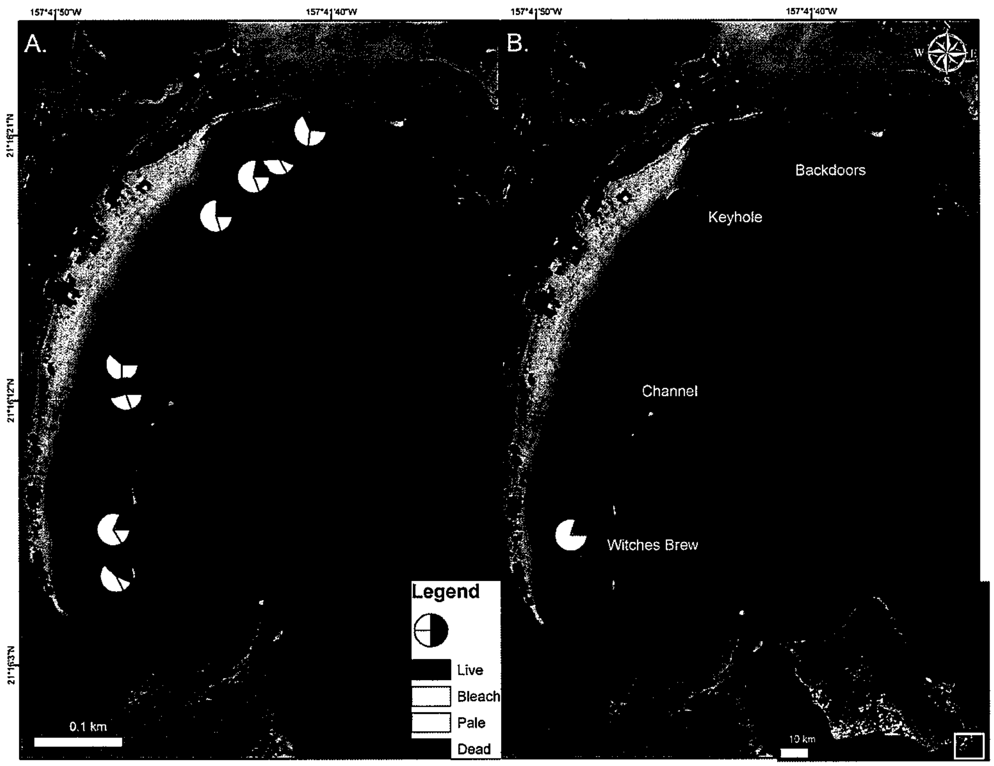

Figure 1 Coral condition on map of Hanauma Bay Nature Preserve. Coral condition in the Hanauma Bay Nature Preserve, Oʻahu, Hawaiʻi in October 2015 (A) and January 2016. (B) Proportion of surveyed corals are shown as normal (red), bleached (white), pale (yellow), and dead (black). Surveys were conducted and temperature loggers deployed at each of the two stations within the four sectors. Photo credit: Quickbird Digital Globe.

threat to the biological sustainability of the HBNP ecosystem and a significant economic threat to the state of Hawaiʻi. Tourism expenditures provided over 15 billion USD to the state's economy in 2015 (*DBEDT, 2016*). Of the over eight million annual visitors to the state of Hawaiʻi, it is estimated that 80% participate in ocean recreational activities and over 1,000 ocean recreation companies exist to accommodate them (*Clark, 2016*).

The HBNP is located adjacent to the strong open-ocean, westward current referred to as the Molokaʻi Express. The outer section of this 40 ha (100 ac) bay can at times experience strong surges, ocean currents, and high wave energy while the protected 8 ha (20 ac) inner reef, located shoreward of the reef crest is relatively calm (*Brock & Kam, 2000*). The overall circulation pattern within Hanauma Bay moves shoreward and westerly from the northeast Toilet Bowl side of the bay towards the southwest Witches Brew side (Fig. 2). This pattern prevails during all tide phases (incoming, outgoing, and mixed) and during both tradewind and calmer south wind conditions. The mean velocity is 3.1 cm sec^{-1} with a range of 0.8–6.5 cm sec^{-1} with higher average velocities near the outer mouth of the bay and decreasing in shallower inner waters (*Whittle, 2003*). Under typical tradewind conditions water continuously enters the inner reef across the reef and boulder boundary.

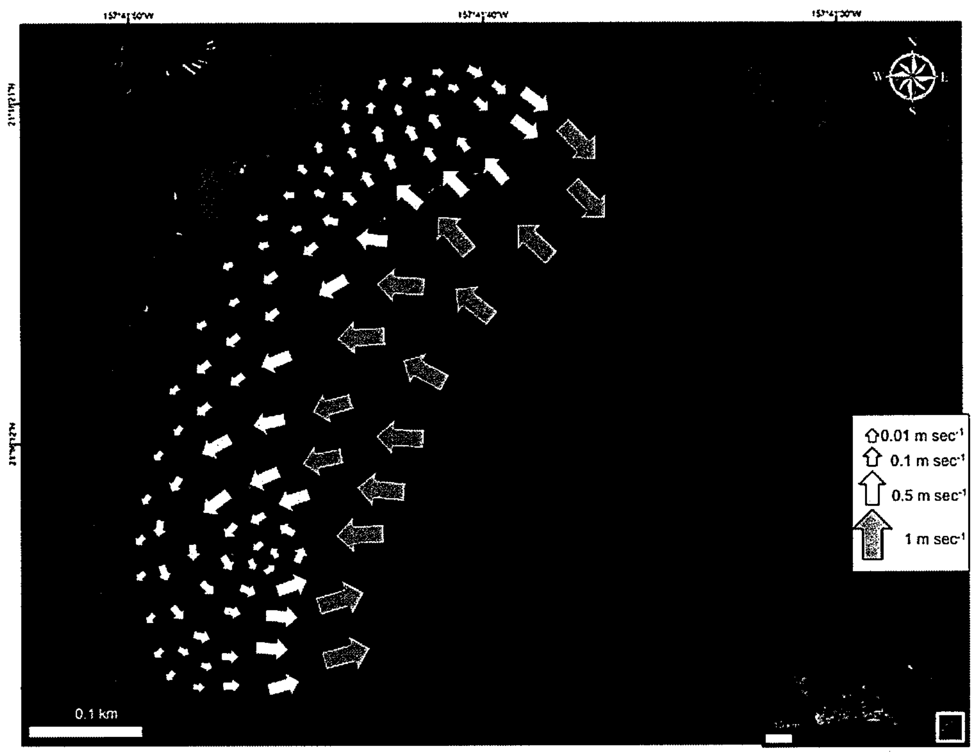

Figure 2 Map of current flow at Hanauma Bay Nature Preserve. Generalized map of current flow in Hanauma Bay Nature Preserve, Oʻahu, Hawaiʻi. Red dots indicate surveyed sites. Photo credit: Quickbird Digital Globe.

Travelling parallel to shore it exits at high velocities (up to 50 cm sec^{-1}) near the ledges on the extreme opposite sides of the bay (Fig. 2) and through the mid-bay channel during outgoing tide at lower speeds.

In 2014, the State of Hawaiʻi Division of Aquatic Resources (DAR) coral bleaching assessments determined 47% of corals exhibited signs of bleaching in the HBNP; however, mortality was not subsequently quantified (*Neilson, 2014*). The main objective of this study was to quantify bleaching prevalence and subsequent mortality within the four major sectors of the HBNP and define how they relate to temperature and currents. These scientific data form a benchmark for the local environmental patterns that can be used to predict the extent and distribution of future bleaching events and aid management preparation strategies.

METHODS & MATERIALS

Coral surveys

In 2015, surveys were conducted to characterize coral bleaching extent and severity in the four major inshore sectors of the Hanauma Bay Nature Preserve (HBNP) (21.2690°N, 157.6938°W). These areas are locally known as Backdoors (BD), Keyhole (KH), Channel (CH), and Witches Brew (WB) (Fig. 1). To define the extent of bleaching, two 15 m × 5 m transects were surveyed in each sector. Transect lines were placed on the reef flat at depths <1 m and all coral colonies within the transect area (75 m^2) were counted. To quantify the severity of the bleaching and mortality, we recorded coral species, colony size, and percent of colony that was live, pale, bleached, and recently dead. Redundant methodologies were used to provide accurate locations for subsequent resurveys using a handheld Garmin Geko 201 GPS unit, graphic and written documentation of positions using triangulation, and underwater photographic imagery of distinct initial and concluding coral colonies on each transect. To avoid error from observer variation, one surveyor collected data in all sectors during both initial bleaching and recovery surveys.

Temperature

From June 2015 to January 2016, seawater temperature at all four sectors within the HBNP was recorded at fifteen-minute intervals using replicate HOBO Water Temperature Pro v2 Data Loggers (Onset, Wareham, MA, USA). The loggers were secured in 6″× 12″ hand-poured concrete "rocks" that mimic the benthic substrate and protect the loggers from solar irradiance and associated heating (*Bahr, Jokiel & Rodgers, 2016*) while providing concealment from human disturbance. The loggers at BD, KH, and CH were placed at 1 m depth, whereas at WB, a somewhat deeper site, the loggers were placed at 3 m to determine temperatures at a long-term monitoring station. To adjust for depth and to determine whether there were finer scale variations, an additional short-term deployment of 32 loggers were deployed at all transect locations on 19 April 2016 from 08:00 (low tide) to 15:00 (high tide). These data were used to calculate mean mid-day differences among transects.

Currents

Current patterns characterized by *Whittle (2003)* primarily covered the region seaward of the reef boundary. To determine the nearshore current patterns, drogues were released and tracked in the water by surveyors. Twenty 2.5″ soft plastic balls were deployed and followed in each of the four sectors ($n = 80$). Drogues were identified by color and numbers written on 4″× 4″ underwater paper attached with a cable tie through small holes in the plastic. These holes also allowed the drogues to fill with water and remain positioned just below the water surface where wind effects are negligible. The position of each drogue was determined by GPS (Garmin eTrex 10) at initial deployment and at each subsequent sighting for eight consecutive hours spanning both low (−0.05 ft) and high (1.15 ft) tides. Drogues were deployed shoreward ($n = 40$) and seaward ($n = 40$) of the reef boundary. Researchers swam parallel to shore in a creeping line pattern from one end of the designated sector to the next dropping each drogue approximately 10 m apart horizontally with 5 m between each deployment line. After eight hours, drogues were retrieved and final location recorded. Drogues reaching shore prior to the end of the final retrieval were randomly redeployed in their original sector. To determine the original sector when drogues moved to another sector, each sector had different colored drogues.

Most of the drogues deployed at BD were carried outside the bay and were not followed by swimmers thus current patterns for this sector remained unclear. Additionally, nearshore areas in the CH sector were not fully covered. Thus, a second deployment was conducted

Table 1 Coral condition by sector in October 2015 and January 2016. Coral condition in October 2015 and January 2016 in the Hanauma Bay Nature Preserve, Oʻahu, Hawaiʻi (mean ± SE). Mean coral condition in 75 m^2 surveyed area.

Sector	Live	Bleach	Pale	Dead
October 2015				
BD	37 ± 6.3	38 ± 6.2	22 ± 4.1	2.9 ± 1.7
CH	47 ± 6.4	31 ± 5.3	22 ± 4.6	0.3 ± 0.3
KH	23 ± 6.1	57 ± 7.1	20 ± 4	0.8 ± 0.6
WB	30 ± 5.2	53 ± 5.6	13 ± 2.9	3.9 ± 2
January 2016				
BD	94 ± 3	0.5 ± 0.4	0.7 ± 0.7	0
CH	77 ± 4.8	0	0.2 ± 0.2	0.5 ± 0.5
KH	85 ± 4.6	0	0	0.3 ± 0.3
WB	85 ± 3.6	8 ± 3.1	2.5 ± 1.7	1.1 ± 0.5

during an incoming tide beginning at low tide (−0.23 ft). In the smaller BD sector, five drogues were released approximately 5 m apart along the eastern boundary. These were deployed over the reef in a perpendicular path to shore from the channel marker buoys. In the larger CH sector, five drogues were released approximately 10 m apart following a path parallel to shore. All drogues were deployed shoreward of the reef boundary and retrieved after three hours with final locations recorded.

Statistical analyses

Bleaching prevalence was analyzed using a General Linear Model (GLM) with sector as a fixed factor and transect nested within sector. Temperature was treated with a repeated measures mixed model by location with transect nested within location. Assumptions of normal distribution, homoscedasticity, and multivariate normality were assessed through graphical analyses of the residuals. All statistical analyses and descriptive statistics were conducted using JMP Pro 12. Calculations of location, distance, and time were determined in ArcGIS 10 and Excel 2010 to characterize current patterns (Fig. 2).

RESULTS

Bleaching prevalence

In October 2015, 45% ± 3.2% (mean ± SE) of corals in the Hanauma Bay Nature Preserve (HBNP) showed signs of bleaching (Table 1). The highest bleaching prevalence was observed in *Pavona varians* and *Pocillopora meandrina* (Fig. 3). Bleaching prevalence was significantly different among sectors (GLM; $F_{(7,143)} = 3.4239$ $p = 0.0020$) with highest levels at Keyhole (KH; 56.6 ± 7.1%) and Witches Brew (WB; 52.7 ± 5.6%) compared to Backdoors (BD; 38.4 ± 6.2%) and Channel (CH; 30.9 ± 5.3%) (Fig. 1). A further 13–22% of corals were paling in all sectors. Coral colony size was not a factor in bleaching prevalence ($R^2 = 0.0246$; $p = 0.0611$) whereas number of colonies was. While colony size in all locations was similar (Oneway ANOVA $F_{(3,290)} = 0.7229$, $p = 0.5391$), number of colonies at WB was higher (28 ± 2.9) (Oneway ANOVA; $F_{(3,12)} = 7.4677$ p<0.0044) compared to the average number of colonies at BD (15.25 ± 2.65), CH (19 ± 1.8), and KH (11 ± 0.8).

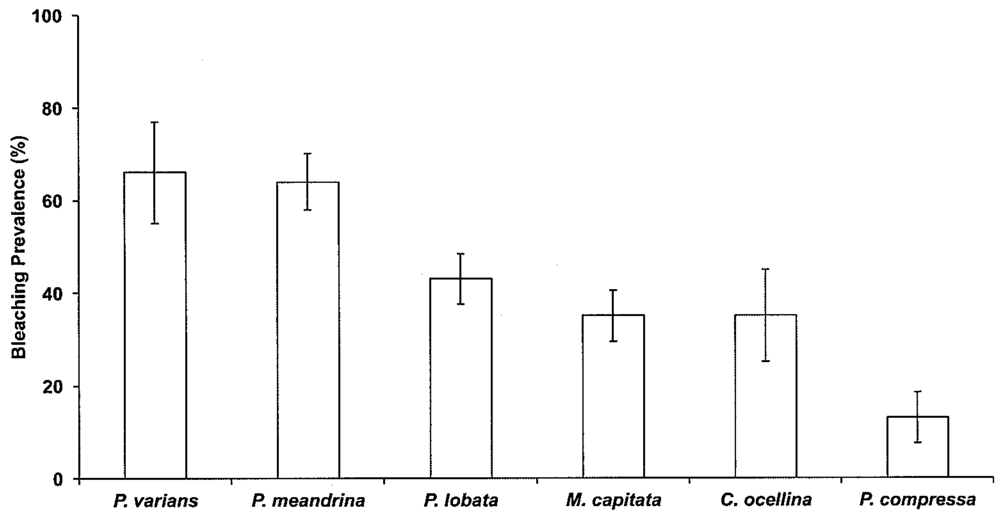

Figure 3 Bleaching prevalence by coral species. Mean bleaching prevalence by coral species in October 2015 in Hanauma Bay Nature Preserve, O'ahu, Hawai'i. Error bars represent standard error.

Coral mortality

In October 2015, the highest average levels of coral mortality occurred at WB (3.9 ± 2%) and BD (2.9 ± 1.7%). Lower mortality rates were observed at KH (0.8 ± 0.6%) and CH (0.3 ± 0.3%). In January 2016, average coral mortality rates by sector were near or below 1% (WB = 1.1 ± 0.5%; BD = 0%; KH = 0.3 ± 0.3%; and CH = 0.5 ± 0.5%), although recovery was slowest in WB. Highest mortality rates were observed in *Porites lobata* and *Pocillopora meandrina* (Fig. 4). Total coral mortality inside the HBNP due to elevated SSTs was calculated with a cumulative value of 9.8% (October = 7.9%; January = 1.9%). Cumulative mortality rates also varied by sector (sum of Oct and January surveys: WB = 5.0%; BD = 2.9%; KH = 1.1%; and CH = 0.8%). No overlap in recently dead corals occurred between October and January determined by rapid algal turf growth over the coral skeleton.

