Supplementary Information for

Global declines in coral reef calcium carbonate production under ocean acidification and warming

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Other supplementary materials for this manuscript include the following:

Datasets S1 to S2

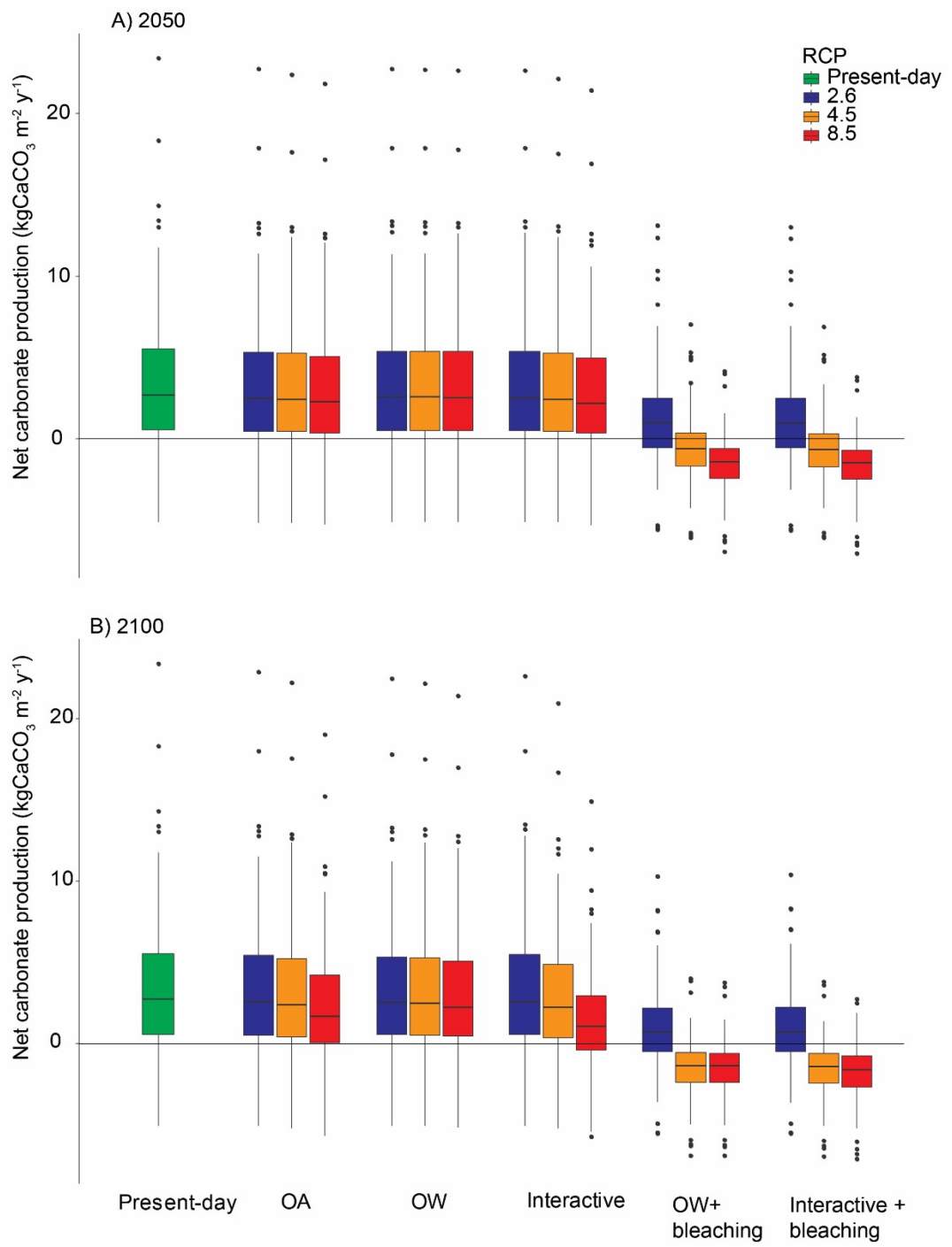

Fig. S1. Net carbonate production (kg $CaCO_3$ m^{-2} y^{-1}) at present-day and under 15 additional scenarios: ocean acidification (OA), ocean warming (OW) the interaction between OA and OW, and examples of the same scenarios with reduced coral cover due to mass coral bleaching, under three emissions scenarios (RCP2.6, 4.5 and 8.5) by 2050 and 2100. Median responses of all 199 sites on 183 reefs. Quartiles, 95% whiskers, and outliers presented.

