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)

# 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

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

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

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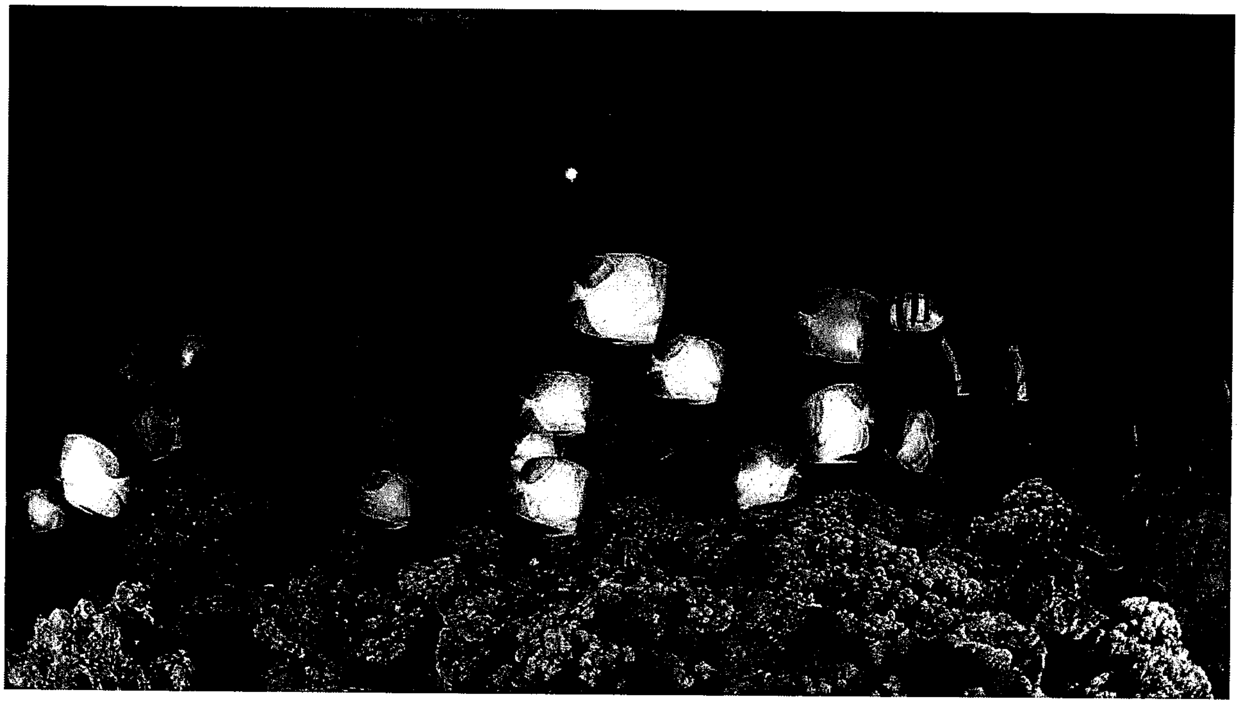

A diver in a reef near Molokini Crater, Maui, Hawaii.

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***

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**

# 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]**

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OPEN ACCESS

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**Data Availability Statement:** The databases described in the paper are available via figshare (https://figshare.com/projects/Coral_Bleaching_Database_V1/19753) and at http://simondonner.com/bleachingdatabase/.

**Funding:** The research was funded by a NSERC Discovery Grant (SD Donner) and UBC AURA award (SD Donner). Support for SF Heron was from the NOAA Coral Reef Conservation Program, via a contract between NOAA Coral Reef Watch and Global Science and Technology, Inc. The funders had no role in the study design, data collection and