Environmental drivers

The patterns of coral bleaching prevalence and mortality in the four sectors in HBNP are linked to localized heating, due to circulation patterns. Incoming currents show a great reduction in flow velocity as oceanic water (1 m s^{-1}) flows over the reef boundary into the shallow, sandy areas (0.5 m s^{-1}). Here, residence time and temperatures increase and the warmer water follows a westerly direction (0.1 m s^{-1}) along shore to the far end (WB) where it turns seaward and flows either to a small gyre or over the reef boundary and out of the bay (Fig. 2). Because water exits the bay at WB, water flow into the sector comes strictly from slow, alongshore currents. A similar small gyre is located at the far eastern end (BD), whereas at the adjacent KH, water flows slowly to shore at 0.01 m s^{-1} (Fig. 2). Inshore currents were faster in CH (0.075 ± 0.011 m s^{-1}) and WB (0.055 ± 0.011 m s^{-1}) compared to KH (0.008 ± 0.011 m s^{-1}) and BD (0.019 ± 0.011 m s^{-1}) (One Way ANOVA; $F_{(3,7)} = 7.717; p = 0.0386$). Notably, the relatively high current velocities at CH and WB

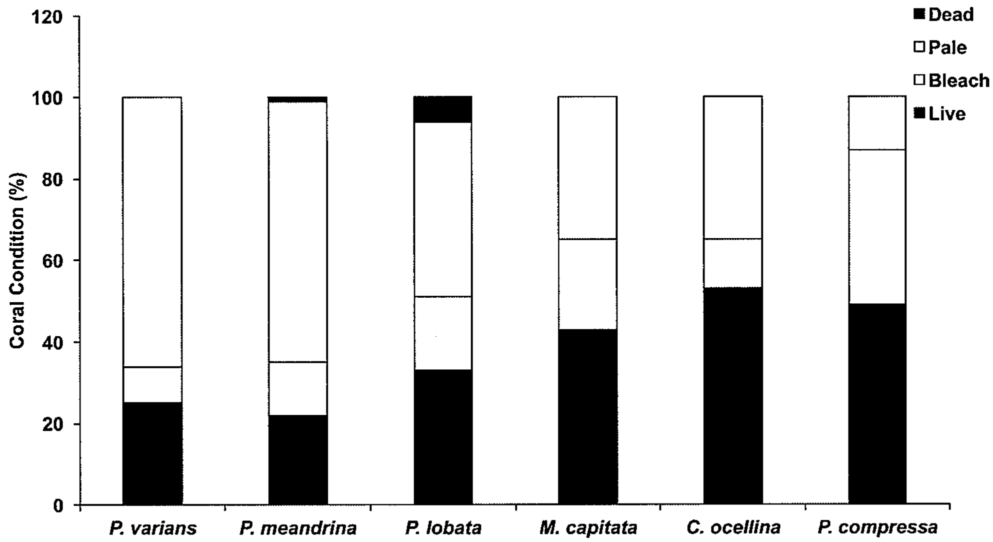

Figure 4 Graph of coral condition in October 2015. Coral condition in October 2015 in Hanauma Bay Nature Preserve, O'ahu, Hawai'i across all sectors. Mean proportion of surveyed corals are indicated by color (Live, brown; pale, yellow; bleach, white; and black, dead).

are substantially different in character. At CH cooler water flows into the shallows from outside the reef boundary, whereas at WB, slow-moving, warm water from as far as KH sector increases in velocity only as it is exiting the shallows.

Analysis of temperature gradients in HBNP revealed temperatures were significantly different throughout the bay (Mixed Model; $R^2 = 0.30$; $F_{(3,4)} = 454.97$; $p < 0.0001$). WB experienced significantly higher mean mid-day temperatures (26.46 ± 0.014 °C) compared to BD (26.05 ± 0.014 °C), CH (26.01 ± 0.014 °C), and KH (25.99 ± 0.014 °C). Additionally, temperatures are variable within locations (Mixed Model; $R^2 = 0.43$; $F_{(1,2)} = 23.27$; $p < 0.0001$). Overall, the largest differences within site occurred at WB (±0.58 °C) and BD (±0.26 °C), while KH (±0.10 °C) and CH (±0.08 °C) were more similar. The effects of the localized heating revealed higher bleaching prevalence in KH (56.6 ± 7.1%) and WB (52.7 ± 5.6%) compared to BD (38.4 ± 6.2%) and CH (30.9 ± 5.3%) (Fig. 1).

DISCUSSION

Bleaching and recovery rates and species tolerance in 2015 were highly variable across islands of the Hawaiian archipelago. In 2015, the warm water approached the islands from the south and this resulted in a maximum 18 DHW for Hawai'i Island and 10 DHWs for eastern shores of O'ahu (*NOAA Coral Reef Watch, 2016*). Extensive surveys in 2015 found between 30 and 86% bleaching on Hawai'i Island with reported mortality at nearly 50% on the island's west coast (*Kramer et al., 2016*). Results of the current study revealed nearly half (47%) the corals surveyed at HBNP were found to exhibit signs of severe bleaching and associated mortality was ~9.8%. It appears localized heating and circulation patterns inside HBNP are driving differences in bleaching-associated mortality. Variation in spatial and temporal temperature patterns account for the differences in bleaching between islands.

Accompanying rates of coral mortality may slow predicted recovery rates of Hawaiian corals and shape future reefs (*Jokiel & Brown, 2004*; *Bahr, Jokiel & Rodgers, 2015*).

The Hanauma Bay Nature Preserve (HBNP) has shown decline in coral cover in shallow waters since 2002 (*Brown et al., 2004*; *Rodgers et al., 2015*) however, global climate change may drive this management-protected reef into more rapid decline. Increasing length, severity, and frequency of coral bleaching events pose an imminent threat to the biological sustainability of the HBNP ecosystem and a significant economic threat to the state of Hawaiʻi. Of the total area surveyed (600 m^2) in the HBNP in 2015, cumulative coral mortality was 9.8%. This Marine Life Conservation District reflects the fish populations in more remote areas distant from anthropogenic impacts due to management restrictions that prohibit any take of marine organisms. However, the organic and nutrient levels at HBNP are much higher than at 60 other sites statewide due to high fish biomass (*Rodgers, 2005*). Minimal levels of fine sediments due to a low contribution of terrigenous material from the influencing watershed are found here. In addition, nearly one million people visit HBNP annually but the majority of visitors using the ocean resources remain on the northern end of the bay in the BD and KH regions. The southern section where WB lies has relatively minimal human use (Fig. 1). Nonetheless, these two areas experienced similar mortality following the bleaching event. These results support global reports of high mortality following bleaching in remote regions removed from anthropogenic influences such as the northern GBR and at Lisianski in Papahānaumokuakea in the Northwestern Hawaiian Islands (NWHI) (*Couch et al., 2016*).

Reef recovery after major disturbances depends not only on the prevailing environmental conditions but also on the species affected. For example, *Pocillopora meandrina* is considered a "competitive" species (*Darling et al., 2012*) and is far more likely to recolonize a degraded reef than longer-lived "stress-tolerant" species such as *Porites lobata and Porites evermanni*. This study revealed bleaching prevalence and mortality to vary by species and location. The highest bleaching prevalence was observed in *Pavona varians* (66%), and *P. meandrina* (64%) while highest mortality occurred in *P. lobata* (5.3%) and *P. meandrina* (1.3%). No mortality was observed in *P. varians*. Bleaching prevalence was highly variable within HBNP due to localized environmental gradients. The highest levels of bleaching and mortality were observed in WB, which is characterized as the sector where warm water accumulates before exiting the bay.

Additionally, WB has the greatest number of coral colonies, particularly *Porites lobata* colonies. *Porites lobata* was also the most abundant species at BD. This sector is characterized as having low water velocity and relatively high temperatures. Cumulative bleaching was relatively low compared to other sectors but mortality was second highest. KH has the lowest number of coral colonies and *P. meandrina* was the most abundant species. Currents head directly from beyond the reef boundary to shore presumably bringing colder water with considerable reduction in velocity into KH. Temperature is lower here than at WB and BD, which may explain why mortality was low although cumulative bleaching was high. Lastly, CH had the lowest bleaching and mortality due to high water circulation and high oceanic input with associated lower temperatures. This sector had the second highest coral abundance, mainly dominated by *P. lobata* and *Montipora capitata*. Because *P. lobata* is the most abundant species in three of four sectors, the observed mortality indicates an important vulnerability that cannot be overcome by circulation or conservation effort. With repeated mortality of the more vulnerable species, shifts in coral composition are likely to occur.

Temperature and circulation are difficult to separate. These two factors are highly correlated with one another since circulation can increase or ameliorate temperatures and account for localized heating differences. Our results suggest circulation patterns facilitate localized heating and influence bleaching dynamics in HBNP. Incoming oceanic water flows shoreward to the reef boundary then follows a counterclockwise pattern west before exiting the bay. Significant heating occurs as incoming water moves over the shallow reef flat and accumulates in the WB sector. This explains the observed ~0.5 °C difference in temperatures between WB and other sectors of HBNP. The observed high circulation rates appear to be movement and accumulation of warm water in WB. This accumulation of warm water likely facilitated increased bleaching prevalence and associated mortality in that area. A similar, but less severe pattern was observed in the BD sector (Fig. 2). The cumulative heating associated with these circulation patterns correlates with the observed high levels of bleaching in these two sectors. Even in the absence of direct anthropogenic stressors (e.g., fishing pressure, pollution, and sedimentation) coral mortality can be high as temperatures increase. Corals live within 1–2 °C of their summer maximum temperatures and will bleach at this threshold whether they inhabit cooler, deeper waters or live on warmer shallow reefs (*Coles, Jokiel & Lewis, 1976*).

CONCLUSION

In summary, bleaching and mortality were highly variable across the main Hawaiian Islands. Differing spatial patterns of warming greatly influence the location and severity of bleaching and associated mortality. Results of this study indicate variability in bleaching and associated mortality can be described by species-specific tolerances, number of colonies, localized environmental patterns of heating, and currents. This study of the marine protected HBNP results determined:

- Bleaching and mortality varied by species and location.
- Bleaching prevalence and associated mortality were the highest in the sectors where warm water accumulated (i.e., BD and WB).
- Regardless of anthropogenic influences, temperatures beyond the thermal tolerances for corals can result in mortality.

Oceans will continue to absorb a significant amount of carbon even once emissions are reduced but we must slow the increase to begin addressing the impacts of climate change. Sound management strategies based on scientific research will increasingly play a more important role. Data from this research will serve as a baseline for future research to better understand the environmental patterns in HBNP and elsewhere. Data on species tolerances, circulation patterns and temperatures can assist managers in predicting the spatial extent, bleaching severity, and distribution of future bleaching events to support planning efforts.

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ADDITIONAL INFORMATION AND DECLARATIONS

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Competing Interests

The authors declare there are no competing interests.

Author Contributions

- Kuʻulei S. Rodgers conceived and designed the experiments, performed the experiments, contributed reagents/materials/analysis tools, wrote the paper, prepared figures and/or tables, reviewed drafts of the paper.
- Keisha D. Bahr conceived and designed the experiments, performed the experiments, analyzed the data, wrote the paper, prepared figures and/or tables, reviewed drafts of the paper.
- Paul L. Jokiel conceived and designed the experiments, performed the experiments, contributed reagents/materials/analysis tools, provided historical bleaching research.
- Angela Richards Donà performed the experiments, wrote the paper, reviewed drafts of the paper.

Data Availability

The following information was supplied regarding data availability:

The raw data was provided as Data S1.

Supplemental Information

Supplemental information for this article can be found online at http://dx.doi.org/10.7717/peerj.3355#supplemental-information.

REFERENCES

ARC Centre of Excellence Coral Reef Studies. 2016. Only 7% of the Great Barrier Reef has avoided bleaching. *Available at https://www.coralcoe.org.au/media-releases/only-7-of-the-great-barrier-reef-has-avoided-coral-bleaching* (accessed on 04 August 2016).

Bahr KD, Jokiel PL, Rodgers KS. 2015. The 2014 coral bleaching and freshwater flood events in Kāneʻohe Bay, Hawaiʻi. *PeerJ* **3**:e1136 DOI 10.7717/peerj.1136.

Bahr KD, Jokiel PL, Rodgers KS. 2016. Influence of solar irradiance on underwater temperature recorded by temperature loggers on coral reefs. *Limnology and Oceanography: Methods* **14(5)**:338–342 DOI 10.1002/lom3.10093.

Baum Lab. 2016. Kirimati's reefs are mostly dead. *Available at http://baumlab.weebly.com/kiritimati-2016.html* (accessed on 09 March 2017).

Brock R, Kam A. 2000. *Carrying capacity study for the Hanauma Bay nature preserve: final report.* Honolulu: Department of Parks and Recreation.

Brown EK, Cox EF, Jokiel PL, Rodgers KS, Smith WR, Tissot B, Coles SL, Hultquist J. 2004. Development of benthic sampling methods for the Coral Reef Assessment and Monitoring Program (CRAMP) in Hawaiʻi. *Pacific Science* **7(2)**:145–158.

Clark A. Hawaiʻi division of aquatic resources. Hawaiʻi's sustainable tourism challenges and opportunities. *Available at http://www.coralreef.gov/meeting16/hawaii_tourism.pdf* (accessed on 04 August 2016).

Coles SL, Jokiel PL, Lewis CR. 1976. Thermal tolerance in tropical versus subtropical Pacific reef corals. *Pacific Science* **30**:156–166.

Couch C, Burns JH, Steward K, Gutlay TN, Liu G, Geiger EF, Eakin CM, Kosaki RK. 2016. Causes and consequences of the 2014 mass coral bleaching event in Papahānaumokuākea Marine National Monument. Technical Report NOAA PMNM. NOAA, Silver Spring.

Darling ES, Alvarez-Filip L, Oliver TA, McClanahan TR, Côté IM. 2012. Evaluating life-history strategies of reef corals from species traits. *Ecology Letters* **15(12)**:1378–1386 DOI 10.1111/j.1461-0248.2012.01861.x.

Eakin CM, Lough JM, Heron SF. 2009. Climate variability and change: monitoring data and evidence for increased coral bleaching stress. In: Van Oppen MJH, Lough JM, eds. *Coral bleaching.* Berlin Heidelberg: Springer-Verlag.

Eakin CM, Rauenzahn JL, Liu G, Heron SF, Skirving WJ, Geiger EF, Strong AE. 2014. Will 2014-2015 be the next big El Niño? If so, what might it mean for coral reefs? *Reef Encounter* **29(5)**:30–35.

Environmental Protection Agency. 2016. Climate change indicators: sea surface temperture. *Available at https://www.epa.gov/climate-indicators/climate-change-indicators-sea-surface-temperature* (accessed on 04 August 2016).

Hoeke RK, Jokiel PL, Buddemeier RW, Brainard RE. 2011. Projected changes to growth and mortality of Hawaiian corals over the next 100 Years. *PLOS ONE* **6(3)**:e18038 DOI 10.1371/journal.pone.0018038.

Jaap WC. 1979. Observations on zooxanthellae expulsion at Middle Sambo Reef, Florida keys. *Bulletin of Marine Science* **29(3)**:414–422.

Jokiel PL, Brown EK. 2004. Global warming, regional trends and inshore environmental conditions influence coral bleaching in Hawaii. *Global Change Biology* **10**:1627–1641 DOI 10.1111/j.1365-2486.2004.00836.x.

Kramer K, Cotton S, Lamson M, Walsh W. 2016. Bleaching and catastrophic mortality of reef-building corals along west Hawaiʻi island: findings and future directions. In: *Proceedings of the 13th international coral reef symposium, Honolulu*, 229–241.

Mora C, Frazier AG, Tong EJ, Longman RJ, Kaiser LR, Dacks RS, Walton MM, Fernandez-Silva I, Stender YO, Anderson JM, Sanchez JJ, Ambrosino CM, Giuseffi LM, Giambelluca TW. 2014. Uncertainties in the timing of unprecedented climates. *Nature* **511**:E5–E6.

Neilson B, Department of Land and Natural Resources Division of Aquatic Resources. 2014. Coral bleaching rapid response surveys September–October. DLNR report. *Available at http://dlnr.hawaii.gov/reefresponse/files/2014/10/DARCoralBleachingSrvy_Results_10.28.2014.pdf* (accessed on 04 August 2016).

NOAA Coral Reef Watch. 2016. Main Hawaiian Islands 5-km bleaching thermal stress gauges. *Available at http://coralreefwatch.noaa.gov/vs/gauges/hawaii.php* (accessed on 15 September 2016).

NOAA Coral Reef Watch. 2017. Global coral bleaching 2014-2017: status and an appeal for observations. *Available at https://coralreefwatch.noaa.gov/satellite/analyses_guidance/global_coral_bleaching_2014-17_status.php* (accessed on 09 March 2017).

Normile D. 2016. El Niño's warmth devastating reefs worldwide. *Science* **352**:15–16 DOI 10.1126/science.352.6281.15.

Rodgers KS. 2005. Evaluation of nearshore coral reef condition and identification of indicators in the main Hawaiian Islands. PhD Dissertation, University of Hawai'i, Dept. of Geography. Honolulu.

Rodgers KS, Jokiel PL, Brown EK, Hau S, Sparks R. 2015. Hawaiʻi coral reef assessment and monitoring program: over a decade of change in spatial and temporal dynamics in coral reef communities. *Pacific Science* **69**:1 DOI 10.2984/69.1.1.

Sabine CL, Feely RA, Gruber N, Key RM, Lee K, Bullister JL, Wanninkhof R, Wong CS, Wallace DWR, Tilbrook B, Millero FJ, Peng T-H, Kozyr A, Ono T, Rios AF. 2004. The oceanic sink for anthropogenic CO_2. *Science* **305**:367–371 DOI 10.1126/science.1097403.

Sandin SA, Smith JE, DeMartini EE, Dinsdale EA, Donner SD, Friedlander AM, Konotchick T, Malay M, Maragos JE, Obura D, Pantos O, Pauley G, Richie M, Rohwer F, Schroeder RE, Walsh S, Jackson JBC, Knowlton N, Sala E. 2008. Baselines and degradation of coral reefs in the Northern Line Islands. *PLOS ONE* **3(2)**:e1548 DOI 10.1371/journal.pone.0001548.