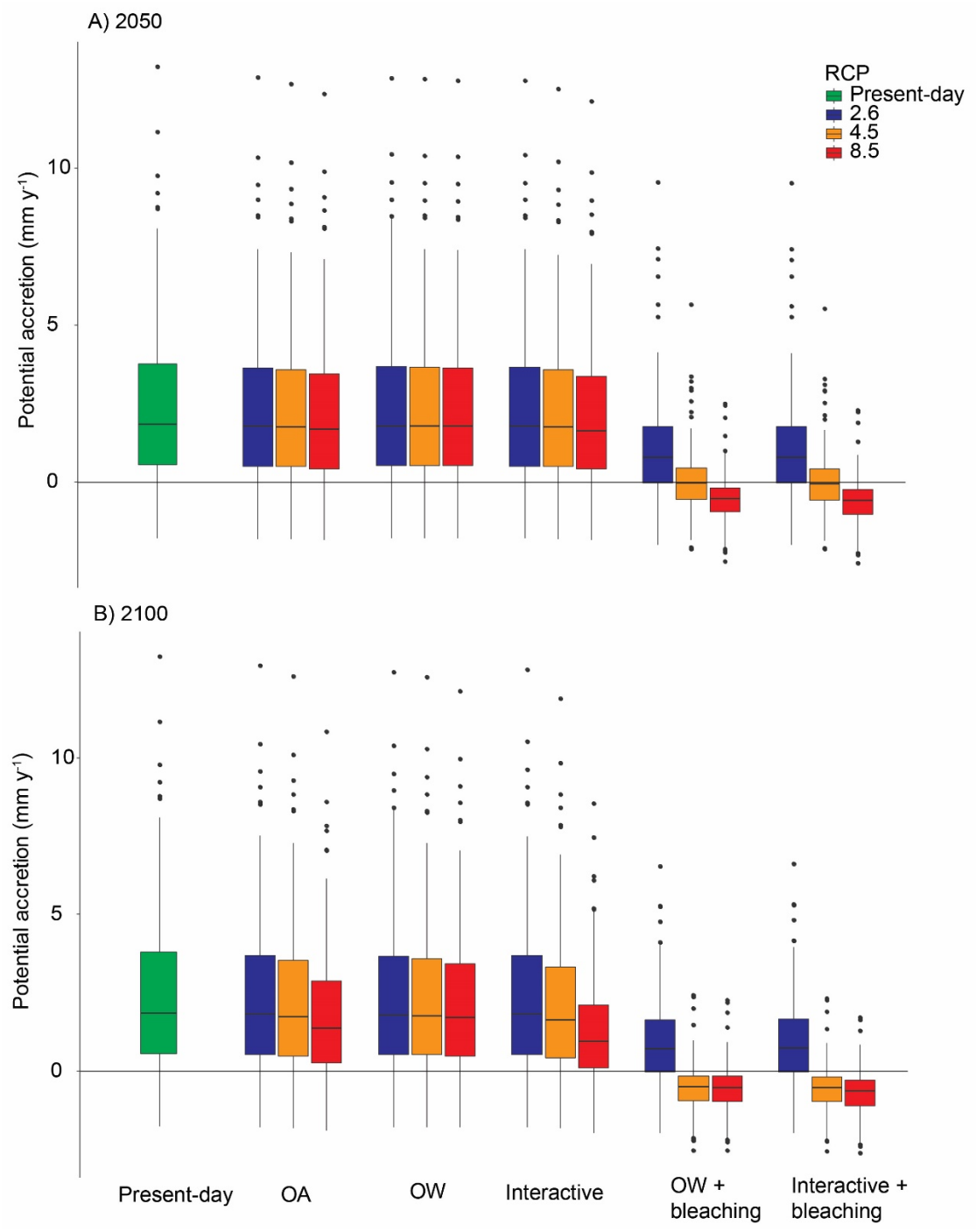

Fig. S2. Reef accretion rates (mm y^{-1}) at present-day and under 15 additional scenarios: ocean acidification (OA), ocean warming (OW) the interaction between OA and OW, and examples of the same scenarios with reduced coral cover due to mass coral bleaching, under three emissions scenarios (RCP2.6, 4.5 and 8.5) by 2050 and 2100. Median responses of all 199 sites on 183 reefs. Quartiles, 95% whiskers, and outliers presented.