## 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

https://doi.org/10.1371/journal.pone.0175490.t002

"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 $0.04^\circ \times 0.04^\circ$ 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 $0.04^\circ \times 0.04^\circ$ 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 $0.04^\circ \times 0.04^\circ$ 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 $0^\circ$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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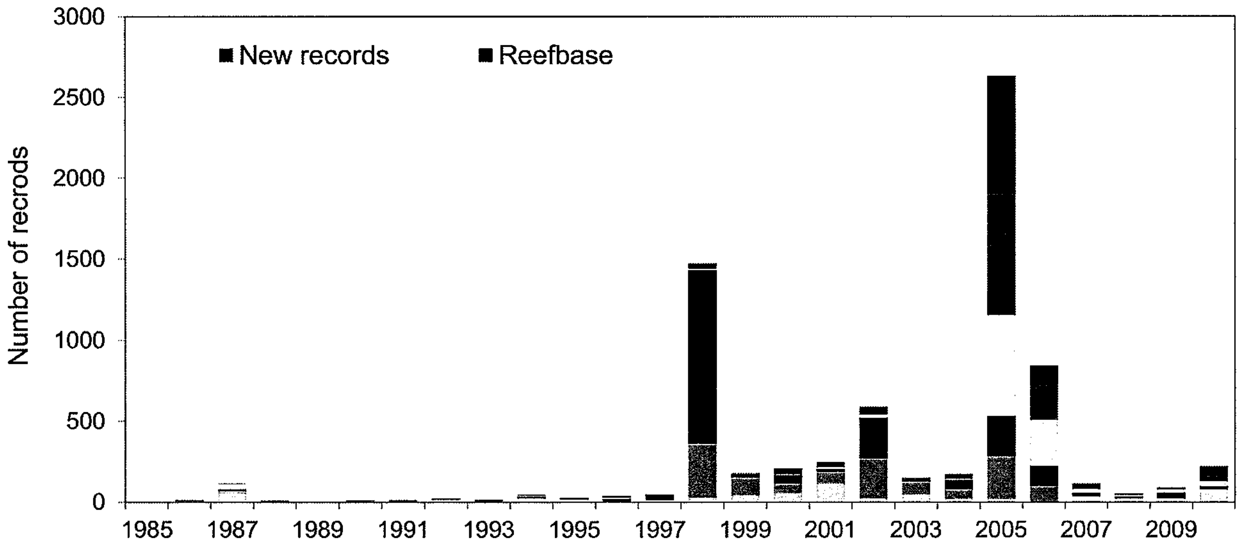


**Fig 1. Annual number of bleaching observations for 1985–2010.** Blue bars represent original ReefBase reports; orange bars represent new reports. Shading reflects bleaching level, from mild (1–10%) or unknown extent of bleaching (levels 1 and -1 in Table 2, lightest colour) to severe (>50%) bleaching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

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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 $0.04^{\circ} \times 0.04^{\circ}$ 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