State of Hawaiʻi Department of Business, Economic Development, and Tourism. 2016. *Available at http://dbedt.hawaii.gov/blog/16-02/* (accessed on 04 August 2016).

Watson M, Claar DC, Baum JK. 2016. Subsistence in isolation: fishing dependence and perceptions of change on Kiritimati, the world's largest atoll. *Ocean & Coastal Management* **123**:1–8 DOI 10.1016/j.ocecoaman.2016.01.012.

Whittle A. 2003. Ecology, abundance, diversity, and distribution of larval fishes and schindleiidae at two sectors on Oʻahu. Hawaiʻi. Dissertation, Department of Zoology, University of Hawaiʻi.

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Warming Trends and Bleaching Stress of the World's Coral Reefs 1985–2012

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Scott F. Heron[1,2,3], Jeffrey A. Maynard[4,5], Ruben van Hooidonk[6,7] & C. Mark Eakin[1]

Coral reefs across the world's oceans are in the midst of the longest bleaching event on record (from 2014 to at least 2016). As many of the world's reefs are remote, there is limited information on how past thermal conditions have influenced reef composition and current stress responses. Using satellite temperature data for 1985–2012, the analysis we present is the first to quantify, for global reef locations, spatial variations in warming trends, thermal stress events and temperature variability at reef-scale (~4 km). Among over 60,000 reef pixels globally, 97% show positive SST trends during the study period with 60% warming significantly. Annual trends exceeded summertime trends at most locations. This indicates that the period of summer-like temperatures has become longer through the record, with a corresponding shortening of the 'winter' reprieve from warm temperatures. The frequency of bleaching-level thermal stress increased three-fold between 1985–91 and 2006–12 – a trend climate model projections suggest will continue. The thermal history data products developed enable needed studies relating thermal history to bleaching resistance and community composition. Such analyses can help identify reefs more resilient to thermal stress.

Record warm temperatures in recent years have been extremely stressful to coral reefs. At the time, 2014 set the record for the warmest global surface temperature. The year 2015 was 0.16 °C warmer than 2014, setting not only the record for the warmest year ever but also the record for the largest single year increase[1]. So far, 2016 has been warmer than 2015 was. Ocean warming, exacerbated by one of the strongest El Niño events on record (comparable with 1997/98 and 1982/83) on top of a general warming trend, has resulted in the longest global coral bleaching event on record. Since mid-2014, reef stakeholders (scientists, managers) have reported observations of bleached corals near-continuously and from across all three tropical ocean basins[2]. As of late-2016 the event was ongoing, with more than 40% of global reef locations having been exposed to temperature stress levels that cause bleaching (G. Liu, pers. comm.).

Reefs are among the most sensitive of all ecosystems to climate change. Stony 'reef-building' corals live in a symbiotic relationship with microscopic algae called zooxanthellae (*Symbiodinium spp.*), whose photosynthesis provides corals with up to 90% of their energy[3]. Environmental stressors can disrupt this relationship. The main driver of contemporary stress on coral reefs is high temperature, which together with high irradiance results in an accumulation of damage to photosystem II[4,5]. Under extreme stress the coral expels algae[4,6], leaving its bright white aragonite skeleton visible through a thin translucent layer of coral tissue and appearing 'bleached'. Anomalously warm sea temperatures across broad scales have been closely linked to spatially extensive 'mass' coral bleaching events in recent decades[7–9].

There is a bleaching continuum. Some coral paling is common in many coral species during warm-season months, and bleached corals can survive mild thermal stress and recover their algae[10]. However, severely bleached

[1]NOAA Coral Reef Watch, NESDIS Center for Satellite Applications and Research, 5830 University Research Ct., E/RA3, College Park, MD 20740, USA. [2]Global Science and Technology, Inc., Greenbelt, MD 20770, USA. [3]Marine Geophysical Laboratory, Physics Department, College of Science, Technology and Engineering, James Cook University, Townsville, Qld 4811, Australia. [4]SymbioSeas and the Marine Applied Research Center, Wilmington NC 28411, USA. [5]CRIOBE – USR 3278, CNRS – EPHE – UPVD, Laboratoire d'Excellence "CORAIL", 58 Av. Paul Alduy - 66860 Perpignan cedex, France. [6]NOAA Atlantic Oceanographic and Meteorological Laboratory, Ocean Chemistry and Ecosystems Division, 4301 Rickenbacker Causeway, Miami, FL 33149, USA. [7]Cooperative Institute for Marine and Atmospheric Studies, Rosenstiel School of Marine and Atmospheric Science, University of Miami, 4600 Rickenbacker Cswy., Miami, FL 33149, USA. Correspondence and requests for materials should be addressed to S.F.H. (email: scott.heron@noaa.gov)

corals can and have died in great numbers when exposed to persistent stressful conditions[11,12]. Thermally stressed corals have higher disease susceptibility[13–15]; and reduced reproductive output[10] and skeletal growth[16]. Eventual impacts of bleaching (over years to decades) can include reduced reef rugosity, coral cover and biodiversity[10]; and perhaps local extinction of coral species[17–18]. Reefs affected by bleaching provide a lower quality habitat for fish and invertebrate species, and provide fewer ecosystem goods and services for dependent human communities[19,20]. As ocean waters warm under climate change, bleaching events are expected to become both more frequent and more severe[21–24].

Historical temperature variation and the cumulative effects of past disturbance events influence not only the condition of reefs but also their capacity to respond to subsequent stress events[25]. Corals are known to have adapted or acclimated to local environmental conditions[26,27]; e.g., temperature thresholds for bleaching vary spatially and have been linked to local summertime conditions[7]. Impacts from thermal stress have been lower at sites where short-term pulses of low-level temperature stress preceded higher thermal stress later in summer[24] or that had been affected by a prior but recent thermal stress event (e.g., Thompson & van Woesik[28], Heron *et al.*[29]). Reef sites dominated by high-frequency variability (5.7-year period) over low-frequency variability (>54-year period) were observed to experience more intense thermal stress and severe bleaching[28]. High SST variability year-round and during the warm season has also been suggested to proffer protection for reefs from bleaching[30–32]. Knowledge of thermal history can shape the lens through which managers and researchers view the current condition of reefs, and how they anticipate and respond to bleaching impacts on reefs. However, until now, high-resolution spatial data on key thermal history characteristics has not been available for all global coral reef locations.

Our objective here is to assess and provide tools to understand thermal history trends and patterns for reefs worldwide at the approximate scale of reefs using 4-km SST archives. Satellite remote sensing using Advanced Very High Resolution Radiometers (AVHRR) provides the capacity to undertake analysis of sea surface temperature (SST)-based metrics over spatially vast areas at high-resolution (4 km) through recent decades. Our period of analysis, 1985–2012, spans the two previous global bleaching events confirmed to have impacted all three tropical ocean basins (i.e., global events) in 1998[11] and 2010[33–38]. We quantify and compare the following metrics for all coral reef areas: (1) rates of change in annual and warm-season SST; (2) the frequency of exposure to and onset timing of bleaching-level thermal stress events; (3) the percentage of reefs exposed to bleaching-level thermal stress each year during the study period; and (4) warm-season temperature variability. Previous studies[32,39–43] included only some of these descriptors of thermal history, were conducted at lower spatial resolution, used shorter time periods and/or were regional in nature. We present spatial analyses of these thermal history metrics globally and for the six reef regions within *Reefs at Risk–Revisited*[44]: Middle East (MID), Indian Ocean (IND), Southeast Asia (SEA), Australia (AUS), Pacific Ocean (PAC) and Atlantic Ocean (ATL). The context of future thermal exposure is included using stress projections based on the latest available global modelling.

Results

In summary, our analysis of thermal history at global coral reef locations revealed warming at almost all reefs in recent decades; summertime temperature increased through the record at the great majority of reefs. One-third of the world's reefs were exposed to bleaching-level thermal stress less than once per decade, with one-third of reefs exposed between once and twice per decade, and the remaining one-third exposed more than twice per decade. The global percentage of reefs impacted by bleaching stress tripled through the 28-year record, explaining the increase in observed bleaching. While the onset of thermal stress mostly coincided with the warmest part of the year, we found that at nearly one-quarter of reefs it did not. The following key points were identified from each set of thermal history parameters.

SST Trends. Coral reef SST warmed during the 28-year period, with cool seasons warming faster than warm seasons. Annual average temperature increased during the study period at nearly all 4-km reef pixels (97% or 58,847 pixels). Globally, coral reefs warmed an average of 0.20 ± 0.11 (spatial SD) °C/decade (Fig. 1a, Table S1a). Reefs across all reef regions warmed but rates varied considerably (Figure S1) with the most rapid warming (Middle East, 0.32 ± 0.13 °C/decade) nearly four times greater than the slowest (Australia, 0.08 ± 0.09 °C/decade; Table S2). The distribution of values is demonstrated by annual average temperature time-series (Fig. 2) for five reef locations for the approximately 99th, 75th, 50th, 25th and 1st percentiles for SST trend. Annual-average SST trend was positive and significant ($p < 0.05$) at 60% of reefs (36,308 pixels), while negative and significant at less than 0.01% of reefs (4 pixels). Locations with cooling temperatures are all in the Atlantic region north of Grand Bahama Island (Fig. 2e), which is in contrast to the general warming across the Atlantic region (0.17 ± 0.12 °C/decade).

Bleaching stress typically occurs during the warm season. Reef SSTs warmed more slowly during the warm season (avg: 0.16 °C/decade) and had greater spatial variability (SD: 0.14 °C/decade) than the overall SST trend (Fig. 1b, Table S1b). Warm-season temperatures increased at 89% of reefs (53,768 pixels) and were significantly positive at 30% of reefs (18,362 pixels, $p < 0.05$). In contrast, significantly negative trends occurred at only <0.03% of reefs (16 pixels). All regional-average warm-season trends were positive (Fig. 3). Across the regions, positive trends were observed at 68–99% of reefs (Table S3). The Atlantic (92%), followed by the Middle East (47%), had the greatest percentage of reefs with statistically significant ($p < 0.05$) positive warm-season trends – consistent with the generally strong annual warming in these regions.

Annual SST warmed faster than the warm-season trend in 70% of locations and by +0.05 °C/decade when averaged across global reefs (Fig. 4), indicating a suppression of seasonality at most reefs. The difference between annual and warm-season trends was greater than 0.1 °C/decade (~1SD about the spatial average) at 37% of the reef pixels (Table S4). The Middle East and Atlantic were the only regions where warm-season trend predominantly

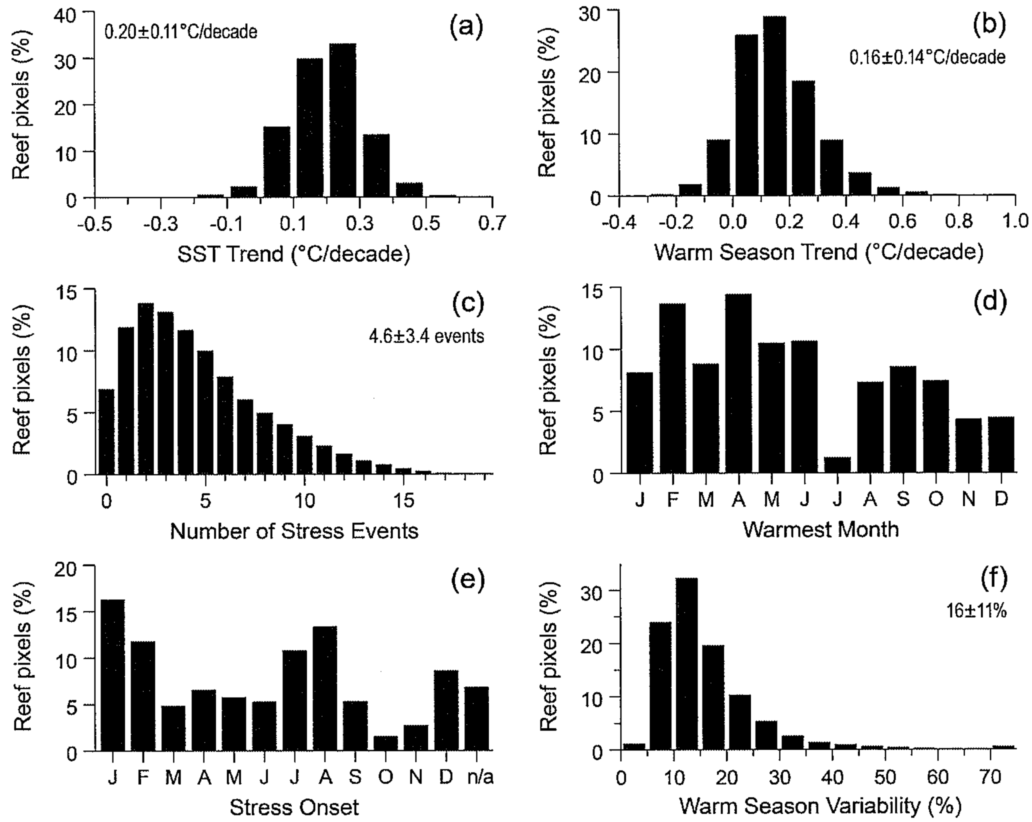

Figure 1. Histograms of thermal history metrics for global reef locations (n = 60,710). Global summary of the data distribution for (**a**) annual and (**b**) warm-season trends; (**c**) bleaching-level thermal stress events; (**d**) warmest month; (**e**) stress onset; and (**f**) warm-season temperature variability, 1985–2012. Warm-season temperature variability is the standard deviation of warm-season temperatures expressed as a percentage of the climatological range. Global averages ± one standard deviation are shown in plots (**a**,**b**,**c** and **f**. Data are provided for each histogram in Table S1.

exceeded annual SST trend (78% for MID and 94% for ATL, see Fig. 4). In all other regions, at least 68% of the pixels had an annual SST trend greater than the warm-season trend.

Thermal Stress. Most reefs (81%, n = 49,321) were exposed to multiple thermal stress events that were at a level likely to cause bleaching[12] during the 28-year period (DHW ≥4 °C-weeks; Fig. 1c, 5). Globally, reefs were exposed to bleaching-level stress 4.6 ± 3.4 times during the 28-year study period (Fig. 1c, Table S1c), and the regional average was above three events (~1/decade) in all reef regions (Fig. 5, Table S5). Bleaching stress on reefs occurred most frequently in the Middle East (9.1 ± 3.6) and least often in the Australia region (3.4 ± 2.8). Globally, 33% of reefs (19,794 pixels) experienced bleaching-level stress two or fewer times during the record (<1/decade). The Australia, Indian Ocean and Southeast Asia regions had the highest proportions of infrequent exposure (<1/decade at 43%, 41% and 38% of reefs, respectively). One-third (33%, n = 19,831) of reefs globally experienced bleaching-level thermal stress events six or more times during the 28-year record (>2/decade), with most reefs in the Middle East and Atlantic affected (81% and 59%, respectively; Table S5, Fig. 5). Severe thermal stress (DHW ≥8 °C-weeks), linked to significant coral mortality[12], affected 57% of global reef pixels at least once (Table S6). Just over 4% of reefs globally were exposed more than twice per decade to mortality-level thermal stress events. The Middle East and Atlantic regions had the highest proportions of reefs with frequent exposure to severe thermal stress (23% and 12%, respectively; Table S6, Figure S2).

Temporal Patterns. In each year of 1985–2012, thermal stress was observed somewhere across global reefs (Fig. 6–left panels; Table S7a). The greatest numbers of reefs were impacted in 1998 (48%), 2010 (48%) and 2005 (32%), corresponding to the two global bleaching events and largest Caribbean bleaching event during this period. In most regions, 1998 and 2010 were the two highest ranked (either 1st or 2nd) years for all reef regions with the exception of the Atlantic (2005, 2010) and Pacific (2009, 2000). When the record was divided into four 7-year periods, the global percentage of reef pixels that were stressed increased steadily (8, 14, 23 and 26%), tripling from 1985–91 to 2006–12 (Fig. 6–right, Table S7b). This increasing trend of bleaching-level stress events was consistent in the Middle East, Southeast Asia, Pacific and Atlantic regions. In contrast, there was no consistent temporal trend in the frequency of bleaching events in Indian Ocean and Australia reef pixels; the number of reef pixels affected in first or second 7-year period is comparable with that of the most recent period (within 1%).