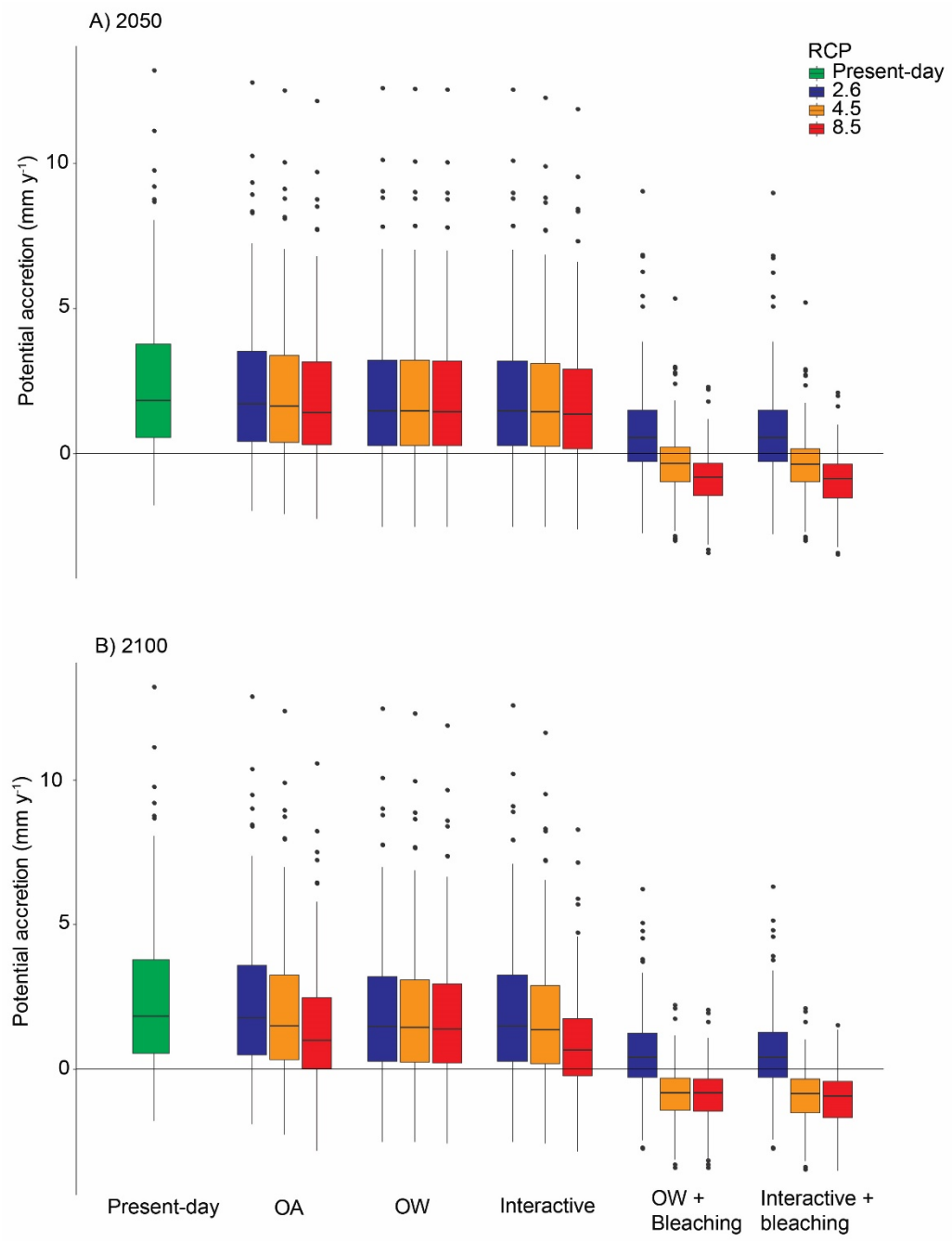

Fig. S3. Reef accretion rates (mm y^{-1}) at present-day and under 15 additional scenarios that include sediment dissolution rates, assuming equal dissolution on reefs as measured in lagoons: ocean acidification (OA), ocean warming (OW) the interaction between OA and OW, and examples of the same scenarios with reduced coral cover due to mass coral bleaching, under three emissions scenarios (RCP2.6, 4.5 and 8.5) by 2050 and 2100. Median responses of all 199 sites on 183 reefs. Quartiles, 95% whiskers, and outliers presented.