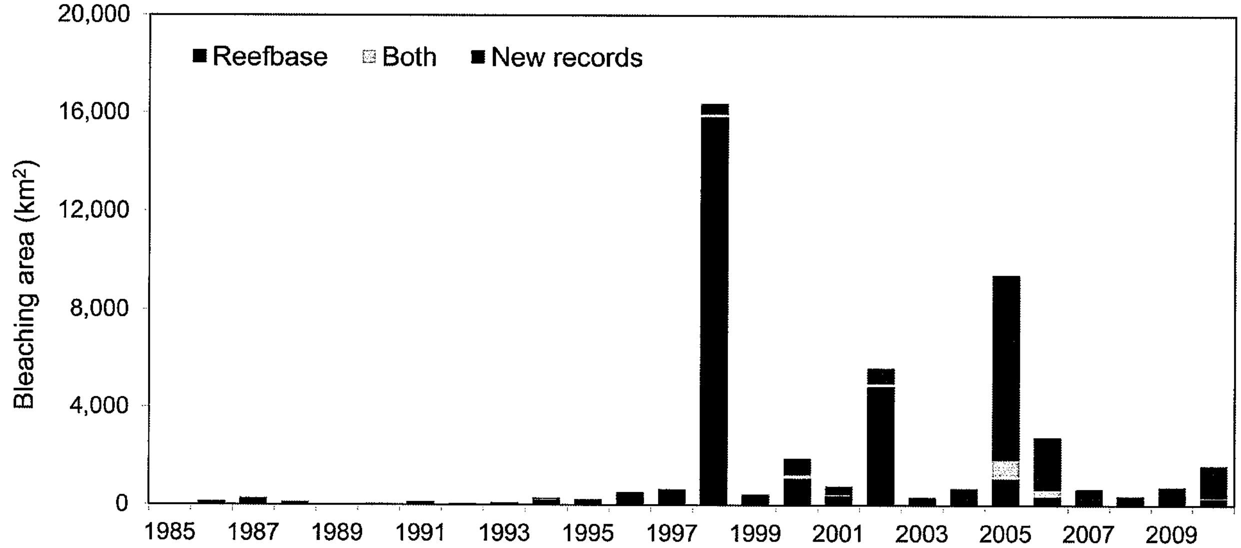


**Fig 2. Annual area of moderate and severe (level 2 and 3) bleaching observations for 1985–2010.** The area is computed from 0.04° × 0.04° latitude-longitude grid cells containing original ReefBase reports (navy blue), new records (orange), and those in both datasets (grey).

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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,

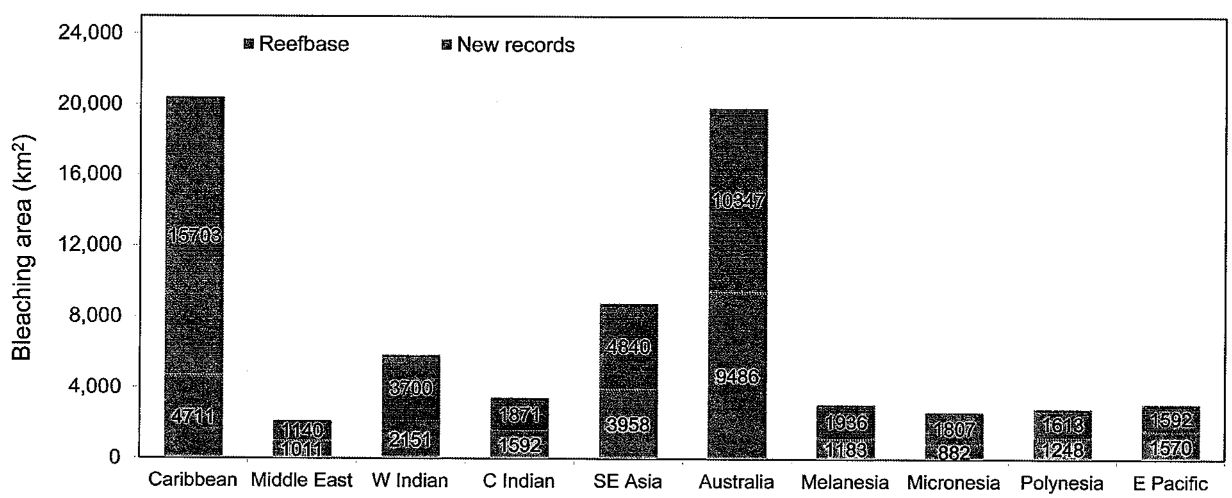


**Fig 3. Total area ($km^2$) of moderate and severe (level 2 and 3) bleaching by region over the 1985–2010 period.** The area is computed based on 0.04° × 0.04° latitude-longitude grid cells representing original ReefBase reports (blue) and new reports (orange).

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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 |

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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