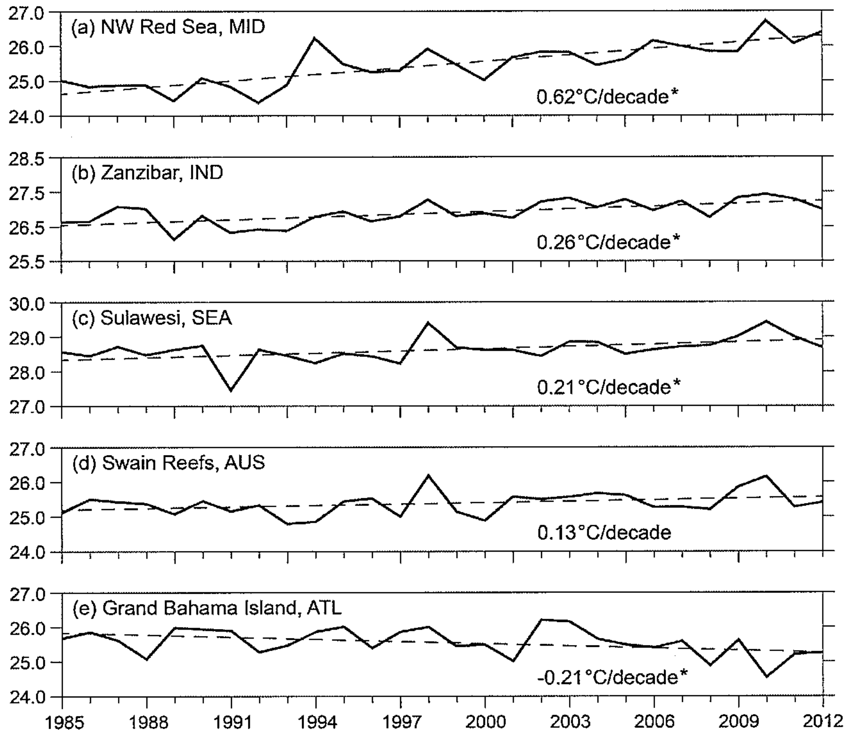

Figure 2. Trends in annual mean temperature at select coral reef locations. These locations approximate the 99th, 75th, 50th, 25th, and 1st percentiles (**a–e**, respectively) of the annual SST Trend values in the global dataset (n = 60,710 reef pixels). Reef regions are MID = Middle East, IND = Indian Ocean, SEA = Southeast Asia, AUS = Australia and ATL = Atlantic Ocean). Trend values shown are significant ($p < 0.05$, denoted by*) excepting for Swain Reefs, AUS.

The percentage of reef locations exposed to bleaching-level thermal stress events is projected by climate models[22] to continue to increase (Fig. 6–right, Table S7b). By 2050, more than 98% of reefs are expected to be exposed to bleaching-level thermal stress in each year[21,22]. Even in the Atlantic region, where projections suggest reduced bleaching around 2030, more than 91% of reefs are likely to experience bleaching-level thermal stress each year by 2050 (consistent with van Hooidonk *et al.*[21]).

Timing. Each of the calendar months was the warmest on a reef somewhere across the globe (Fig. 1c,S3). Within each region, two or three consecutive months predominated as the warmest for reefs – e.g., April-June in Southeast Asia and August-October in the Atlantic. Sub-region maps (Figure S3–left panels) indicate that geographic/oceanographic physical separation and latitudinal variation were factors defining warmest month areas. When considered globally, peaks in the onset of stress were in January/February and July/August, following the astronomical solstice events (Fig. 1e). However, many locations had onset months between solstice events, particularly reefs near the equator (in the Indian Ocean, Southeast Asia and Pacific regions; Figure S4).

Of the 93% of reefs that experienced bleaching-level thermal stress (56,521 pixels), average stress onset coincided with the warmest month at 29% (16,383) of these and occurred in the preceding 1–2 months at a further 49% (27,824) of sites. The onset of bleaching stress did not coincide with or immediately precede the warmest month in nearly one quarter of reef locations. While some of these reefs were found in each of the six regions, most were in the Southeast Asia and Pacific regions. This may reflect timing delays due to the Southeast Asian monsoon cycle and the relatively high interannual variability in the equatorial Pacific (linked to El Niño-Southern Oscillation events), respectively. Understanding spatial patterns of stress onset timing can inform managers' preparations during broad-scale thermal events.

Warm-season Variability. High SST variability in summer has been linked with reduced sensitivity to thermal stress[45]. However, research to date has provided no clear threshold defining "high" variability. We considered the globally most-variable locations (approximately the upper quartile) as having high variability and examined the distribution of these reefs. Nearly one-quarter of global reefs (23%) had warm-season variability at or above 20% of the climatological range (Fig. 1f). There were no high-variability reef pixels in the Middle East, and very few in Australia (1%) and the Atlantic (9%); in contrast, between one- and two-thirds of reef pixels in Southeast Asia, the Indian Ocean and the Pacific Ocean were among the most variable (Figure S5, Table S8). Greater exposure to variable warm-season temperature may be important in stimulating adaptive responses in corals[46].

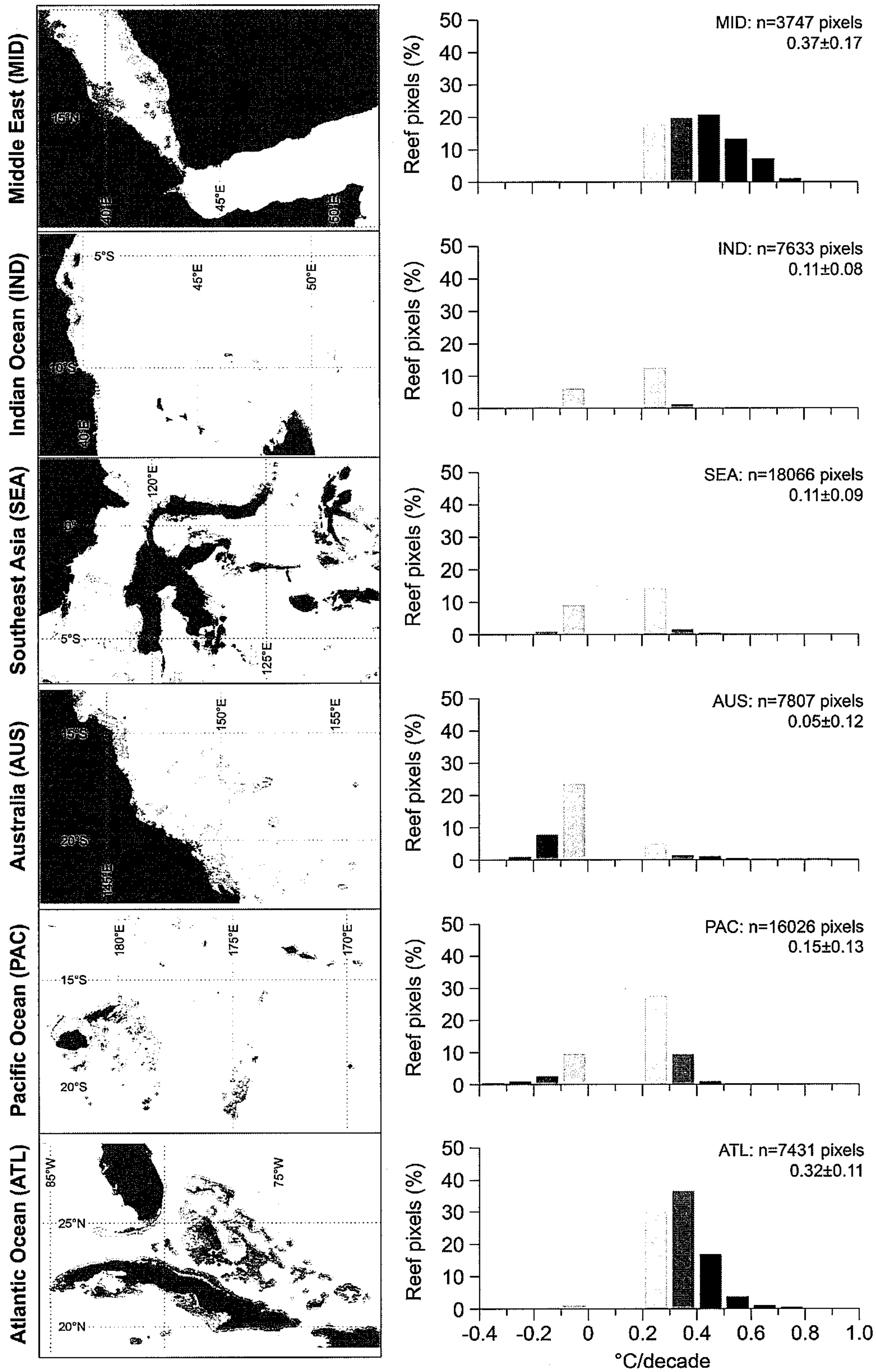

Figure 3. Trend in three-month warm-season temperatures among reef regions, 1985–2012. Trend values are in °C/decade. Maps (left) show results for a subset of each region; histograms (right) show the distribution of results in the full region with the regional average ± one standard deviation. Reef regions are as per Burke *et al.* 2011. Data are provided for each histogram in Table S3. Data visualisations produced using IDL [8.3] (Exelis Visual Information Solutions, Boulder, Colorado).

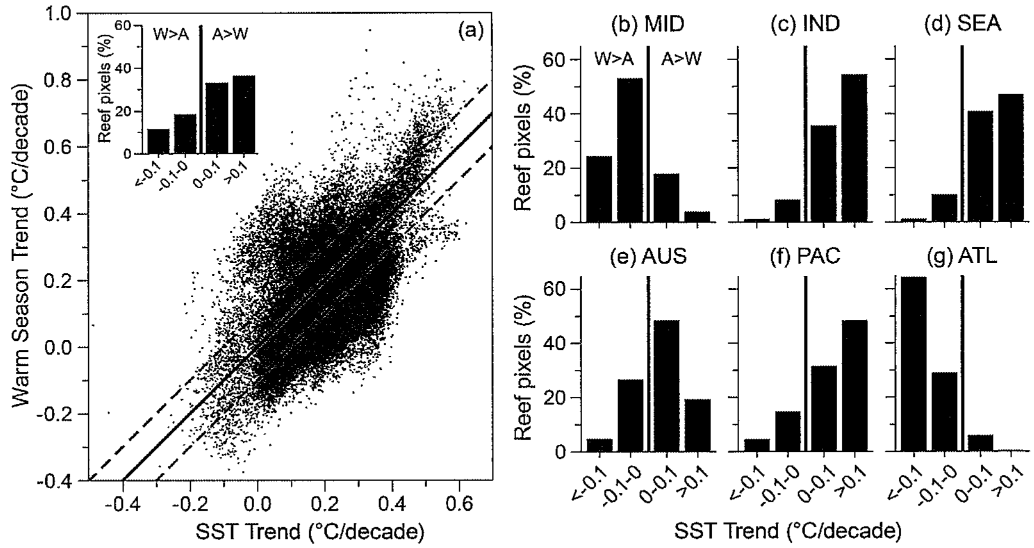

Figure 4. Scatterplot comparing annual SST and three-month warm-season trends globally and by reef region. Line of unity (solid) and ±0.1 °C/decade about this (dashed) are shown. Dashed lines approximate one SD of the by-pixel difference between the trends (0.11 °C/decade). Histograms show the distribution of annual SST minus warm-season trends; the solid line (at zero) corresponding to the scatterplot line of unity. Reef regions are as per Burke *et al.* 2011 (MID = Middle East, IND = Indian Ocean, SEA = Southeast Asia, AUS = Australia, PAC = Pacific Ocean and ATL = Atlantic Ocean). Data are provided for each histogram in Table S4.

Discussion

Temperature trends indicate accelerated warming in recent decades. Overall, reefs have been increasingly exposed to bleaching stress through this period. However, when comparing changes in exposure frequency across the record with the local summertime warming trend, some reefs experienced a lower-than-expected increase to stress exposure based on the global pattern, suggesting these locations as potential refugia. Using our analysis we identify reefs potentially more resilient to climate change impacts to inform conservation efforts.

SST Trends. Warming of coral reef waters (Fig. 1a, S1) was distinctly higher than that reported for ocean waters in general, both globally (0.10–0.12 °C/decade, 1971–2010[47,48]) and regionally (0.02–0.13 °C/decade, 1950–2009[23]). Consistent with IPCC findings, warming in the Indian Ocean (from the Middle East and Indian Ocean regions) exceeded that in the Pacific (from the Southeast Asia, Australia and Pacific Ocean regions), which in turn was greater than that in the Atlantic. Higher trends on reefs likely reflect the accelerated rate of warming from the most recent 28-year period (compared with the longer timeframes used in IPCC analyses), and potentially result from better resolution and improved accuracy of data closer to land[39]. Regional trends in annual and warm-season temperature (Fig. 3, S1) were consistent with earlier studies in the Atlantic[40,41] and in Southeast Asia[42].

Warming trends vary broadly across reefs – annual average temperature in the northwestern Red Sea, Middle East (99th percentile) increased at approximately three times the global average. In contrast, temperature to the north of Grand Bahama Island in the Atlantic (1st percentile) declined at −0.21 °C/decade – comparable to the rate of average global increase (Fig. 2). Recent cooling observations in parts of the Atlantic region have been linked to an increase in winter cold-air fronts from the North American continent since the 1990s[49], including unusually cold weather causing coral mortality in Florida in 2010[50]. Warm-season trends in the Atlantic region were predominantly greater than annual SST trends (Fig. 4g), consistent with Chollett *et al.*[41]. Warm-season warming may have been driven by the negative- to positive-phase change of the Atlantic Multidecadal Oscillation around the mid-to-late 1990s[51], also linked to increased oceanic heat content and Atlantic tropical storm activity in recent years[52].

Faster warming in winter than in summer for 70% of global reefs (Fig. 4) is consistent with both observations through the past century and future predictions that winter temperatures are warming faster than summer temperatures[53,54]. The consequence for corals has been a steady reduction in the cool-season reprieve from warm-season temperatures, which can enhance disease outbreaks[55,56]. In contrast, reefs experiencing more rapid warming of their warm seasons may experience increased bleaching and infectious disease[13–15].

Thermal Stress. Reefs with infrequent bleaching stress events (DHW ≥4 °C-weeks, <1/decade; Fig. 1c, 5) would likely, all else being equal, have had sufficient time to recover between events[10,57]. This applies to 33% of reef pixels worldwide and to more than 41% of the pixels in the Indian Ocean and Australia regions, but to far fewer in the Atlantic (14%) and Middle East (4%). While low past exposure does not guarantee future refuge from stress,

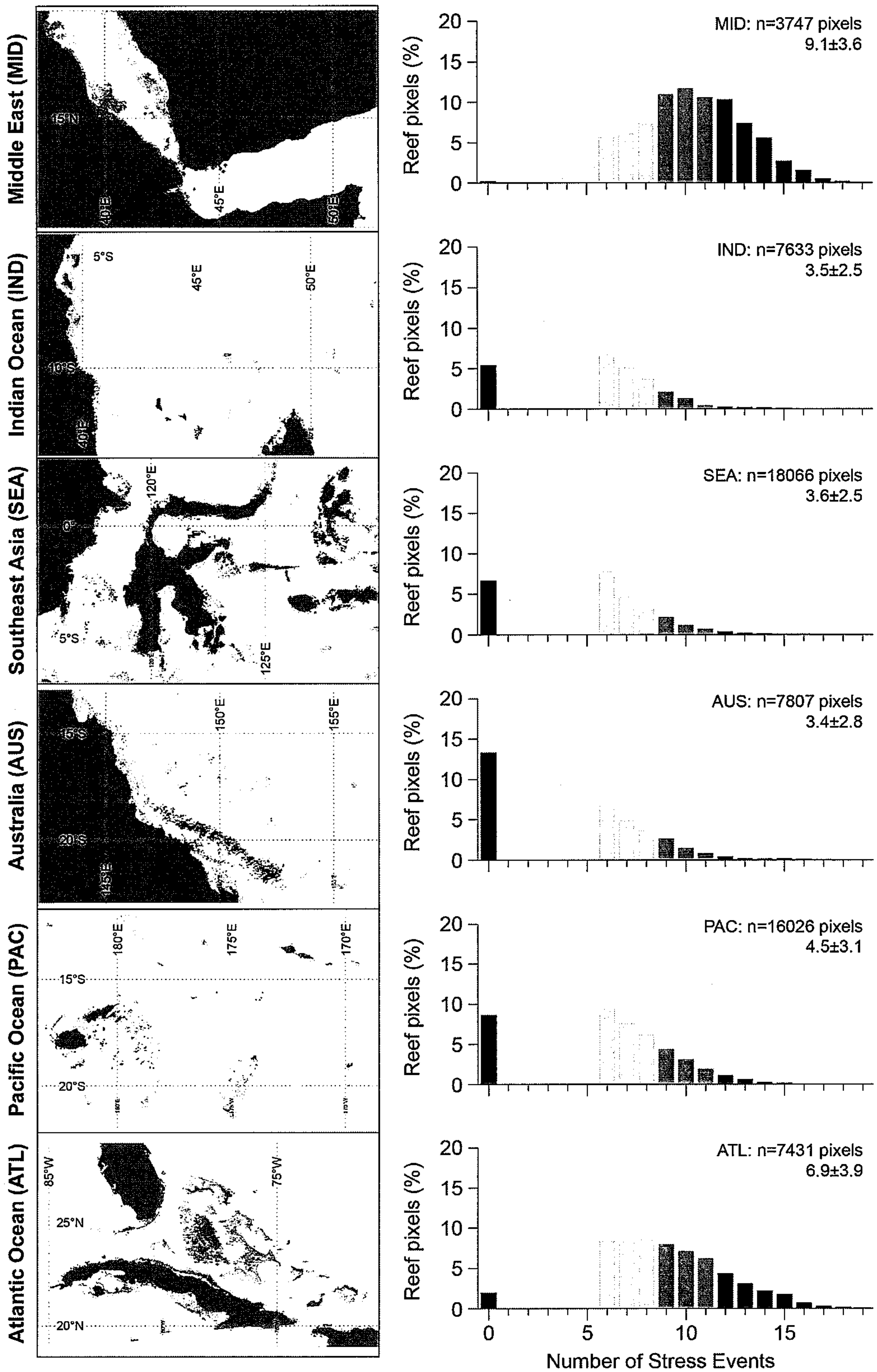

Figure 5. Frequency of bleaching-level thermal stress events among reef regions, 1985–2012. Bleaching-level stress is defined as DHW $\geq$ 4 °C-weeks. Maps (left) show results for a subset of each region; histograms (right) show the distribution of results in the full region with the regional average $\pm$ one standard deviation. Reef regions are as per Burke *et al.* 2011. Data are provided for each histogram in Table S5. Data visualisations produced using IDL [8.3] (Exelis Visual Information Solutions, Boulder, Colorado).