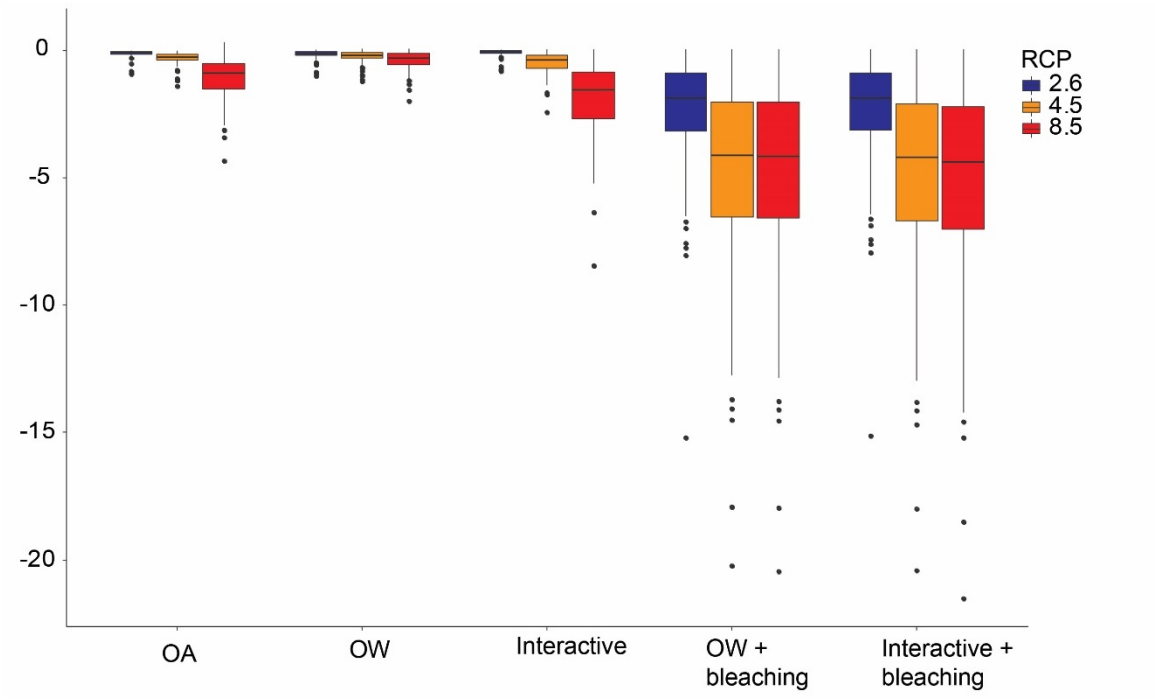

Fig. S4. Declines in net carbonate production (kg $CaCO_3$ m^{-2} y^{-1}) by 2100, projected including solely metabolic effects on calcification and bioerosion processes (ocean acidification [OA], ocean warming [OW], and their interactive effects [interactive]), as well as the effects of mass coral bleaching (under ocean warming [OW+ bleaching] and the interactive effects of ocean warming and acidification [Interactive + bleaching]). All scenarios are displayed under RCP2.6, 4.5 and 8.5. Medians, 75% quartiles, 95% whiskers and outliers displayed.

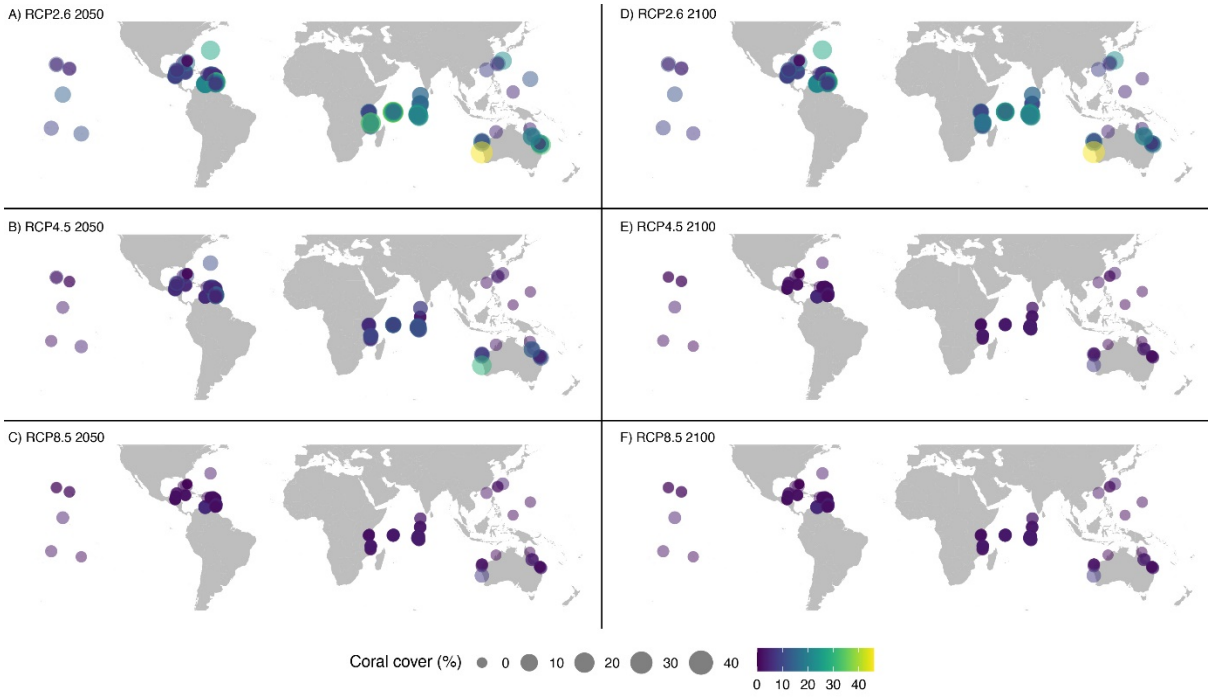

Fig. S5: Coral cover at our 183 reefs we use in our model by 2050 and 2100 under projections of interactive effects of ocean acidification, warming and mass coral bleaching by 2050 at A) RCP2.6, B) RCP4.5 C) RCP8.5 and by 2100 under D) RCP2.6, E) RCP4.5, F) RCP8.5.