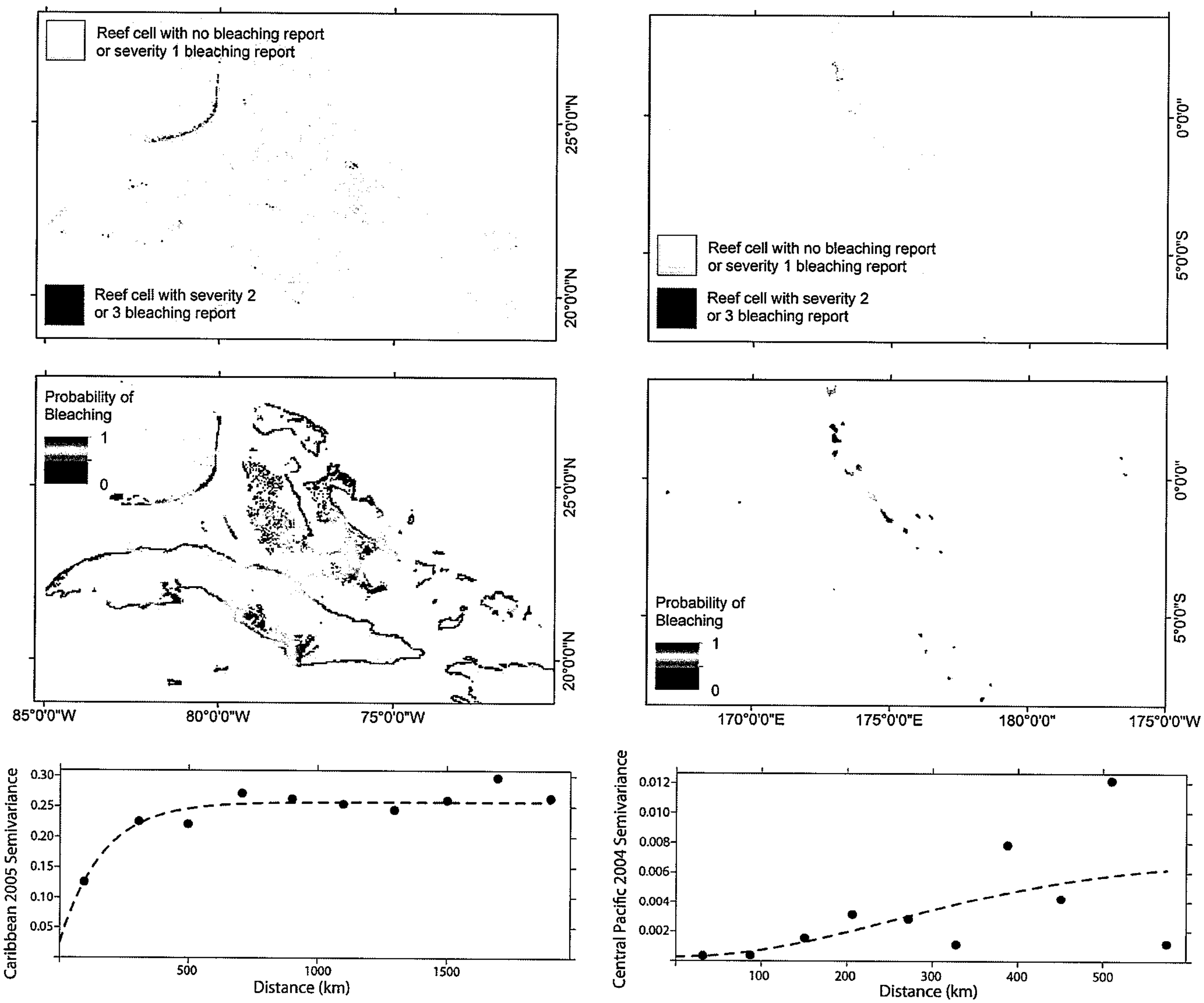


**Fig 4. Examples of bleaching observations and probabilities for the Caribbean in 2005 (a,c,e) and central-west equatorial Pacific in 2004 (b,d,f).** Top panels (a,b) show the raw observations of moderate and severe bleaching (level 2 and 3) from the database; middle panels (c,d) show the interpolated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