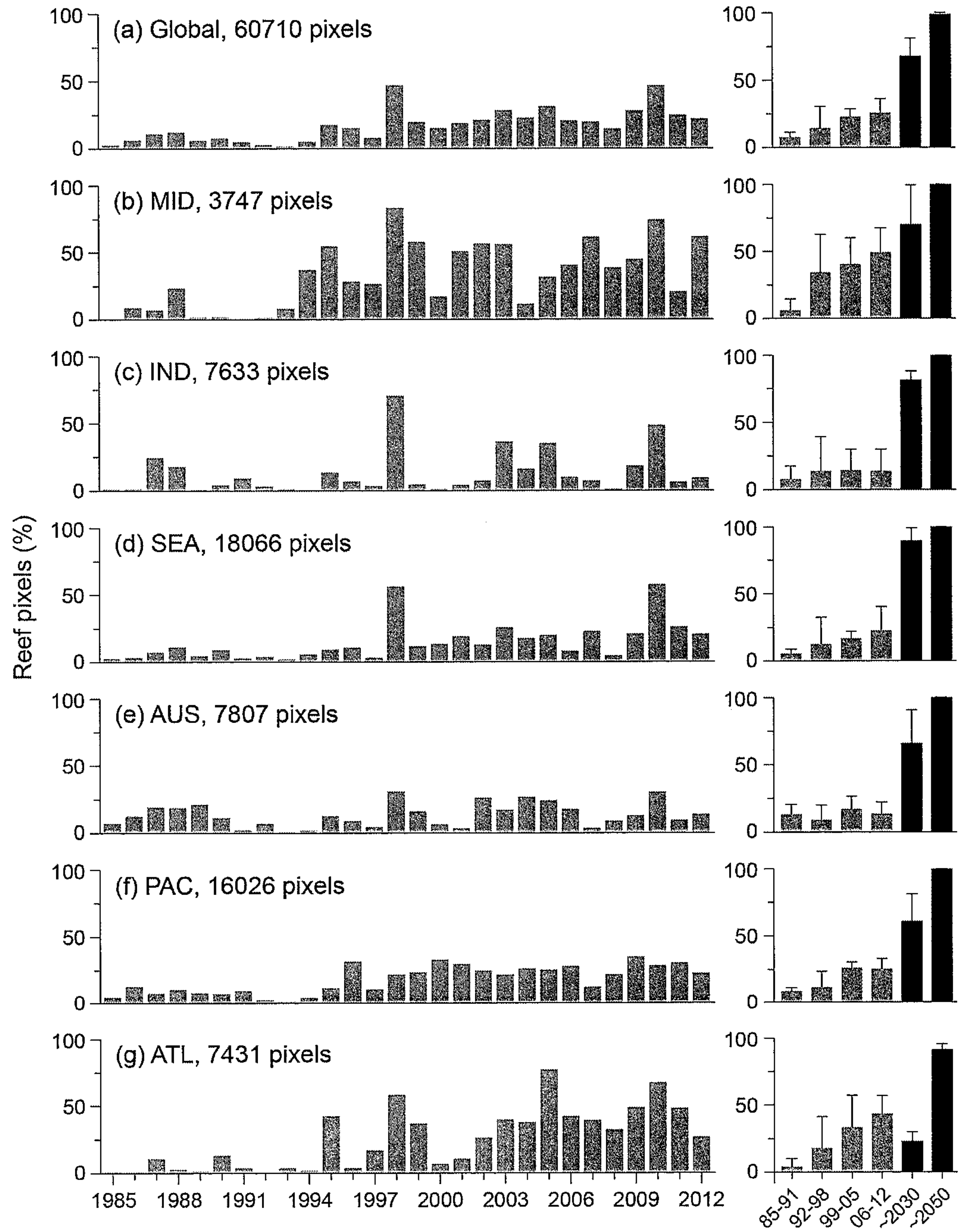

Figure 6. Histograms of bleaching-level thermal stress events, 1985–2012. Bleaching-level stress is defined as DHW ≥4 °C-weeks; plots refer to the % of reef pixels. The 28-year study period is divided into four 7-year periods in the histograms on the right (light grey), which show the average percentage of reef pixels affected by bleaching-level thermal stress across each period. The dark grey shade in the histograms show the average percentage of reef projected to experience bleaching-level thermal stress events under emissions scenario RCP8.5 for the 7-year periods centered on 2030 and 2050, following methods in van Hooidonk *et al.* 2014. Whiskers in the histogram are one standard deviation. Reef regions are as per Burke *et al.* 2011 (MID = Middle East, IND = Indian Ocean, SEA = Southeast Asia, AUS = Australia, PAC = Pacific Ocean and ATL = Atlantic Ocean). Data are provided for each histogram in Tables S7a,b.

it can indicate localised features (e.g., upwelling) that, if these persist, may provide some protection from thermal stress[58,59]. Alternatively, such locations may simply have been 'lucky so far' in escaping exposure to stress[60].

In contrast, reefs with high frequency of bleaching-level exposure (>2/decade) may have impaired function or may have already experienced shifts from susceptible to tolerant coral communities[10,57]. This applied to 33%

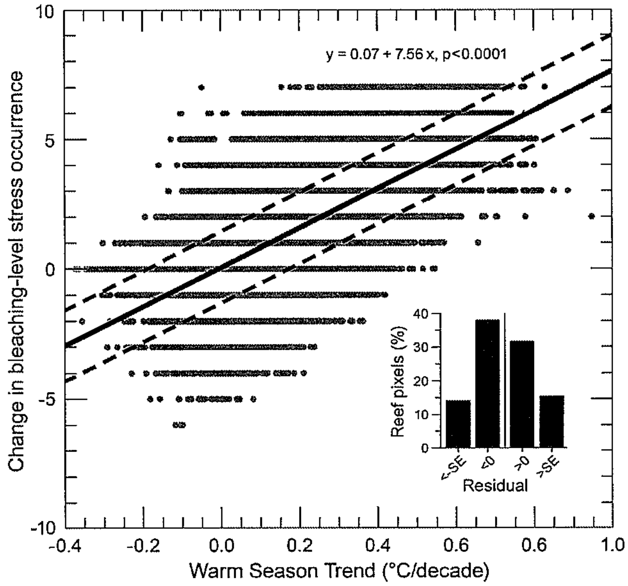

Figure 7. Change in bleaching stress occurrence with warm-season temperature trend. Difference in number of bleaching-level stress events (DHW ≥4 °C-weeks) between the 1985–1991 and 2006–2012 periods compared with warm-season trend for global reef pixels. Solid line shows linear regression; dashed lines are one standard error of estimate (SE = 1.37) above and below this. Histogram shows the proportions of reef pixel residuals distinguished by the lines. Data are provided for the histogram in Table S9.

of reefs globally and >59% in the Middle East and Atlantic regions, but <21% of reefs in the Indian Ocean, Southeast Asia and Australia regions. Corals that have survived past frequent bleaching stress events may be among the hardier and more resistant species or may have acclimated to stressful conditions[28]. Such reefs may be the most likely to persist when exposed to future stress events, though probably with the cost of reduced species and genetic diversity of surviving corals (e.g., refs 10, 29 and 57). Reefs that have persisted despite frequent exposure to mortality-level stress (DHW ≥8 °C-weeks, >2/decade) may prove critical for the continued existence of corals into the future. Nearly 24% of global reef locations (n = 14,672) experienced mortality-level thermal stress in one or both of 1998 and 1999, suggesting that the reported 16% loss of reefs[11] from the first recorded global bleaching may have been substantially underestimated.

Temporal patterns in bleaching-level thermal stress (Fig. 6) show that reefs have been increasingly exposed to stress in recent decades, with variation across the regions. Dramatic increases in the regional percentage of stressed reefs were likely associated with switches in basin-scale oceanographic phenomena: in the Middle East region during 1992–98, coinciding with the switch in the Indian Ocean Dipole[61] and resulting in increased bleaching[62]; and in the Pacific region during 1999–2005, following the ca. 1998 phase shift in the Pacific Decadal Oscillation[63].

Our assessment of both trends and stress exposure provides, for the first time, the opportunity to examine how these interact. We evaluated how summertime warming rate affected the frequency of bleaching stress events. The increase of bleaching-level events from 1985–91 to 2006–12 was associated with warm-season warming for many reefs (Fig. 7). For over 14% of reefs (8,704 pixels, Table S9), however, the change in stress exposure was more than one SE below the global linear regression. These reefs, present in all regions, had less increase to exposure than expected given their summertime warming rate.

Warm-season Variability. Several field studies[45,46,64,65] show that higher temperature variability reduces susceptibility to thermal stress on local scales; however, no variability threshold for or quantitative relationship with the mitigation of stress has been defined. To examine this, we considered the warm-season variability values at the reefs from these studies. With the exception of the study of Oliver & Palumbi[45], each spanned multiple pixels. No absolute threshold value could be ascribed to distinguish sites (e.g., the "low variability" location from Carilli *et al.*[65] had a metric value greater than that of the "high variability" location in Castillo *et al.*[64]). This suggests that spatial patterns in temperature variability on a regional-to-local scale may be more important than a global threshold in identifying reefs resistant to thermal stress. The warm-season temperature variability data product enables broad-scale studies to test the hypothesis that high temperature variability reduces bleaching impacts[66].

Application to Conservation. Identifying reefs with reduced exposure and/or less sensitivity can assist in identifying short-term target locations for conservation, which is critical given that projections of future bleaching indicate near-complete exposure of reefs to annual bleaching-level stress around 2050 (Fig. 6a–right, van Hooidonk *et al.*[21]). The production of the maps and spatial data presented here creates an opportunity to test hypotheses of how bleaching impact may be influenced by thermal history. With the third global coral bleaching event in progress at the time of writing, observations from this event can be used to validate how aspects of thermal history influence the severity of bleaching responses and levels of bleaching-induced mortality.

Here, we consider three characteristics of thermal history to identify reefs potentially resilient to thermal stress: (i) the frequency of past exposure; (ii) how that frequency has changed in the context of warm-season trend; and (iii) the level of warm-season variability. For each, we provide high-resolution images of identified reefs to inform conservation and research efforts (Figures S6–S8).

There is potential for both low and high frequency of past thermal exposure to be important for conservation (Figure S6). Regions with low historical exposure (blue), which are potential thermal refugia, include the Maldives and the southern Great Barrier Reef. Those with high exposure (red), which may have developed resistance, include Zanzibar and the Meso-American Barrier Reef. Some areas had both low and high exposure reefs within tens of kilometres (e.g., New Caledonia, the Florida Keys). Magris *et al.*[40] identified reefs in southern Brazil as historical refugia due to relatively low past thermal exposure (among Brazilian reefs); our study found several reefs in this region that experienced relatively low exposure frequency (Figure S6).

Reefs with a lower increase in stress exposure (the number of bleaching stress events) than expected from their summertime warming rate (i.e., reefs with large negative residuals in Fig. 7) are potential refugia. While it is unknown if this may continue into the future, this characteristic warrants consideration of these sites as priorities for management action (Figure S7). This trait was apparent at reefs in the eastern Persian Gulf, the northern Great Barrier Reef, New Caledonia and around the Bahamas and Greater Antilles. Maina *et al.*[67] identified reefs along the southern African coast and east of Madagascar as among western Indian Ocean reefs with the lowest susceptibility to thermal stress; reef locations in this region were also identified in Figure S7.

Reef locations with the highest observed warm-season variability ($\geq$20% of the climatological range) were found in the Maldives, western Sumatra, the Solomon Islands and Micronesia, several islands in the south Pacific, and the Caribbean coast of Panama (Figure S8). Given the lack of information on a threshold for warm-season variability, we propose that these reefs, which have the highest variability globally, be considered as priority conservation sites. However, consideration might also be given to the most variable reefs within individual regions/sub-regions.

Reefs with slower future warming could also be valuable sites for conservation. These can be identified globally once downscaled model projections, such as those for the Caribbean presented in van Hooidonk *et al.*[68], are available for all reef regions.

Understanding the capacity of corals to cope with thermal stress exposure may be the most important factor in predicting future reef trajectories[69]. Guided by remote sensing products that monitor thermal stress in near real-time[29,70] and modelled seasonal outlooks providing up-to-four-month advance warming[71], observers are surveying reef impacts across global reef regions. The thermal history data products described here (and available at: http://coralreefwatch.noaa.gov/satellite/thermal_history/) enable studies relating thermal history to bleaching resistance and community composition. Such analyses are needed, especially in light of thermal exposure during the current global event, to expand on the efforts presented here in helping identify reefs more resilient to thermal stress.

Conclusion

This study is the most comprehensive retrospective analysis of sea surface temperature and historical thermal stress in coral reef areas undertaken to date. Results from 1985–2012 show that: (i) 97% of reef pixels warmed through this period; (ii) cooler seasons represented less of a reprieve from warm-season stress; and (iii) more than three times as many reef pixels were exposed to bleaching-level thermal stress at the end of the record than was characteristic of the late 1980s, with even more drastic increases expected in coming decades. Importantly, the spatial heterogeneity seen in the analysis may identify locations that either represent refugia, or have reduced sensitivity to thermal stress and which could be less impacted during future disturbance. Coral bleaching events have become and will continue to become more frequent and severe – it is critical that we identify and conserve resilient reefs to help coral reefs survive while efforts are underway to control damaging anthropogenic global warming.

Methods

We used the NOAA Pathfinder version-5.2 daily, 1/24° (~4 km) sea surface temperature (SST) dataset, derived from satellite remote sensing and an official NOAA Climate Data Record for SST[72]. This latest version of Pathfinder provides continuous and consistently derived reef-scale temperatures over recent decades, currently available through 2012. This product provides skin temperature whilst previous versions of Pathfinder reported bulk temperatures, which have an average offset of ~0.16 °C[73]. This offset can vary with wind speed, cloud cover and other atmospheric parameters[73]. However, the internal consistency of this dataset and the fact that it spans both previous global coral bleaching events in 1998 and 2010 (see introduction) are key considerations supporting its use. Pathfinder SST data were composited to weekly resolution and then gap-filled using temporal and spatial-comparison techniques for 1985–2012 following Heron *et al.*[55].

We assessed which pixels contain coral reefs by combining three published global reef-locations datasets (ReefBase[74], Millennium Maps[75], Reefs at Risk–Revisited[44,76]). This was further augmented by other documented coral reef locations from collaborative reef studies; the reef-pixel dataset is available at coralreefwatch.noaa.gov. SST analysis was performed for 60,710 reef-containing pixels; maps presented here include pixels within ~9 km of reefs (total n = 175,585) to enhance visual interpretation of the results.

A range of thermal history metrics was developed in consultation with reef scientists and managers and arranged into six themes: 1. Trends (SST rates of change); 2. Climatology (long-term average conditions); 3. SST Variability (seasonal and annual); 4. Annual History (maximum SST, anomaly and DHW, by year); 5. Stress

Frequency (number of events for different stress levels); and 6. Onset Timing (expected onset and variability). From within these six themes, this study focused on seven metrics (numbered below).

SST trend in temperature [metric 1a] provides the long-term (28-year) historical trajectory of annual-mean temperature (SST_{ann}) as the slope, ω_{ann}, of a linear generalised least squares model (after Weatherhead *et al.*[77]):

$$SST_{ann} = \mu + \omega_{ann}t + N_t, \tag{1}$$

where μ is constant, t is time in years and N_t is the residual assumed to be autoregressive of the order of 1. The residual at a given time is a linear function of the residual at the previous time step and a random variable, ε_t (i.e., $N_t = \phi N_{t-1} + \varepsilon_t$). Statistical significance of the trends was determined at the 5% level (i.e., $p < 0.05$). To ensure appropriate representation of global coral reef regions (see below), regional results were compiled for all trends as well as the subset that were statistically significant.

Expected intra-annual temperature variations on reefs can be described by long-term monthly averages (climatologies), developed here following Heron *et al.*[78]. The warmest of these, the Maximum of the Monthly Means (MMM, °C), is used by NOAA Coral Reef Watch (CRW) as the stress threshold for monitoring conditions conducive to bleaching[70]. The climatologically *warmest month* [2] varies across global reef locations and indicates the period when bleaching-level thermal stress is most likely.

To examine factors during the intra-annual period when there is potential for coral bleaching, we defined the three-month warm season as centred on the warmest month for each pixel. *Warm-season trend* in temperature [1b] is the slope, ω_{ws}, of the generalised least squares model with autoregressive covariance (order 1) during the thermal stress period, calculated using three-month average temperature for the warm season, SST_{ws}, within each year, as:

$$SST_{ws} = \mu + \omega_{ws}t + N_t. \tag{2}$$

Parameters and statistical significance for warm-season trend are as described for the annual SST trend. The difference between SST trend and warm-season trend provides an indication of how the seasonality may have increased, or become suppressed, through the record. Reef locations for which SST trend exceeds warm-season trend indicate a suppressed seasonality, and therefore less respite from summertime temperature. Locations with a marked reduction in seasonality were identified by calculating the standard deviation of the trend difference across global reef pixels, and then determining where the trend difference was greater than approximately one standard deviation.