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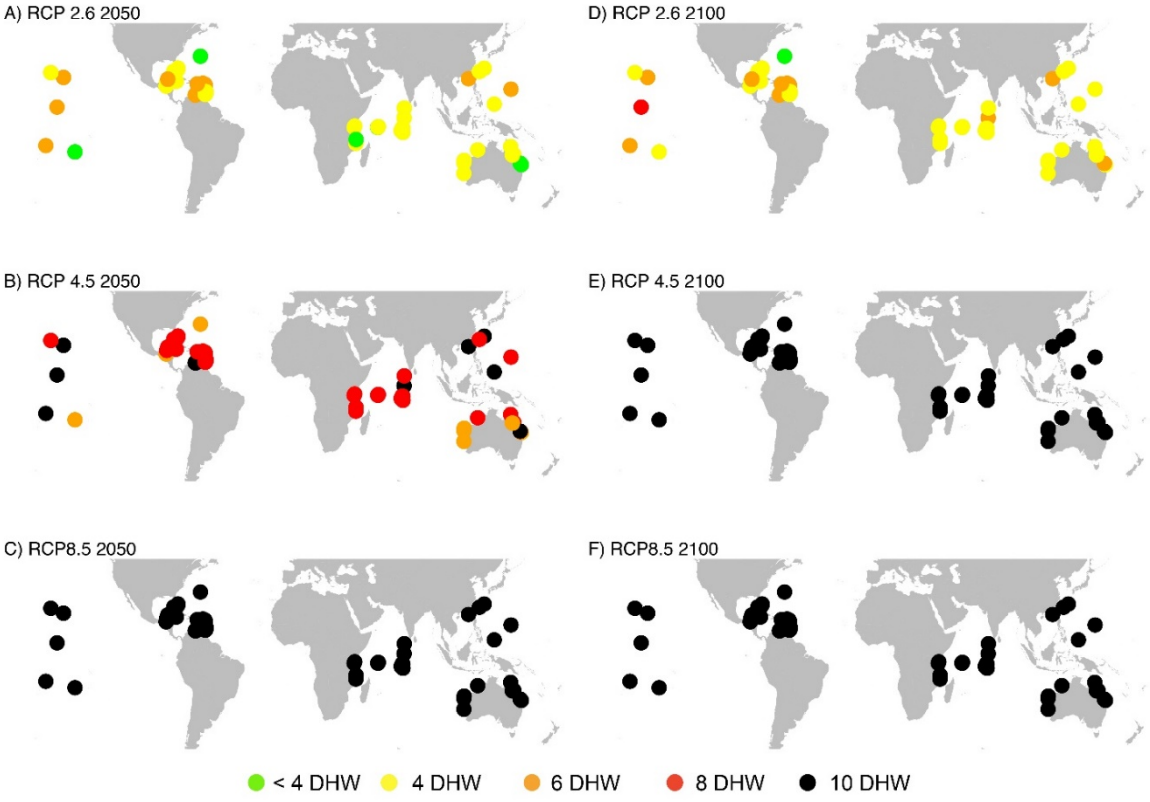

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105 **Fig. S6.** Frequency of twice-decade Degree Heating Weeks (DHW) events predicted at our
106 183 reefs we use in our model by 2050 and 2100. A) present-day, and projections of
107 interactive effects of ocean acidification, warming and mass coral bleaching by 2050 at B)
108 RCP2.6, C) RCP4.5 D) RCP8.5 and by 2100 under F) RCP2.6, G) RCP4.5, H) RCP8.5.

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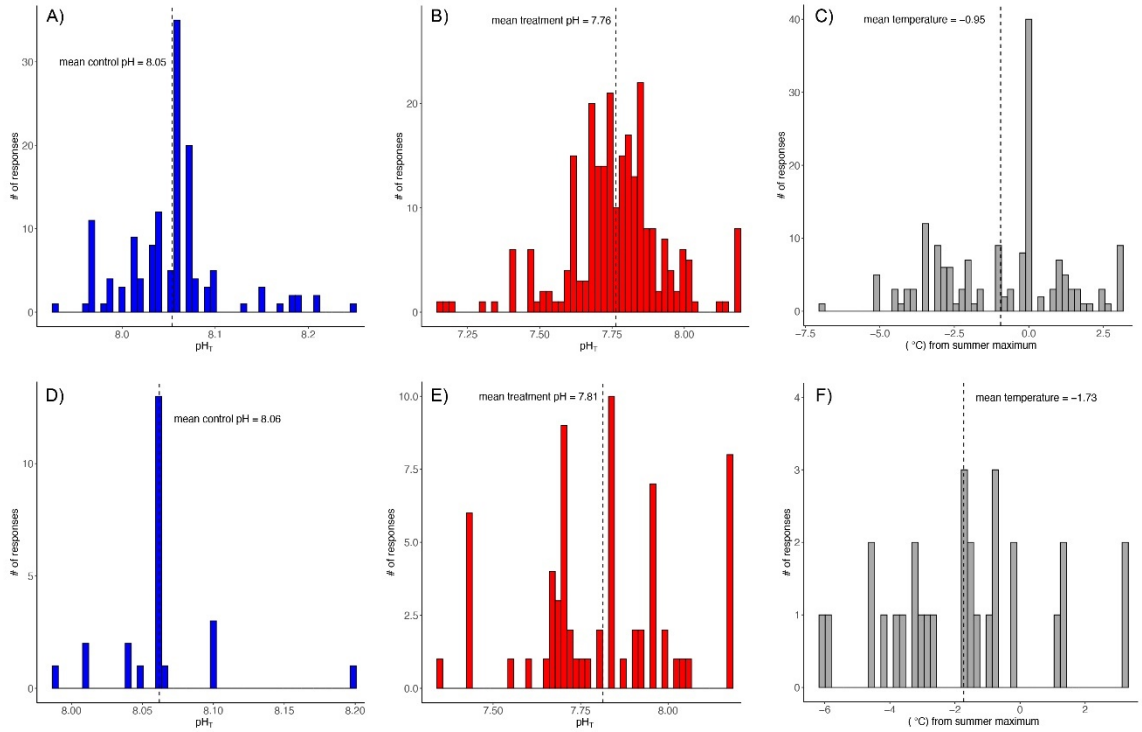