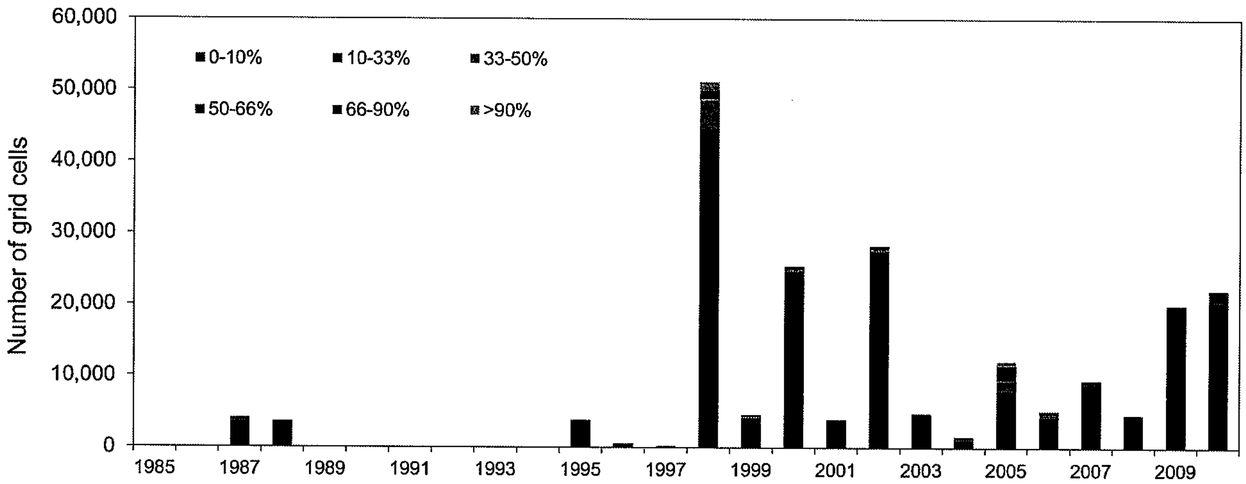


**Fig 5. Number of 0.04° × 0.04° latitude-longitude grid cells with different estimated probabilities of bleaching from 1985–2010.** Note that the density of bleaching reports was too low in years 1985, 1986, and 1989–94 for the interpolation to succeed.

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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

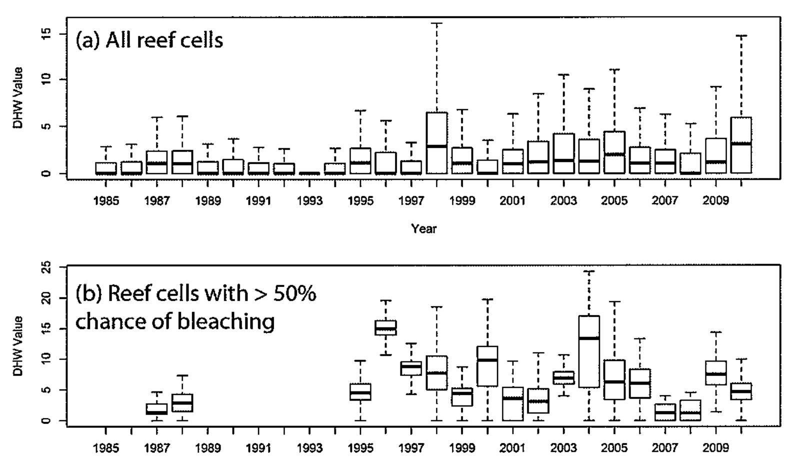


**Fig 6. Mean, quartile range, and 5th and 95th percentile of reef area-weighted annual maximum DHW of a) all reef cells and b) reef cells with at least 50% probability of bleaching (more likely than not) from 1985–2010.** Note that the density of bleaching reports was too low in years 1985, 1986, and 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 $0.04° \times 0.04°$ 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 dataset 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° × 0.04° 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 backfilling the database with older missing reports, and thus better inform the spatial modeling of bleaching probabilities.

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**Supervision:** SDD.

**Validation:** SDD.

**Visualization:** SDD GJMR.

**Writing – original draft:** SDD.

**Writing – review & editing:** SDD GJMR SFH.

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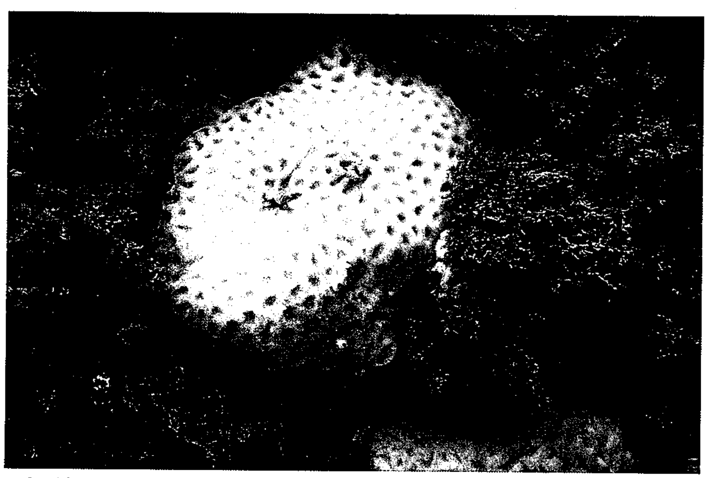
# Cientistas detectam imenso branqueamento de corais no sudeste brasileiro

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."