Bleaching-level thermal stress was calculated using Degree Heating Weeks (DHW), which combines magnitude and duration of temperature exceeding the MMM[70]. DHW of 4 °C-weeks has been linked to ecologically significant coral bleaching[12] and was used here to indicate bleaching-level thermal stress. DHW of 8 °C-weeks is associated with significant coral mortality[12] and was used as the threshold for mortality-level thermal stress. Knowledge of the likely onset timing of the bleaching season, and the spatial context of this information, can assist reef stakeholders in long-term planning, short-term preparation and monitoring. The mean timing of *stress onset* [3] (month) for thermal stress that reached 4 °C-weeks or greater was documented for all locations. Information on annual historical exposure can guide managers in understanding past thermal stress; identifying local DHW thresholds (i.e., if different from the broadly used values of 4 and 8 °C-weeks[12]); and distinguishing between thermal and non-thermal bleaching events. *Annual maximum DHW* [4] provides the highest accumulated thermal stress in each year. We quantified the *number of bleaching-level stress events* [5] through the 28-yr record, describing the historical incidence of annual maximum DHW at or above DHW of 4 °C-weeks. Reefs that experienced bleaching-level stress with frequency <1 event/decade (two or fewer occurrences) were defined as having had relatively low frequency of exposure to thermal stress, while those with >2 events/decade (six or more occurrences) were defined as having high frequency of exposure (see Donner *et al.*[57] and discussion therein). The number of mortality-level stress events through the record was determined using the DHW threshold of 8 °C-weeks.

The spatial distribution of the potential for increased thermal tolerance due to temperature variability was evaluated by defining *warm-season variability* [6], the standard deviation around the long-term mean of three-month warm-season temperature. This metric was calculated following the removal of the warm-season trend to separate the effects of long-term change and variability. Previous global mapping of SST variability at reduced resolution (0.5–1.0°) indicated strong influence of latitudinal variation[32]. To eliminate the effect of latitudinal variation, the warm-season variability was expressed here as a percentage of the climatological temperature range; i.e., the difference between the maximum (MMM) and minimum of the monthly mean climatologies. As the level of variability that confers bleaching resistance is unknown, we identified locations where the variability scaled by the local climatological range was in the approximately upper quartile of global values.

Spatial analysis of the aforementioned metrics was undertaken for reef locations globally (n = 60,710). To provide further insight into regional (ocean basin/sub-basin) patterns of the metrics while aligning with existing conservation management knowledge, spatial analyses were also undertaken for the six regions defined by the World Resources Institute's Reefs at Risk–Revisited analysis[44]. These reef regions are as follows: Middle East (MID), Indian Ocean (IND), Southeast Asia (SEA), Australia (AUS), Pacific Ocean (PAC) and Atlantic Ocean (ATL). Global and regional summaries for each metric were calculated as the average and standard deviation (SD) across reef pixels within these regions and globally. Maps from within each region in the main text and supplementary material display within-region variation for each metric. The areas shown are centred on: the southern Red Sea (Middle East), Comoros (Indian Ocean), Sulawesi (Southeast Asia), the central Great Barrier Reef (Australia), Fiji/Samoas (Pacific Ocean) and the Bahamas (Atlantic Ocean). Distributions of data from reef locations globally and from across each region are presented as histograms, and the corresponding data are provided in the supplementary material. Time-series and trends of annual-mean SST are displayed for five reef locations (across five of the six regions) that represent the ~99th, ~75th, ~50th, ~25th and ~1st percentiles of annual SST trend.

Temporal patterns in the historical incidence of bleaching- and mortality-level stress were considered annually and by dividing the 28-year period into four 7-year periods (1985–91, 1992–98, 1999–2005, 2006–12). Global and regional historical patterns were augmented using projections of thermal stress (DHW), based on monthly SST data from the World Climate Research Programme's Coupled Model Intercomparison Project Phase 5 (CMIP5) dataset[79]. Projected stress was calculated from 33 available GCMs under relative concentration pathway (RCP) 8.5 following the methods presented in van Hooidonk *et al.*[21] (model list in van Hooidonk *et al.*[22]). For the projections, the equivalent DHW value for bleaching-level thermal stress was 6 °C-weeks[21]. The median year for the start of annual bleaching conditions under RCP8.5 was reported as 2040[21]. To allow comparison with temporal patterns from the 7-year periods in the historical satellite data, we calculated the percentage of reef pixels with bleaching-level stress across 7-year periods centred on 2030 and 2050 (10 years prior and subsequent to the reported median year). We present regionally summarised information of projected thermal stress for comparisons with the four 7-year periods between 1985 and 2012; projections at full resolution are in refs 21, 22 and 56.

Remote sensing data collation, spatial analysis and data visualization was undertaken using Interactive Data Language (IDL) v8.1-3 and python 2.7.

References

1. NOAA National Centers for Environmental Information, State of the Climate: Global Analysis for Annual 2015, published online January 2016, retrieved on February 26, 2016 from http://www.ncdc.noaa.gov/sotc/global/201513 (2016).
2. Eakin, C. M. *et al.* Global coral bleaching 2014–2017: Status and an appeal for observations. *Reef Encounter* **31,** 20–26 (2016).
3. Stanley, G. D. Photosymbiosis and the evolution of modern coral reefs. *Science* **312,** 857–858 (2006).
4. Brown, B. Coral bleaching: Causes and consequences. *Coral Reefs* **16,** 129–138 (1997).
5. Iglesias-Prieto, R., Matta, J. L., Robins, W. A. & Trench, R. K. Photosynthetic response to elevated temperature in the symbiotic dinoflagellate *Symbiodinium microadriaticum* in culture. *Proc. Natl. Acad. Sci.* **89,** 10302–10305 (1992).
6. Jokiel, P. L. & Coles, S. L. Response of Hawaiian and other Indo-Pacific reef corals to elevated temperature. *Coral Reefs* **8,** 155–162 (1990).
7. Glynn, P. W. & D'Croz, L. Experimental evidence for high temperature stress as the cause of El Niño-coincident coral mortality. *Coral Reefs* **8,** 181–191 (1990).
8. Reaser, J. K., Pomerance, R. & Thomas, P. O. Coral bleaching and global climate change: Scientific findings and policy recommendations. *Conserv. Biol.* **14,** 1500–1511 (2000).
9. Oliver, J. K., Berkelmans, R. & Eakin, C. M. Coral bleaching in space and time. In: Oppen, M. J. H. & Lough, J. M. (eds) *Coral Bleaching*. (Springer, 2009).
10. Baker, A. C., Glynn, P. W. & Riegl, B. Climate change and coral reef bleaching: An ecological assessment of long-term impacts, recovery trends and future outlook. *Estuar. Coast. Shelf Sci.* **80,** 435–471 (2008).
11. Wilkinson, C. R. *Status of Coral Reefs of the World: 1998*. (Australian Institute of Marine Science, 1998).
12. Eakin, C. M. *et al.* Caribbean corals in crisis: Record thermal stress, bleaching, and mortality in 2005. *PLoS ONE* **5,** e13969 (2010).
13. Miller, J. *et al.* Coral disease following massive bleaching in 2005 causes 60% decline in coral cover on reefs in the US Virgin Islands. *Coral Reefs* **28,** 925–937 (2009).
14. Mydlarz, L. D., Couch, C. S., Weil, E., Smith, G. & Harvell, C. D. Immune defenses of healthy, bleached and diseases *Montastrea faveolata* during a natural bleaching event. *Dis. Aquat. Org.* **87,** 67–78 (2009).
15. Burge, C. A. *et al.* Climate change influences on marine infectious diseases: implications for management and society. *Ann. Rev. Mar. Sci.* **6,** 249–277 (2014).
16. Cantin, N. E. & Lough, J. M. Surviving Coral Bleaching Events: *Porites* Growth Anomalies on the Great Barrier Reef. *PLoS ONE* **9,** e88720 (2014).
17. Brainard, R. E. *et al. Status Review Report of 82 Candidate Coral Species Petitioned Under the U.S. Endangered Species Act*. (U.S. Dep. Commer., NOAA Tech. Memo. NOAA-TM-NMFS-PIFSC-27, https://www.pifsc.noaa.gov/library/pubs/tech/NOAA_Tech_Memo_PIFSC_27.pdf, 2011).
18. Brainard, R. E. *et al.* Incorporating climate and ocean change into extinction risk assessments for 82 coral species. *Conserv. Biol.* **27,** 1169–1178 (2013).
19. Munday, P. L., Jones, G. P., Pratchett, M. S. & Williams, A. J. Climate change and the future for coral reef fishes. *Fish Fish.* **9,** 261–285 (2008).
20. Doshi, A. *et al.* Loss of economic value from coral bleaching in S.E. Asia. In: *Proc. 12th International Coral Reef Symposium*, http://www.icrs2012.com/proceedings/manuscripts/ICRS2012_22D_1.pdf, accessed November 06, 2012 (2012).
21. van Hooidonk, R., Maynard, J. A. & Planes, S. Temporary refugia for coral reefs in a warming world. *Nature Clim. Change* **3,** 508–511 (2013).
22. van Hooidonk, R., Maynard, J. A., Manzello, D. & Planes, S. Opposite latitudinal gradients in projected ocean acidification and bleaching impacts on coral reefs. *Glob. Change Biol.* **20,** 103–112 (2014).
23. Hoegh-Guldberg, O. *et al.* The Ocean. In: Barros, V. R. *et al.* (eds) *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. (Cambridge University Press, 2014).
24. Ainsworth, T. D. *et al.* Climate change disables coral bleaching protection on the Great Barrier Reef. *Science* **352,** 338–342 (2016).
25. Maynard, J. A., Anthony, K. R. N., Marshall, P. A. & Masiri, I. Major bleaching events can lead to increased thermal tolerance in corals. *Mar. Biol.* **155,** 173–182 (2008).
26. Logan, C. A., Dunne, J. P., Eakin, C. M. & Donner, S. D. Incorporating adaptive responses into future projections of coral bleaching. *Glob. Change Biol.* **20,** 125–139 (2013).
27. Palumbi, S. R., Barshis, D. J., Traylor-Knowles, N. & Bay, R. A. Mechanisms of Reef Coral Resistance to Future Climate Change. *Science* **344,** 895–898 (2014).
28. Thompson, D. M. & van Woesik, R. Corals escape bleaching in regions that recently and historically experienced frequent thermal stress. *Proc.* R. Soc. *B* **276,** 2893–2901 (2009).
29. Heron, S. F. *et al.* Validation of reef-scale thermal stress satellite products for coral bleaching monitoring. *Remote Sens.* **8,** 59, doi: 10.3390/rs8010059 (2016).
30. Ateweberhan, M. & McClanahan, T. R. Relationship between historical sea-surface temperature variability and climate change-induced coral mortality in the western Indian Ocean. *Mar. Poll. Bull.* **60,** 964–970 (2010).
31. McClanahan, T. R. & Maina, J. Response of coral assemblages to the interaction between natural temperature variation and rare warm-water events. *Ecosystems* **6,** 551–563 (2003).
32. Donner, S. D. An evaluation of the effect of recent temperature variability on the prediction of coral bleaching events. *Ecol. Appl.* **21,** 1718–1730 (2011).

33. Thomas, C. R. & Heron, S. F. South-East Asia coral bleaching rapid response: final report. Commonwealth Scientific and Industrial Research Organisation, Wealth from Oceans Flagship, Australia. 24pp (2011).
34. Tan, C. H. & Heron, S. F. First observed severe mass bleaching in Malaysia, Greater Coral Triangle. *Galaxea* **13,** 27–28 (2011).
35. van Woesik, R., Houk, P., Isechal, A. L., Idechong, J. W., Victor, S. & Golbuu, Y. Climate-change refugia in the sheltered bays of Palau: analogs of future reefs. *Ecology and Evolution* **2,** 2474–2484 (2012).
36. Moore, J. A. Y. *et al.* Unprecedented mass bleaching and loss of coral across 12° of latitude in Western Australia in 2010–11. *PLoS ONE* **7,** e51807 (2012).
37. Furby, K. A., Bouwmeester, J. & Berumen, M. L. Susceptibility of central Red Sea corals during a major bleaching event. *Coral Reefs* **32,** 505–513 (2013).
38. Alemu I, J. B., & Clement, Y. Mass Coral Bleaching in 2010 in the Southern Caribbean. *PLoS ONE* **9,** e83829 (2014).
39. Good, S. A., Corlett, G. K., Remedios, J. J., Noyes, E. J. & Llewellyn-Jones, D. T. The Global Trend in Sea Surface Temperature from 20 Years of Advanced Very High Resolution Radiometer Data. *J. Clim.* **20,** 1255–1264 (2007).
40. Magris, R. A., Heron, S. F. & Pressey, R. L. Conservation Planning for Coral Reefs Accounting for Climate Warming Disturbances. *PLoS ONE* **10,** e0140828 (2015).
41. Chollett, I., Müller-Karger, F. E., Heron, S. F., Skirving, W. & Mumby, P. J. Seasonal and spatial heterogeneity of recent sea surface temperature trends in the Caribbean Sea and southeast Gulf of Mexico. *Mar Poll Bull* **64,** 956–965 (2012).
42. Peñaflor, E. L., Skirving, W. J., Strong, A. E., Heron, S. F. & David, L. T. Sea-surface temperature and thermal stress in the Coral Triangle over the past two decades. *Coral Reefs* **28,** 841–850 (2009).
43. Selig, E. R., Casey, K. S. & Bruno, J. F. New insights into global patterns of ocean temperature anomalies: implications for coral reef health and management. *Global Ecol. Biogeogr.* **19,** 397–411 (2010).
44. Burke, L., Reytar, K., Spalding, M. & Perry, A. *Reefs At Risk Revisited* (World Resources Institute, 2011).
45. Oliver, T. A. & Palumbi, S. R. Do fluctuating temperature environments elevate coral thermal tolerance? *Coral Reefs* **30,** 429–440 (2011).
46. Guest, J. R. *et al.* Contrasting Patterns of Coral Bleaching Susceptibility in 2010 Suggest an Adaptive Response to Thermal Stress. *PLoS ONE* **7,** e33353 (2012).
47. Hartmann, D. L. *et al.* Observations: Atmosphere and Surface. In: Stocker, T. F. *et al.* (eds) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press, 2013).
48. Rhein, M. *et al.* Observations: Ocean. In: Stocker, T. F. *et al.* (eds) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press, 2013).
49. Wang, C., Liu, H. & Lee, S. The record-breaking cold temperatures during the winter of 2009/2010 in the Northern Hemisphere. *Atmos. Sci. Lett.* **11,** 161–168 (2010).
50. Lirman, D. *et al.* Severe 2010 cold-water event caused unprecedented mortality to corals of the Florida reef tract and reversed previous survivorship patterns. *PLoS ONE* **6,** e23047 (2011).
51. Knight, J. R., Allan, R. J., Folland, C. K., Vellinga, M. & Mann, M. E. A signature of persistent natural thermohaline circulation cycles in observed climate. *Geophys. Res. Lett.* **32,** L20708 (2005).
52. Trenberth, K. E. & Shea, D. J. Atlantic hurricanes and natural variability in 2005. *Geophys. Res. Lett.* **33,** L12704 (2006).
53. Houghton, J. T. *et al.* (eds) *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press, 2001).
54. Trenberth, K. E. *et al.* Observations: surface and atmospheric climate change. In: Solomon, S. *et al.* (eds) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press, 2007).
55. Heron, S. F. *et al.* Summer hot snaps and winter conditions: Modelling white syndrome outbreaks on Great Barrier Reef corals. *PLoS ONE* **5,** e12210 (2010).
56. Maynard, J. *et al.* Projections of climate conditions that increase coral disease susceptibility and pathogen abundance and virulence. *Nature Clim. Change* **5,** 688–694 (2015).
57. Donner, S., Skirving, W., Little, C., Oppenheimer, M. & Hoegh-Guldberg, O. Global assessment of coral bleaching and required rates of adaptation under climate change. *Glob. Change Biol.* **11,** 2251–2265 (2005).
58. Skirving, W. J., Heron, M. L. & Heron, S. F. The hydrodynamics of a bleaching event: Implications for management and monitoring. pp. 145–161 In: Phinney, J. T. *et al.* (eds) *Coral Reefs and Climate Change: Science and Management* (AGU Coastal and Estuarine Series, Vol. 61, 2006).
59. West, J. M. & Salm, R. V. Resistance and Resilience to Coral Bleaching: Implications for Coral Reef Conservation and Management *Conservation Biology* **17,** 956–967 (2003).
60. Wooldridge, S. A. *et al.* Excess seawater nutrients, enlarged algal symbiont densities and bleaching sensitive reef locations: 2. A regional-scale predictive model for the Great Barrier Reef, Australia. *Mar. Pollut. Bull.*, doi: 10.1016/j.marpolbul.2016.09.045 (in press).
61. Saji, N. H., Goswami, B. N., Vinayachandran, P. N. & Yamagata, T. A dipole mode in the tropical Indian Ocean. *Nature* **401,** 360–363 (1999).
62. Riegl, B. M., Purkis, S. J., Al-Cibahy, A. S., Abdel-Moati, M. A. & Hoegh-Guldberg, O. Present limits to heat-adaptability in corals and population-level responses to climate extremes. *PLoS ONE* **6,** e24802 (2011).
63. Newman, M., Compo, G. P. & Alexander, M. A. ENSO-Forced Variability of the Pacific Decadal Oscillation. *J. Clim.* **16,** 3853–3857 (2003).
64. Castillo, K. D., Ries, J. B. & Weiss, J. M. Decline of forereef corals in response to recent warming linked to history of thermal exposure. *Nature Clim. Change* **2,** 756–760 (2012).
65. Carilli, J., Donner, S. D. & Hartmann, A. C. Historical temperature variability affects coral response to heat stress. *PLoS ONE* **7,** e34418 (2012).
66. McClanahan, T. R. *et al.* Evidence-based resilience assessments to support coral reef management in a changing climate. *PLoS ONE* **7,** e42884 (2012).
67. Maina, J., Venus, V., McClanahan, T. R. & Ateweberhan, M. Modelling susceptibility of coral reefs to environmental stress using remote sensing data and GIS models. *Ecological Modelling* **212,** 180–199 (2008).
68. van Hooidonk, R., Maynard, J. A., Liu, Y. & Lee, S. Downscaled projections of Caribbean coral bleaching that can inform conservation planning. *Glob. Change Biol.* doi: 10.1111/gcb.12901 (2015).
69. Bruno, J. F. & Valdivia, A. Coral reef degradation is not correlated with local human population density. *Sci. Rep.* **6,** 29778 (2016).
70. Liu, G. *et al.* Reef-scale thermal stress monitoring of coral ecosystems: new 5-km global products from NOAA Coral Reef Watch. *Remote Sens.* **6,** 11579–11606 (2014).
71. Eakin, C. M., Liu, G., Chen, M. & Kumar, A. Ghost of bleaching future: Seasonal Outlooks from NOAA's operational Climate Forecast System. *Proc. 12th International Coral Reef Symposium,* http://www.icrs2012.com/proceedings/manuscripts/ICRS2012_10A_1.pdf, accessed June 04, 2015 (2012).
72. Casey, K. S., Brandon, T. B., Cornillon, P. & Evans, R. The Past, Present and Future of the AVHRR Pathfinder SST Program. pp. 323–341 In: Barale, V., Gower, J. F. R. & Alberotanza, L. (eds). *Oceanography from Space: Revisited* (Springer, 2010).