Fig. S7. Frequency of responses measured: A) control coral responses to pCO_2, B) "treatment" coral responses to pH , C) coral responses to temperature from the summer maximum at collection location, C) control coralline algal responses to pH, E) "treatment" coralline algal responses to pH , F) coralline algal responses to temperature from the summer maximum at collection location.

Table S1. List of studies used to determine the response of calcifying coral reef taxa to ocean warming, acidification, and their interaction. Also listed are studies with *in situ*, or similar calcification based on hydrochemical methods, used to inform reef-scale responses.

Reference	Use of data here*	Scenario, for meta-analysis	Location, for *in situ* data only
Achlatis et al. (2017)(1)	Bioerosion	OA and OW	
Albright and Langdon (2011)(2)	Coral calcification	OA	
Albright et al. (2010)(3)	Coral calcification	OA	
Albright et al. (2013)(4)	Net carbonate production		Davies Reef
Albright et al. (2015)(5)	Net carbonate production		Heron Island
Anderson et al. (2017)(6)	Coral calcification, *in situ*		Great Barrier Reef
Anlauf et al. (2011)(7)	Coral calcification	OA and OW	
Anthony et al. (2008)(8)	Coralline algal and coral calcification	OA and OW	
Atkinson and Grigg (1984)(9)	Net carbonate production		French Frigate Shoals
Bahr et al. (2016)(10)	Coral calcification	OA and OW	

Bedwell-Ivers et al. (2016)(11)	Coral calcification	OA	
Béraud et al. (2014)(12)	Coral calcification	OW	
Biscéré et al. (2015)(13)	Coral calcification	OA	
Brien et al. (2015)(14)	Coral calcification	OA	
Browne et al. (2013)(15)	Net carbonate production		Middle Reef and Paluma Shoals
Castillo et al. (2014)(16)	Coral calcification	OA and OW	
Chauvin et al. (2011)(17)	Coral calcification	OA	
Chazottes et al. (1995)(18)	Bioerosion, present day		Moorea
Chisholm et al. (2000)(19)	Coralline algal calcification, *in situ*		Lizard Island
Cohen et al. (2017)(20)	Coral calcification	OA	
Comeau et al. (2013)(21)	Coral calcification	OA	
Comeau et al. (2013)(22)	Coralline algal and coral calcification	OA	Pacific (non GBR sites)
Comeau et al. (2014)(23)	Coralline algal and coral calcification	OA and OW	
Comeau et al. (2014)(24)	Coralline algal and coral calcification	OA	Pacific (non GBR sites)
Comeau et al. (2014)(25)	Coralline algal and coral calcification	OA	Hawaii and French Frigate Shoals sites
Comeau et al. (2015)(26)	Sediment dissolution	OA	
Comeau et al. (2016)(27)	Coralline algal and coral calcification,	OA and OW	
Comeau et al. In SI data 2	Net carbonate production		Tallon Island
Cornwall et al. (2018)(28)	Coralline algal and coral calcification		OA
Cornwall et al. In SI data 2	Coralline algal and coral calcification		Tallon Island
Cornwall et al. In SI data 2	Coralline algal calcification		Ningaloo
Courtney et al. (2016)(29)	Net carbonate production and coral calcification		Bermuda
Cyronak et al. (2013)(30)	Sediment dissolution	OA	
Davies and Hutchings (1983)(31)	Bioerosion, present day		Lizard Island
DeCarlo et al. (2015)(32)	Bioerosion, present day		
DeCarlo et al. (2017)(33)	Net carbonate production		Dongsha Atoll
Doo and Carpenter In SI data 2	Net carbonate production		Moorea
Doropolous et al. (2012)(34)	Coralline algal calcification	OA	