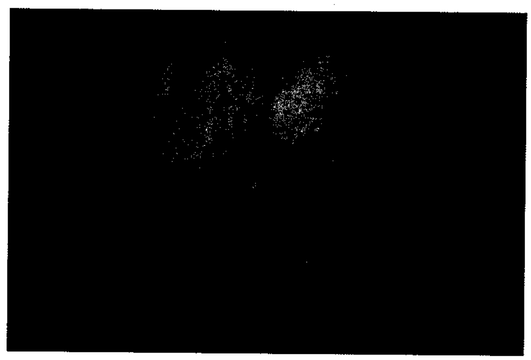


Foto: Thomás Banha.

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."

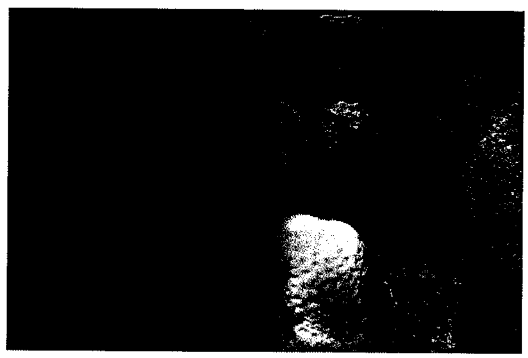


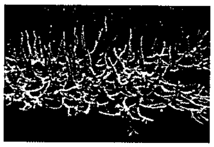
Foto: Thomás Banha.

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

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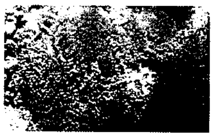
## Os corais mais ameaÃ§ados do planeta



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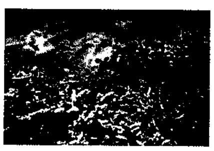
## Peixes de corais sofrem de â€œsÃndrome de Doryâ€□



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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Review Article

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

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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-

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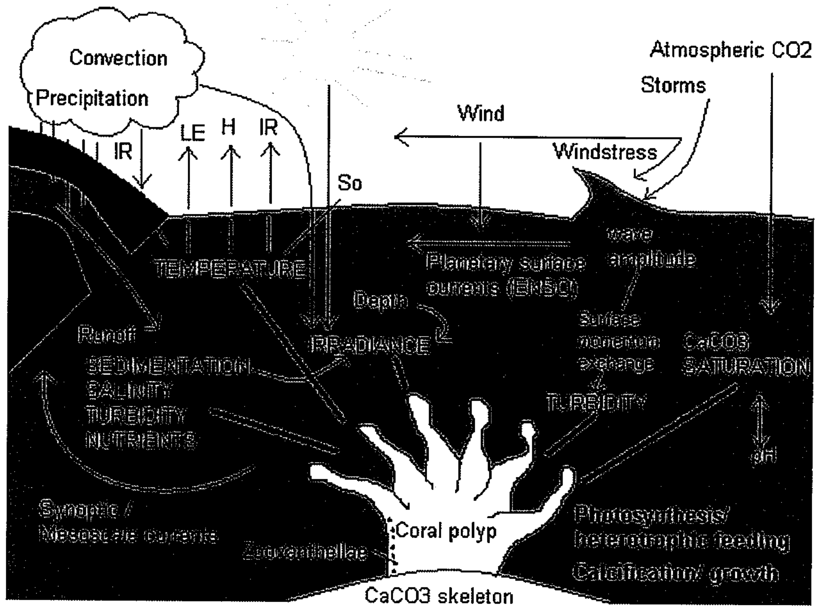


**Fig. 1.** Schematic diagram summarizing key meteorological processes and coral requirements controlling calcification, photosynthesis, and survival. Adapted from Crabbe et al. (2008a) and Crabbe et al. (2008b).

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, 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).