73. Weeks, S. J., Berkelmans, R. & Heron, S. F. Thermal Applications. pp. 313–339 In: Goodman, J. A., Purkis, S. J., Phinn, S. R. (eds) *Coral reef remote sensing: A guide for mapping, monitoring and management.* (Springer, 436pp., 2013).
74. ReefBase reef locations from http://www.reefbase.org/gis_maps/datasets.aspx, accessed May 08, 2014.
75. Millennium Maps reef locations from http://data.unep-wcmc.org/datasets/1, accessed May 14, 2014.
76. Reefs at Risk Revisited reef locations from http://www.wri.org/resources/data-sets/reefs-risk-revisited, accessed February 19, 2014.
77. Weatherhead, E. C. *et al.* Factors affecting the detection of trends: Statistical considerations and applications to environmental data. *J Geophys Res* **103,** 17149–17161 (1998).
78. Heron, S. F. *et al.* Improvements to and Continuity of Operational Global Thermal Stress Monitoring for Coral Bleaching. *J. Oper. Oceanogr.* 7, 3–11 (2014).
79. CMIP5 project description at http://cmip-pcmdi.llnl.gov, accessed August 29, 2016.

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Author Contributions

S.F.H. and J.A.M. conceived the study, with input from all authors. S.F.H. and J.A.M. wrote the text with assistance from and review by all other authors.

Additional Information

Supplementary information accompanies this paper at http://www.nature.com/srep

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COSMETOLOGIA

ANEXO IV

Declarações de entidades internacionais renomadas (CHPA, PCPC)

04 May 2018

American Academy of Dermatology Association statement on sunscreen access

ROSEMONT, Ill. (May 4, 2018) — *Statement from Suzanne M. Olbricht, MD, FAAD, president, American Academy of Dermatology Association*

The American Academy of Dermatology Association is concerned that the public's risk of developing skin cancer could increase due to potential new restrictions in Hawaii that impact access to sunscreens with ingredients necessary for broad-spectrum protection, as well as the potential stigma around sunscreen use that could develop as a result of these restrictions. Sadly, the death rate from melanoma, the deadliest form of skin cancer, in Hawaii is already 30 percent higher than the national average.

The AADA wants the public to know that sunscreen remains a safe, effective form of sun protection. As one component of a daily sun protection strategy, sunscreen is an important tool in the fight against skin cancer. Claims that sunscreen ingredients currently approved by the U.S. Food and Drug Administration are toxic to the environment or a hazard to human health have not been proven. Furthermore, scientific evidence supports the benefits of applying sunscreen to minimize short- and long-term damage to the skin from the sun's harmful ultraviolet rays.

Research indicates that about 95 percent of melanoma cases are attributable to UV exposure, so the AADA encourages everyone to protect themselves from the sun by seeking shade, wearing protective clothing, and using a broad-spectrum, water-resistant sunscreen with an SPF of 30 or higher.

sunscreens with ingredients other than oxybenzone and octinoxate, such as zinc oxide or titanium dioxide. We also encourage the public to closely read product labeling, use products as directed, and contact a board-certified dermatologist if they have any questions.

Although there are many safe and effective sunscreen products on the market, the AADA continues to support the introduction of new sunscreen ingredients in the United States. The best sunscreen is the one that individuals will use every day. The more sun protection options consumers have at their disposal, the more likely they will be to find an option they like and will use regularly.

More Information

Find a Dermatologist (/find-a-derm)
Prevent skin cancer (/public/spot-skin-cancer/learn-about-skin-cancer/prevent/how-to-select-a-sunscreen)
AADA letter to Hawaii State Legislature (/File Library/Top navigation/Media/HI-AADA-Oppose-SB2571-House-and-Senate.pdf)

About the AADA

Headquartered in Rosemont, Ill., the American Academy of Dermatology, founded in 1938, is the largest, most influential and most representative of all dermatologic associations. A sister organization to the Academy, the American Academy of Dermatology Association is the resource for government affairs, health policy and practice information for dermatologists, and plays a major role in formulating policies that can enhance the quality of dermatologic care. With a membership of more than 19,000 physicians worldwide, the Academy is committed to excellence in the diagnosis and medical and surgical treatment of skin disease; advocating high standards in clinical practice, education and research in medical dermatology, surgical dermatology and dermatopathology; and supporting and enhancing patient care to reduce the burden of disease. For more information, contact the Academy at (888) 462-DERM (3376) or aad.org (/home/home). Follow the Academy on Facebook (https://www.facebook.com/AADskin)(American Academy of Dermatology), Twitter (https://twitter.com/AADskin) (@AADskin) and YouTube (https://www.youtube.com/user/AcademyofDermatology)(AcademyofDermatology).

News (/media/news-releases)

Statement from the Consumer Healthcare Products Association(CHPA)Regarding Hawaii Sunscreen

19

"Today the health, safety and welfare of millions of Hawaii residents and tourists has been severely compromised by the passage of SB 2571 that will ban at least 70 percent of the sunscreens on the market today, based on weak science blaming sunscreens for damage to coral reefs. This irresponsible action will make it more difficult for families to protect themselves against the sun's harmful ultraviolet rays, and it is contrary to the many concerns expressed by Hawaii's medical doctors, dermatologists, and public health experts."

"Overwhelming scientific evidence shows that excess sun exposure without effective sunscreen increases the risk of developing skin cancer in both adults and children. Banning oxybenzone and octinoxate – key ingredients in effective sunscreens on the market – will drastically and unnecessarily reduce the selection of safe and effective sunscreen products available to residents and visitors. Oxybenzone and octinoxate, found in the majority of sunscreens, are safe and effective over-the-counter (OTC) active ingredients recognized by the Food and Drug Administration (FDA) as important aides in decreasing the risk of developing skin cancer, the most common cancer in the U.S."

"This ban also avoids the real causes of coral decline according to scientists in Hawaii and around the world: global warming, agricultural runoff, sewage, and overfishing. This ban creates false hope that banning sunscreen will restore the health of coral reef around the Hawaiian Islands, but it will have little to no positive impact on the health of coral reefs. Rather, it has the potential to create a public health crisis which is why the Hawaii Medical Association, Hawaii Dermatological Society, Hawaii Skin Cancer Coalition, and Hawaii Department of Health have also expressed concerns with this legislation."

###

The Consumer Healthcare Products Association (CHPA) is the 137-year-old national trade association representing the leading manufacturers and marketers of over-the-counter (OTC) medicines and dietary supplements. Every dollar spent by consumers on OTC medicines saves the U.S. healthcare system $6-$7, contributing a total of $102 billion in savings each year. CHPA is committed to empowering self-care by preserving and expanding choice and availability of consumer healthcare products. chpa.org

Contact: Mike Tringale (MTringale@chpa.org)

202.429.3520

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Examine all available evidence before making decisions on sunscreen ingredient bans

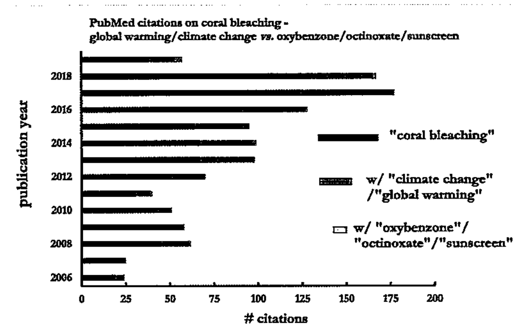
Jay Sirois

Regulatory & Scientific Affairs, Consumer Healthcare Products Association, 1625 I St NW, Suite 600, Washington, DC 20006, United States of America.

HIGHLIGHTS

- Coral bleaching resulting from climate change has occurred worldwide for decades.
- Recent *in vitro* studies suggest sunscreen ingredients could cause coral to bleach.
- Sunscreen ingredient bans are likely to be ineffective in restoring coral health.
- Ingredient bans will likely result in decreased use and increased UV exposure.
- All scientific evidence needs to be considered before banning sunscreen ingredients.

GRAPHICAL ABSTRACT



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ABSTRACT

Coral bleaching is a worldwide problem and more needs to be done to determine causes and potential solutions. A myopic focus on sunscreen ingredients as the proximate cause of coral bleaching provides consumers a false belief that enacted bans of these ingredients will erase decades of coral reef decline. Instead, these bans will likely only lead to decreased sunscreen use and exposure to potentially harmful UV radiation. A closer examination of all available evidence on the causes of coral reef bleaching needs to be undertaken, including a more thorough appraisal of studies conducted under artificial conditions using higher concentrations of sunscreen ingredients.

Coral bleaching is a worldwide problem and more needs to be done to determine causes and potential solutions. To date, limited evidence generated in laboratory studies suggests that active ingredients in sunscreens are responsible for coral bleaching (Downs et al., 2016; Danovaro et al., 2008; He et al., 2019a; He et al., 2019b; Tsui et al., 2017). Despite this, widespread media attention has focused on results from these studies often using single, unreplicated data points to suggest that ingredients in sunscreen pose a hazard to coral reefs and should thus be banned. Although results from these studies merit consideration, and suggest the need for further study, as with all scientific evidence, there are inherent limitations and results from these studies cannot be easily extrapolated to what might occur in a native coral reef setting. Instead of relying on results from isolated studies to

E-mail address: jsirois@chpa.org.

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0048-9697/

promote proposed solutions to coral decline, a closer examination of all available evidence on the causes of coral reef bleaching should be undertaken. This should include a more thorough appraisal not only of these studies, conducted under artificial conditions using higher concentrations of sunscreen ingredients, but also of other evidence demonstrating the significant role that climate change and other factors have played in coral bleaching over the past 50 years.

Unfortunately, coral reef bleaching has occurred worldwide for the past several decades irrespective of whether a particular coral reef is impacted by a high level of human recreational activity (Bruno and Valdivia, 2016; Barkley et al., 2018). There is a vast amount of scientific evidence pointing to changes in ocean temperature resulting from climate change as a primary mediator of coral reef bleaching (Hughes et al., 2017; Heron et al., 2018; National Oceanic and Atmospheric Administration (NOAA), n.d.; National Aeronautics and Space Administration (NASA), n.d.; Heron et al., 2018). Further, results from other studies (Johnsen, 2018; et al., 2017; Reef Safe, 2016) suggest that exposure to sunscreens (including those that contain oxybenzone or octinoxate) does not negatively affect coral reef populations. In some cases, these experiments utilized exposure conditions which more closely reflected what might happen in a native coral reef setting and found no difference in the health of coral between sunscreen and control groups. Moreover, recent evidence demonstrating lower levels of sunscreen ingredients (including oxybenzone and octinoxate) in coral reef habitats (Mitchelmore et al., 2019) compared to earlier work suggests the need for careful examination of all available data.

Banning individual sunscreen ingredients based on preliminary results obtained under conditions which may not accurately reflect native coral reef settings is highly irresponsible, as it risks the diversion of resources towards efforts which will likely have no measurable effect. Further, reducing the number of available sunscreen ingredients will inhibit consumer choice of broad-spectrum sunscreen products shown to be effective in reducing skin cancer (Green et al., 2011; Van der Pols et al., 2006; Olsen et al., 2018; Watts et al., 2018).

One in five people will develop skin cancer in their lifetime and more than 5 million new cases of skin cancer were diagnosed in the U.S. in 2018 (American Cancer Society, Cancer Facts, and Figures, 2018). There are more new cases of skin cancer each year than breast, prostrate, lung and colon cancer combined. Overwhelming evidence demonstrates that excess sun exposure without sunscreen increases the risk of developing skin cancer in both adults and children (Preston and Stern, 1992; English et al., 1998). Sun-protective behaviors to reduce exposure to harmful UVA and UVB radiation should be practiced whenever possible and sunscreens are one effective option. Dermatologists agree that the best sunscreen is the one that is used on a regular basis.

A broad array of healthcare professionals recommends using a broad-spectrum sunscreen daily to prevent against sunburn and skin cancer. Indeed, a recent survey of dermatologists (Farberg et al., 2016) found that 99% agreed that regular use of sunscreen helps lower skin cancer risk. Similarly, a diverse group of professional societies/expert bodies recommends use of a broad-spectrum sunscreen to help protect against the harmful effects of UV radiation and reduce the risk of skin cancer.

When viewed in its entirety, the currently available evidence on the causes of coral reef bleaching and mortality, in Hawaii, Florida and the world over, overwhelmingly demonstrates that climate change (Hughes et al., 2017) is primarily responsible. There is evidence suggesting that other factors such as ocean acidification (Cyronak et al., 2018), runoff (Brodie et al., 2010; De'ath and Fabricius, 2010; Fabricius, 2005) and sewage discharge also contribute to an overall decline in coral reef populations. Coral damage resulting from runoff or sewage discharge could be a consequence of numerous factors (Marques et al., 2019) including changes in salinity (Aguilar et al., 2019) or bacterial count (Staley et al., 2017).

An open, honest and unbiased discussion of the available science on the multifactorial causes of coral reef bleaching and possible solutions to this problem needs to be conducted. The current focus on implicating chemical sunscreen ingredients as the proximate cause of coral bleaching provides consumers a false belief that enacted bans of these ingredients will erase decades of coral reef decline. Instead, these bans will likely only lead to decreased sunscreen use and increased exposure to potentially harmful UV radiation.

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The Consumer Healthcare Products Association (CHPA) is the 138-year-old national trade association representing the leading manufacturers and marketers of over-the-counter (OTC) medicines (including sunscreen manufacturers).