Doropolous et al. (2012)(35)	Coral calcification	OA	
Drenkard et al. (2013)(36)	Coral calcification	OA	
Dufault et al. (2012)(37)	Coral calcification	OA	
Dufault et al. (2013)(38)	Coral calcification	OA	
Edinger et al. (2000)(39)	Bioerosion, present day		
Edmunds (2005)(40)	Coral calcification	OW	
Edmunds (2011)(41)	Coral calcification	OA	
Edmunds and Yavid (2017)(42)	Coral calcification	OA	
Edmunds et al. (2011)(43)	Coral calcification	OW	
Edmunds et al. (2012)(44)	Coral calcification	OA and OW	
Enochs et al. (2014)(45)	Coral calcification	OA	
Enochs et al. (2015)(46)	Bioerosion	OA	
Enochs et al. (2016)(47)	Bioerosion, present day		
Evensen and Edmunds (2017)(48)	Coral calcification	OA	
Evensen et al. (2015)(49)	Coral calcification	OA	
Eyre et al. (2018)(50)	Sediment dissolution	OA	
Falter et al. (2012)(51)	Net carbonate production		Ningaloo
Fang et al. (2013)(52)	Bioerosion	OA and OW	
Foster et al. (2014)(53)	Coral calcification		Ningaloo
Foster et al. (2015)(54)	Coral calcification	OW	
Gao and Zheng (2010)(55)	Coralline algal calcification	OA	
Grottoli et al. (2014)(56)	Coral calcification	OW	
Hamylton (2014)(57)	Net carbonate production		Lady Elliot Island
Hoadley et al. (2016)(58)	Coral calcification	OA and OW	
Huang et al. (2014)(59)	Coral calcification	OA	
Houlbrèque et al. (2012)(60)	Coral calcification	OA	
Houlbrèque et al. (2015)(61)	Coral calcification	OA	
Hovarth et al. (2016)(62)	Coral calcification	OA and OW	
Hutchings et al. (1995)(63)	Bioerosion, present day		Lizard Island
Iguchi et al. (2012)(64)	Coral calcification	OA	
Iguchi et al. (2014)(65)	Coral calcification	OA	
Inoue et al. (2011)(66)	Coral calcification	OA and OW	
Johnson and Carpenter (2012)(67)	Coralline algal calcification	OA and OW	
Johnson et al. (2014)(68)	Coralline algal calcification	OA	
Johnson et al. (2014)(69)	Coralline algal calcification	OA	
Jokiel et al. (2008)(70)	Coralline algal calcification	OA	

Kaniewska et al. (2012)(71)	Coral calcification	OA	
Kato et al. (2014)(72)	Coralline algal calcification	OA	
Kavousi et al. (2015)(73)	Coral calcification	OA and OW	
Kavousi et al. (2015)(74)	Coral calcification	OA	
Kayanne et al. (2005)(75)	Net carbonate production		Palau and Shirado Reef
Kennedy and Diaz-Pulido In SI data 2	Coralline algal calcification, *in situ*		Great Barrier Reef
Kiene and Hutchings (1994)(76)	Bioerosion, present day		Lizard Island
Krief et al. (2010)(77)	Coral calcification	OA	
Koweek et al. (2015)(78)	Net carbonate production		Ofu
Koweek et al. (2015)(79)	Net carbonate production		Palmyra
Kuffner et al. (2008)(80)	Coralline algal calcification	OA	
Lantz et al. (2014)(81)	Net carbonate production		Hawaii
Lantz et al. (2017)(82)	Sediment dissolution	OW	
Lantz et al. (2017)(83)	Sediment dissolution	OA	
Lantz et al. (2018)(84)	Sediment dissolution	OW	
Lenz and Edmunds (2017)(85)	Coral calcification	OA and OW	
Levas et al. (2013)(86)	Coral calcification	OW	
Manzello et al. (2008)(87)	Bioerosion, present day		
Marubini and Atkinson (1999)(88)	Coral calcification	OA	
Marubini et al. (2003)(89)	Coral calcification	OA	
Muehllehner and Edmunds (2008)(90)	Coral calcification	OA and OW	
Nakamura et al. (2009)(91)	Net carbonate production		Shirado Reef
Nakamura et al. (2017)(92)	Coral calcification	OA	
Ohde and van Woesik (1999)(93)	Net carbonate production		Rukan-sho
Ohiki et al. (2013)(94)	Coral calcification	OA	
Okazaki et al. (2017)(95)	Coral calcification	OA and OW	
Ordoñez et al. (2014)(96)	Coralline algal calcification	OA	
Pari et al. (2002)(97)	Bioerosion, present day		Moorea
Perez et al. (2018)(98)	Net carbonate production		Heron Island and Saipan
Perry et al. (2018)(99)	Bioerosion, coralline and coral calcification, present day		Atlantic and Indian oceans.