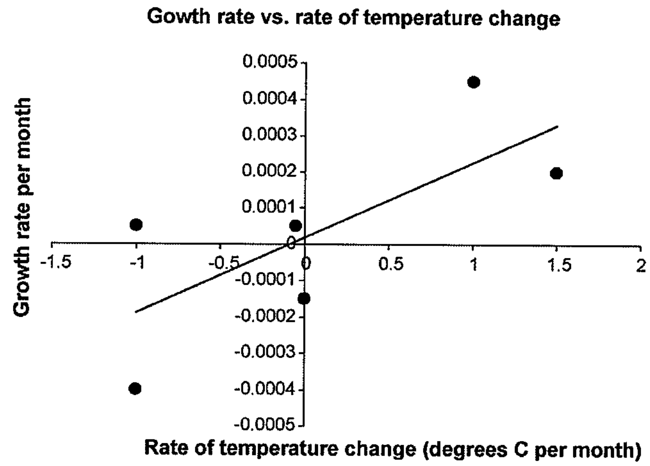


**Fig. 2.** Influence of the rate of change of temperature on the growth rate of an *Acropora palmata* coral colony from Curaçao (Bak, 1976). $R^2 = 0.53$. For details see the text.

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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LETTERS
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nature climate change

# Ecological memory modifies the cumulative impact of recurrent climate extremes

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**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-

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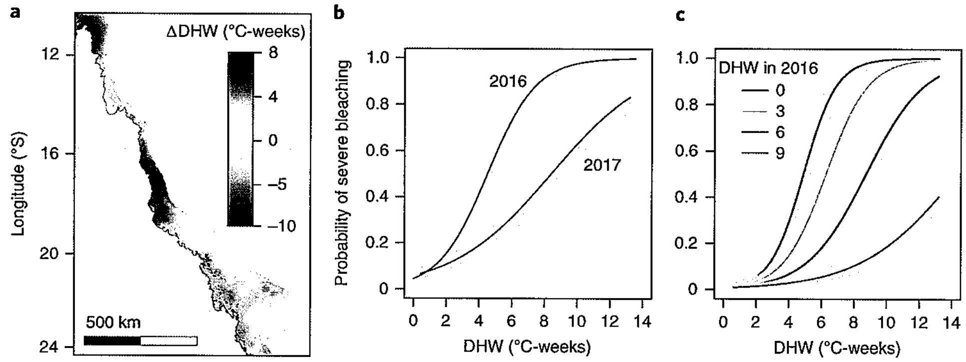


**Fig. 1 | The bleaching response of corals on the Great Barrier Reef was diminished in a second summer heatwave, despite higher exposure to heat stress. a**, Change in cumulative heat exposure on the Great Barrier Reef, measured on 3,863 individual reefs by satellites as DHW, in 2017 compared with 2016. 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