References

Aguilar, C., et al., 2019. Transcriptomic analysis reveals protein homeostasis breakdown in the coral *Acropora millepora* during hypo-saline stress. BMC Genomics 20 (1), 148.
American Cancer Society, Cancer Facts & Figures, 2018. . available at. https://www.cancer.org/content/dam/cancer-org/research/cancer-facts-and-statistics/annual-cancer-facts-and-figures/2018/cancer-facts-and-figures-2018.pdf.
Barkley, H.C., et al., 2018. Repeat bleaching of a Central Pacific coral reef over the past six decades (1960–2016). Commun Biol 1, 177. https://doi.org/10.1038/s42003-018-0183-7.
Brodie, J.E., et al., 2010. Terrestrial pollutant runoff to the Great Barrier Reef: an update of issues, priorities and management responses. Mar. Pollut. Bull. 65 (4–9), 81–100.
Bruno, J.F., Valdivia, A., 2016. Coral reef degradation is not correlated with local human population density. Sci. Rep. https://doi.org/10.1038/srep29778.
Cyronak, T., et al., 2018. Taking the metabolic pulse of the world's coral reefs. PLoS One 13 (1), e0190872.
Danovaro, R., et al., 2008. Sunscreens cause coral bleaching by promoting viral infections. Environ. Health Perspec. 116 (4), 441–447.
De'ath, G., Fabricius, K.E., 2010. Water quality as a regional driver of coral biodiversity and macroalgae on the Great Barrier Reef. Ecol. Appl. 20, 840–850.
Downs, C.A., et al., 2016. Toxicopathological effects of the sunscreen UV filter, Oxybenzone (Benzophenone-3), on coral planulae and cultured primary cells and its environmental contamination in Hawaii and the U.S. Virgin Islands. Arch. Environ. Contam. Toxicol. 70 (2), 265–288.
English, D.R., et al., 1998. Case-control study of sun exposure and squamous cell carcinoma of the skin. Int. J. Cancer 77 (3), 347–353.
Fabricius, K.E., 2005. Effects of terrestrial runoff on the ecology of corals and coral reefs: review and synthesis. Mar. Pollut. Bull. 50, 125–146.
Farberg, A.S., et al., 2016. Online survey of US dermatologist's sunscreen opinions: perceptions, recommendation factors, and self-usage. J. Drugs Dermatol. 15 (9), 1121–1123.
Green, A.C., et al., 2011. Reduced melanoma after regular sunscreen use: randomized trial follow-up. J. Clin. Oncol. 29 (3), 257–263.
He, T., et al., 2019a. Comparative toxicities of four benzophenone ultraviolet filters to two life stages of two coral species. Sci. Total Environ. 651 (pt 2), 2391–2399.
He, T., et al., 2019b. Toxicological effects of two organic ultraviolet filters and a related commercial sunscreen product in adult corals. Environ. Pollut. 245, 462–471.
Heron, S.F., et al., 2018. Impacts of Climate Change on World Heritage Coral Reefs: Update to the First Global Scientific Assessment. UNESCO World Heritage Centre, Paris available at. https://www.icriforum.org/sites/default/files/265625e.pdf.
Hughes, T.P., et al., 2017. Global warming and recurrent mass bleaching of corals. Nature 543 (7645), 373–377. https://doi.org/10.1038/nature2170.
Johnsen, E.C., 2018. Toxicological Effects of Commercial Sunscreens on Coral Reef Ecosystems: New Protocols for Coral Restoration. Nova Southeastern Univ, NSUWorks https://nsuworks.nova.edu/cnso_stucap/335/.
Marques, J.A., et al., 2019. Environmental health in southwestern Atlantic coral reefs: geochemical, water quality and ecological indicators. Sci. Total Environ. 651 (Pt 1), 261–270.
Mitchelmore, C., et al., 2019. Occurrence and Distribution of UV-Filters and Other Anthropogenic Contaminants in Coastal Surface Water, Sediment, and Coral Tissue from Hawaii.
National Aeronautics and Space Administration (NASA), d. https://earthobservatory.nasa.gov/images/88057/warm-seas-lead-to-extensive-coral-bleaching.
National Oceanic and Atmospheric Administration (NOAA), d. https://aamboceanservice.blob.core.windows.net/oceanservice-prod/facts/coralbleaching.pdf.
Olsen, C.M., et al., 2018. How many melanomas might be prevented if more people applied sunscreen regularly? Br. J. Dermatol. 178 (1), 140–147.
Preston, D.S., Stern, R.S., 1992. Nonmelanoma cancers of the skin. N. Engl. J. Med. 327 (23), 1649–1662.
Reef Safe, 2016. Coral testing – proven non-toxic to tested corals. available at. https://www.reefsafesun.com/pages/real-science.
Staley, C., et al., 2017. Differential impacts of land-based sources of pollution on the microbiota of Southeast Florida Coral reefs. Appl. Environ. Microbiol. 83 (10) e03378–16.
Tsui, M.M.P., et al., 2017. Occurrence, distribution, and fate of organic UV filters in coral communities. Environ. Sci. Technol. 51 (8), 4182–4190.
Van der Pols, J.C., et al., 2006. Prolonged prevention of squamous cell carcinoma of the skin by regular sunscreen use. Cancer Epidemiol. Biomark. Prev. 15 (12), 2546–2548.
Watts, C.G., et al., 2018. Sunscreen use and melanoma risk among young Australian adults. JAMA Dermatol. 154 (9), 1001–1009.
Sharp *et al.*, 2017 unpublished personal communication as Cited in Sweden Ministry of the Environment and Energy, 2018 Impacts of Sunscreens on Coral Reefs.

Statement from the Consumer Healthcare Products Association (CHPA) and the Personal Care Products Council (PCPC) Regarding Sunscreen Ingredient Ban

Feb 05, 2019

FOR IMMEDIATE RELEASE

Contacts: Mike Tringale, 202.429.3520, mtringale@chpa.org

Lisa Powers, 202.466.0489, powersl@personalcarecouncil.org

"The Consumer Healthcare Products Association (CHPA) and Personal Care Products Council (PCPC) are disappointed with the action taken by the Key West City Commission to ban certain sunscreen ingredients found in numerous sunscreens, cosmetics, shampoos, lip balms, and other health and personal care products. While we respect the emotion around coral reef decline, the ban represents a bad policy that is not based on scientific evidence. This ban is unlikely to have a positive effect on Florida's coral but it will have a profound negative impact on the health and wellbeing of residents and visitors in Key West.

"Oxybenzone and octinoxate contribute to broad-spectrum protection from the effects of both UVA and UVB rays. UVA and UVB rays contribute to skin damage, skin aging, and melanoma, the leading cause of skin cancer-related deaths. Manufacturers, health professionals, and many others are opposed to a ban on these ingredients which provide critical defense against excess ultraviolet (UV) radiation exposure. Banning these ingredients will drastically – and unnecessarily – reduce the selection of safe and effective sunscreens and other products available to residents and visitors in Key West.

"There is no definitive scientific evidence that products containing oxybenzone or octinoxate damage coral in natural environments like Key West, nor any evidence that banning these ingredients improves the plight of coral. The ingredient ban in Key West ignores the real causes of coral decline according to scientists in Florida and from around the world: global warming, agricultural runoff, sewage, and overfishing. Public policy that will likely adversely impact public health should not be based on a limited number of exploratory lab-based studies alone.

"Oxybenzone and octinoxate, found in the majority of sunscreens in the U.S., are safe and effective over-the-counter (OTC) active ingredients recognized by the Food and Drug Administration (FDA) as an important aide in decreasing the risk of developing skin cancer – the most common cancer in the U.S."

The Consumer Healthcare Products Association (CHPA) is the 138-year-old national trade association representing the leading manufacturers and marketers of over-the-counter (OTC) medicines and dietary supplements. Every dollar spent by consumers on OTC medicines saves the U.S. healthcare system $6-$7, contributing a total of $102 billion in savings each year. CHPA is committed to empowering self-care by preserving and expanding choice and availability of consumer healthcare products. www.chpa.org

Based in Washington, D.C., the Personal Care Products Council is the leading national trade association representing the global cosmetic and personal care products industry. Founded in 1894, PCPC's 600 member companies manufacture, distribute, and supply the vast majority of finished personal care products marketed in the U.S. As the makers of a diverse range of products millions of consumers rely on every day, from sunscreens, toothpaste and shampoo to moisturizer, lipstick and fragrance, personal care products companies are global leaders committed to product safety, quality and innovation.

# # #

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About Us

Leadership

1620 L Street, NW, Suite 1200
Washington, D.C. 20036

Phone: (202) 331-1770
Fax: (202) 331-1969

Contact Us
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Personal Care Products Council
Committed to Safety, Quality & Innovation

FOR IMMEDIATE RELEASE
October 22, 2015

Contact: Lisa Powers, (202) 466-0489 or Lauren Brady, (202) 454-0316

Statement by Iain Davies, PhD, Senior Environmental Scientist
The Personal Care Products Council
In Response to Study on Sunscreens and Coral Reefs

Washington, D.C. – "Benzophenone-3 (BP-3; oxybenzone) is an important sunscreen ingredient found in many personal care products and is designed to protect people against the damaging effects of ultraviolet (UV) light. In fact, according to the American Academy of Dermatology (AAD), oxybenzone is one of the few available sunscreen ingredients that effectively protect skin from both UVA and UVB rays that can contribute to skin cancer and premature skin aging.

"A study published recently in *Archives of Environmental Contamination and Toxicology* suggests that this common sunscreen ingredient could be harmful to coral and contributing to the decline of reefs around the world. This conclusion is based upon research conducted under laboratory conditions, which do not accurately reflect the complexity of the natural marine environment.

"Degradation of the world's coral reefs is a serious concern. According to the U.S. National Oceanic and Atmospheric Administration's (NOAA) Coral Reef Conservation Program, coral reefs are threatened by an increasing array of impacts – primarily from global climate change, unsustainable fishing and other factors. There is no scientific evidence that under naturally-occurring conditions, sunscreen ingredients, which have been safely used around the world for decades, are contributing to this issue.

"Our greatest concern is that this report may result in fewer people wearing sunscreens. In fact, a recent survey by the Centers for Disease Control and Prevention (CDC) published in the *Journal of the American Academy of Dermatology* found that approximately 43% of men and 27% of women never use sunscreen on their faces or other exposed skin. This is particularly concerning when we consider:

- Every year, there are more than 63,000 new cases of melanoma, the deadliest form of skin cancer, resulting in nearly 9,000 deaths;
- Skin cancer is the most commonly diagnosed cancer in the United States, with 5 million people treated each year;
- More than 1 out of every 3 Americans reports getting sunburned each year. Sunburn is a clear sign of overexposure to the sun's UV rays, a major cause of skin cancer – a single bad burn in childhood doubles the risk of developing melanoma later in life.

(MORE)

"We all can play an important role in the fight against skin cancer. In addition to FDA, the Centers for Disease Control and Prevention (CDC), the U.S. Surgeon General, AAD, the Skin Cancer Foundation and health care professionals worldwide all emphasize that using sunscreens is a critical part of a safe sun regimen. The dangers of unprotected sun exposure are clear and universally recognized by public health professionals and dermatologists.

"As sunscreen manufacturers, our goal is to provide Americans with access to a wide variety of safe, effective and innovative sunscreens to use as an important part of an overall sun safe regimen."

For more information on cosmetic and personal care products, please visit www.CosmeticsInfo.org.

Based in Washington, D.C., the Personal Care Products Council is the leading national trade association representing the global cosmetic and personal care products industry. Founded in 1894, the Council's more than 600 member companies manufacture, distribute, and supply the vast majority of finished personal care products marketed in the U.S. As the makers of a diverse range of products millions of consumers rely on every day, from sunscreens, toothpaste and shampoo to moisturizer, lipstick and fragrance, personal care products companies are global leaders committed to product safety, quality and innovation.

###

PARECER AO PROJETO DE LEI Nº 0077.0/2019

"Dispõe sobre a proibição de fabricação e comercialização de protetores solares com substâncias químicas tóxicas para recifes de corais."

Autor: Deputado Kennedy Nunes
Relator: Deputado Fabiano da Luz

I – RELATÓRIO

Trata-se de proposição de iniciativa parlamentar que dispõe sobre a proibição de registro, fabricação, importação, exportação, distribuição, comercialização, transporte, armazenamento e uso de protetores solares considerados tóxicos para os recifes de coral, no âmbito do Estado de Santa Catarina (art. 1º).

Da Justificação à proposição (fl. 04), trago à colação o seguinte:

> Os recifes de corais são os ecossistemas mais diversos dos mares por concentrarem, globalmente, a maior densidade de biodiversidade marinha.
> [...]
> Estima-se que 14 mil toneladas de protetor solar vão parar nos oceanos a cada ano, e desse total, de 4 a 6 mil toneladas se acumulam sobre recifes de corais de todo o planeta, o que demonstra a gravidade do problema, principalmente quando consideramos que as pesquisas mencionadas constataram que pequenas quantidades das substâncias estudadas são tóxicas para os corais.
> [...]

A matéria foi lida no Expediente da Sessão Plenária do dia 10 de abril de 2019 e, posteriormente, encaminhada a esta Comissão, na qual me foi designada a relatoria, nos termos do art. 130, VI, do Regimento Interno deste Poder.

No entanto, antes de emitir parecer conclusivo, solicitei, na forma regimental, diligência, aprovada pelo Colegiado, à Agência Nacional de Vigilância

Sanitária (ANVISA), órgão vinculado ao Ministério da Saúde, e ao Sindicato das Indústrias Químicas e Farmacêuticas do Estado de Santa Catarina (SINQFESC), para que encaminhasse a este Parlamento manifestação sobre a proposição em comento (fls. 05, 06 e 07).

Em resposta à diligência (fls. 13/16), o SINQFESC manifestou-se no sentido do arquivamento do Projeto de Lei em tela, juntando a manifestação da Associação Brasileira de Cosmetologia, que também conclui de forma contrária ao referido Projeto, nos seguintes termos:

> [...]
> Com base nas evidências científicas citadas, concluímos que:
>
> 1. Os estudos preliminares bem como o estudo publicado em 2016, utilizado como base para a proibição do uso dos protetores solares no Havaí e Palau, não refletem as condições reais em que vivem os recifes de corais, portanto não podem ser utilizados como ferramentas para definição de políticas públicas.
>
> 2. Os estudos evidenciam que, a maior causa do fenômeno de branqueamento dos corais é o aumento da temperatura dos oceanos, em função do aquecimento global. Portanto, proibir o uso de protetores solares contendo as substâncias citadas no PL 616/2019, não é uma medida efetiva que contribui para a preservação dos recifes de corais.
>
> 3. A redução do número de substâncias de proteção UV restringe as opções de proteção eficaz do consumidor contra os raios ultravioletas, aumentando assim a incidência de câncer de pele na população brasileira e acarretando aumento dos gastos do governo com saúde pública.
> [...]

É o relatório.

II – VOTO

Inicialmente, em consonância com o que preconiza o Regimento Interno desta Casa, em seu art. 144, I, nesta fase processual cabe analisar a admissibilidade da matéria quanto aos aspectos de constitucionalidade, legalidade, juridicidade, regimentalidade e de técnica legislativa, função pertinente à Comissão de Constituição e Justiça.

Da análise, de acordo com o art. 23, VI, da Constituição Federal, cabe aos Estados, junto com os demais entes federativos, proteger o meio ambiente e combater a poluição em qualquer de suas formas. Assim, independentemente de lei, compete-lhes dar efetividade a esse comando constitucional, buscando medidas administrativas tendentes à consecução dos seus objetivos.

Por sua vez, o art. 24, VI e VIII, também da CF/88, atribui competência concorrente à União, aos Estados e ao Distrito Federal para legislar sobre **conservação da natureza, proteção do meio ambiente e responsabilidade por dano ao meio ambiente.**

A proibição de fabricação e comercialização de protetores solares que contenham, em sua composição, as substâncias tóxicas especificadas no §1º do art. 1º, busca, exatamente, proteger o banco de colônias de coral submerso na Reserva Biológica Marinha do Arvoredo.

De outro vértice, não há que falar em violação ao princípio da livre iniciativa, inserido no art. 170, *caput,* da Carta Federal. Isso porque o referido princípio deve ser sopesado com outros, também constitucionais, como, por exemplo, o da defesa do meio ambiente, inclusive a este conferindo tratamento diferenciado, conforme o impacto ambiental causado**,** como no presente caso.

Entretanto, não obstante os bons propósitos visados pelo anteprojeto de lei em epígrafe, constato que este **padece de vício de inconstitucionalidade formal**, porquanto sua execução, aparentemente sem implicar em aumento de despesa, irá alterar a organização administrativa e o funcionamento da Secretaria de Estado da Agricultura e da Pesca e do Instituto do Meio Ambiente de Santa Catarina (IMA/SC), órgãos subordinados ao Poder Executivo, incidindo, assim, em violação ao princípio da independência e harmonia dos Poderes do Estado, inscrito no art. 2º da Constituição Federal e reproduzido pelo art. 32 da Carta Estadual, bem como em flagrante invasão de competência legiferante, visto que, conforme estatuído pelo art. 71, I e IV, “a”, da Carta Política Estadual, abaixo transcrito, a legitimidade para tal é privativa do Governador do Estado:

> Art. 71 — São atribuições privativas do Governador do Estado:
>
> I - exercer, com o auxílio dos Secretários de Estado, a direção superior da administração estadual;
> [...]
> IV - dispor, **mediante decreto**, sobre:
>
> a) **organização e funcionamento** da administração estadual, **quando não implicar aumento de despesa** nem criação ou extinção de órgãos públicos;
> [...]
> (grifado)

Nesse contexto, em face do vício de inconstitucionalidade apontado, dispensa-se a análise da proposta legislativa em causa quanto aos demais pressupostos de observância obrigatória por parte deste Colegiado.

Ante o exposto, com base nos arts. 144, I e 145, todos do Regimento Interno deste Poder, voto, no âmbito desta Comissão, pela **REJEIÇÃO** da tramitação processual do Projeto de Lei nº 0077.0/2019.

Sala da Comissão,

Deputado Fabiano da Luz
Relator

COM. DE CONSTITUIÇÃO E JUSTIÇA

Comissão de Constituição e Justiça Fls 165 RUBRICA

Folha de Votação

A Comissão de Constituição e Justiça, nos termos dos arts. 146, 149 e 150 do Regimento Interno,

☒ aprovou ☒ unanimidade ☐ com emenda(s) ☐ aditiva(s) ☐ substitutiva global
☐ rejeitou ☐ maioria ☐ sem emenda(s) ☐ supressiva(s) ☐ modificativa(s)

o RELATÓRIO do(a) Senhor(a) Deputado(a) Fabiano da Luz, referente ao processo PL./0077.0/2019, constante da(s) folha(s) número(s) 161 a 164.

OBS:

ABSTENÇÃO	VOTO FAVORÁVEL	VOTO CONTRÁRIO
Dep. Romildo Titon	Dep. Romildo Titon	Dep. Romildo Titon
Dep. Coronel Mocellin	Dep. Coronel Mocellin	Dep. Coronel Mocellin
Dep. Fabiano da Luz	Dep. Fabiano da Luz	Dep. Fabiano da Luz
Dep. Ivan Naatz	Dep. Ivan Naatz	Dep. Ivan Naatz
Dep. João Amin	Dep. João Amin	Dep. João Amin
Dep. Luiz Fernando Vampiro	Dep. Luiz Fernando Vampiro	Dep. Luiz Fernando Vampiro
Dep. Maurício Eskudlark	Dep. Maurício Eskudlark	Dep. Maurício Eskudlark
Dep. Milton Hobus	Dep. Milton Hobus	Dep. Milton Hobus
Dep. Paulinha	Dep. Paulinha	Dep. Paulinha

Despacho: dê-se o prosseguimento regimental.

Sala da Comissão, 15 de outubro de 2019.

Dep. Romildo Titon