			See source paper for sites.
Pettay et al. (2015)(100)	Coral calcification	OW	
Putnam and Edmunds (2011)(101)	Coral calcification	OW	
Renegar et al (2005)(102)	Coral calcification	OA	
Reyes-Nivia et al. (2013)(103)	Bioerosion	OA and OW	
Reyes-Nivia et al. (2014)(104)	Bioerosion	OA and OW	
Reynaud et al. (2003)(105)	Coral calcification	OA and OW	
Reynaud et al. (2007)(106)	Coral calcification	OW	
Ries et al. (2009)(107)	Coralline algal calcification	OA	
Rodrigues and Grottoli (2006)(108)	Coral calcification	OW	
Schoepf et al. (2013)(109)	Coral calcification	OA and OW	
Shaw et al. (2012)(110)	Net carbonate production		One Tree Island and Lady Elliot Island
Shaw et al. (2015)(111)	Net carbonate production		One Tree Island
Shaw et al. (2016)(112)	Coral calcification	OA and OW	
Short et al. (2014)(113)	Coralline algal calcification	OA	
Silbiger and Donohue (2015)(114)	Bioerosion	OA and OW	
Silverman et al. (2012)(115)	Net carbonate production		One Tree Island
Silverman et al. (2014)(116)	Net carbonate production		Lizard Island
Smith et al. (1981)(117)	Coral calcification, *in situ*		Houtman Abrolos
Smith et al. (2007)(118)	Coral calcification, *in situ*		Ofu
Stubler and Peterson (2016)(119)	Bioerosion	OA	
Stubler et al. (2015)(120)	Bioerosion	OA	
Suzuki et al. (1995)(121)	Net carbonate production		Shiraho Reef
Takahashi and Kurihara (2013)(122)	Coral calcification	OA	
Tanaka et al. (2014)(123)	Coral calcification	OA	
Tanaka et al. (2016)(124)	Coralline algal calcification	OW	
Towle et al. (2015)(125)	Coral calcification	OA	
Towle et al. (2016)(126)	Coral calcification	OA and OW	

Tribollet et al. (2002)(127)	Bioerosion, present day		Lizard Island
Tribollet and Golubic (2005)(128)	Bioerosion, present day		Lizard Island
Tribollet et al. (2009)(129)	Bioerosion	OA	
Trnovsky et al. (2016)(130)	Sediment dissolution	OA and OW	
Vasquez-Elizondo and Enriquez (2016)(131)	Coralline algal calcification	OA and OW	
Venn et al. (2013)(132)	Coral calcification	OA	
Vogel et al. (2015)(133)	Coral calcification	OA and OW	
Vogel et al. (2016)(134)	Coralline algal calcification	OA and OW	
Webb et al. (2017)(135)	Bioerosion	OA and OW	
Wijgerde et al. (2014)(136)	Coral calcification	OA	
Wisshak et al. (2012)(137)	Bioerosion	OA and OW	

Table S2: Definitions and terminology for methods measuring processes within carbonate budgets.

Method	**Term**	**Definition**	**Important References**
Census-based carbonate budgets	Gross framework calcium carbonate production	Biologically-produced $CaCO_3$ that contributes to surficial reef framework and is based on organism relative abundance and calcification rate (e.g. corals and CCA)	(15, 138-144)
Census-based carbonate budgets	Bioerosion	The biological removal of framework $CaCO_3$ through both physical (e.g. parrotfish, urchins, internal borers) and chemical (e.g. internal borers) processes	

Census-based carbonate budgets	Net framework calcium carbonate production	The net change (increase or decrease) in biological produced framework $CaCO_3$ (over time) as a product of framework $CaCO_3$ production and bioerosion	
Hydrochemical carbonate budgets	Reef calcium carbonate production	The precipitation of $CaCO_3$ (or $Ca_{1-x}Mg_xCO_3$) via biological or chemical means	(145-147)
Hydrochemical carbonate budgets	Dissolution	The transition of the solid phase back into its dissolved component which can be facilitated by chemical or biological means	
Hydrochemical carbonate budgets	Net calcium carbonate production	The sum of all calcification and dissolution processes (that can be measured by chemical means)	
Sediment budgets	Gross sediment production	The total amount of carbonate sediment produced either through direct sediment production (e.g. molluscs, forams etc.) or indirect sediment production (e.g. coral breakage, grazing)	(148-151)
Sediment budgets	Sediment dissolution	The rate of carbonate sediment loss through chemical means	(30, 50, 152)

Sediment budgets	Net sediment production	The amount of carbonate sediment produced from direct and indirect sediment producers minus sediment loss from dissolution	(153, 154)
Sediment budgets	Sediment transport	The movement of sediment within the reef (re-distribution), off reef (export) and on to the reef (import)	(155-157)
Carbonate budgets, generic	Physical erosion	The removal of reef framework by physical forces such as wave action and strong current	(158-160)
Carbonate budgets, generic	Reef accretion	The maximum potential rate of vertical reef growth and is the product of net (framework) calcium carbonate production	(99)

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Dataset S1 Organism Responses (separate file). Calculated response slopes and standard deviations used to calculate impacts of ocean warming, acidification and their interaction on corals and coralline algae.

Dataset S2 Site Data (separate file). Characteristics of each site used in our analysis.

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