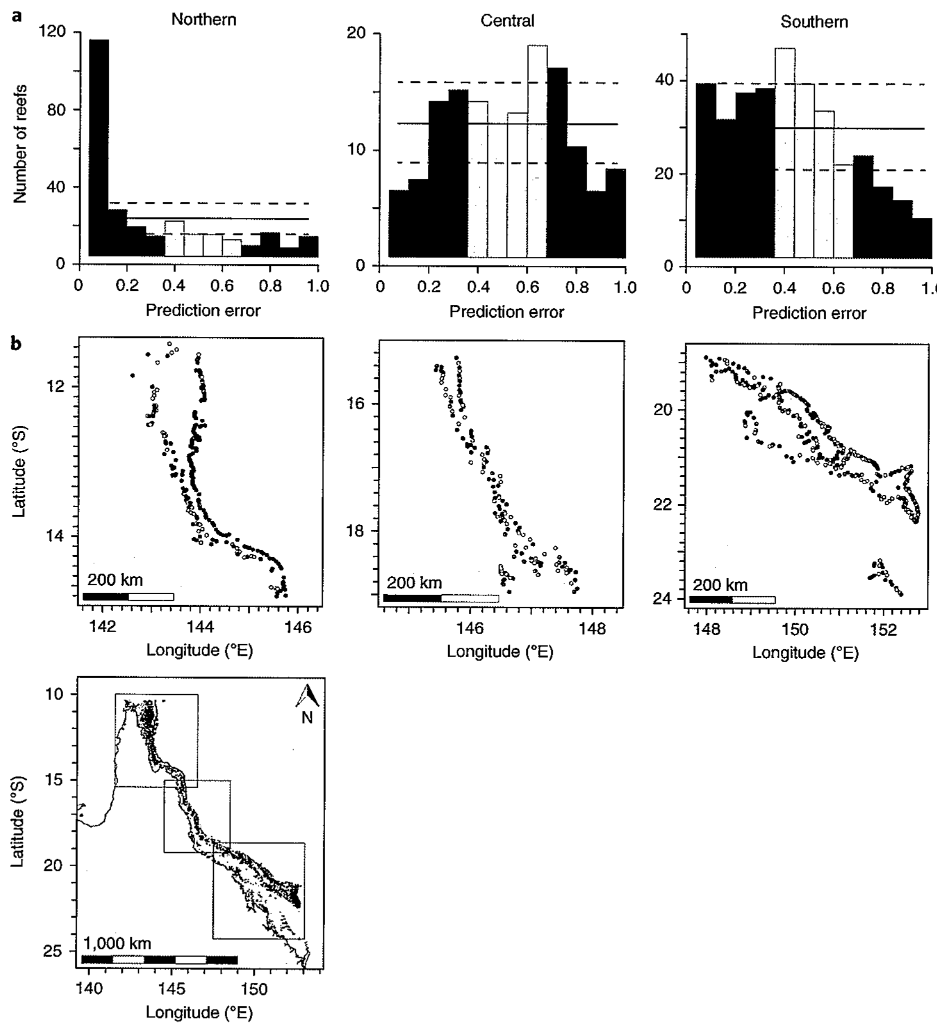


**Fig. 2 | Ecological memory of the 2016 bleaching event unfolds differently in the northern, central and southern Great Barrier Reef. a**. Histograms of standardized errors in predicting the 2017 bleaching event based on the 2016 response curve, in northern, central and southern regions of the Great 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

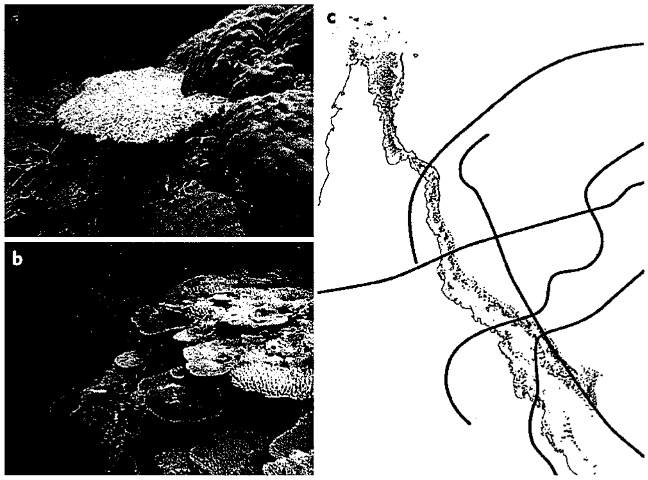

**Fig. 3 | Legacy effects of multiple disturbance. a**, Disproportionate loss of abundant, susceptible tabular and branching *Acropora* corals on northern reefs in 2016, compared with more resistant mound-shaped *Porites*, increased community resistance to recurrent bleaching in 2017. **b**, Corals in 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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## 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/).

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| ☐ | ☒ | The exact sample size (*n*) for each experimental group/condition, given as a discrete number and unit of measurement |
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| ☐ | ☒ | A full description of the statistics including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals) |
| ☒ | ☐ | For null hypothesis testing, the test statistic (e.g. *F*, *t*, *r*) with confidence intervals, effect sizes, degrees of freedom and *P* value noted<br>*Give P values as exact values whenever suitable.* |
| ☒ | ☐ | For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings |
| ☒ | ☐ | For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes |
| ☐ | ☒ | Estimates of effect sizes (e.g. Cohen's *d*, Pearson's *r*), indicating how they were calculated |
| ☒ | ☐ | Clearly defined error bars<br>*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 |

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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 |