# Projections of coral bleaching and ocean acidification for coral reef areas based on ensembles of IPCC AR5 climate models

**Methods (adapted from van Hooidonk et al. 2013).**

van Hooidonk R, Maynard J, Manzello D, Planes S (2013) Opposite latitudinal gradients in projected ocean acidification and bleaching impacts on coral reefs. *Global Change Biology*, doi: 10.1111/gcb.12394.

Ensembles of climate models were used to generate projections of thermal stress events severe enough to cause bleaching and of changes in Ωarag. To produce the projections, monthly data for the following variables were obtained from fully coupled models in the Coupled Model Intercomparison Project 5 (CMIP5; http://pcmdi9.llnl.gov/esgf-web-fe/) for all four RCP experiments (Moss *et al.*, 2010): sea surface temperature (SST), surface pressure of $CO_2$, pH and salinity. All modeled data were remapped to a 1º x 1º resolution grid. Model outputs were reduced to a sub-set of only reef locations. These were obtained from the UNEP-WCMC's Millennium Coral Reef Mapping Project Seascape (http://imars.usf.edu/MC/). A cell was counted as a reef cell if it contained any tropical coral reefs according to the original Seascape database. We have added in all of the main Hawaiian islands.

To calculate DHWs all available models (at the time of writing) that archived SST were used (see Table 1); totaling 25, 35, 17, and 33 models for RCPs 2.5, 4.5, 6.0 and 8.5, respectively. To calculate Ωarag only the models that produce all of the following variables were used: SST, surface pressure of $CO_2$, pH and salinity (Table 2). This ensures input variables for calculating Ωarag are not sourced from different models, rather an Ωarag projection is produced for a single model prior to model outputs being combined into our ensembles. Total model counts for Ωarag are 7, 8, 4 and 9 for RCP experiments 2.5, 4.5, 6.0 and 8.5, respectively (Tables 1 and 2). Model outputs were adjusted to the mean and annual cycle of observations of SST based on the OISST V2 1982-2005 climatology (as in van Hooidonk & Huber, 2012; van Hooidonk *et al.*, 2013).

Degree Heating Months were calculated by summing the positive anomalies above the warmest monthly temperature from the OISST V2 1982-2005 climatology (Reynolds *et al.*, 2002) for each 3-month period. Degree Heating Months are then converted to DHWs by multiplying by 4.35 (see also Donner *et al.*, 2005; van Hooidonk *et al.*, 2013). The outputs for the projections we present for all four RCPs are: 1) the year when DHWs exceed 6 twice in the following decade, 2) the year when DHWs exceed 8 twice in the following decade, 3) the year when DHWs exceed 6 annually, and 4) the year when

DHWs exceed 8 annually. (4) is referred to here as the onset of annual severe bleaching. This is a total of 16 projections.

Aragonite saturation state was computed by adopting the routines in the Matlab program CO2SYS (http://cdiac.ornl.gov/oceans/CO2rprt.html) with K1 and K2 constants used from Mehrbach (1973), refit by Dickson (1987).

Several outputs were generated for the acidification projections including: 1) year when Ωarag declines below 3.5, 3.25, 3.0, and 2.75, 2) year when percent changes in Ωarag exceed 5, 10, and 15% between 2006 and 2100, and 3) as declines in calcification when 8 DHWs start to occur annually based on multiplying the change in Ωarag by 15. 15 is the median value for the relationship between Ωarag and calcification from Chan and Connolly (2013). This is a total of 31 projections.

Table 1. Models used to calculate DHWs.

| | RCP26 | RCP45 | RCP60 | RCP85 |
|---|---|---|---|---|
| ACCESS1-0 | | 1 | | 1 |
| ACCESS1-3 | | 1 | | 1 |
| bcc-csm1-1-m | 1 | 1 | 1 | 1 |
| bcc-csm1-1 | 1 | 1 | 1 | 1 |
| CanESM2 | 1 | 1 | | 1 |
| CCSM4 | 1 | 1 | 1 | 1 |
| CESM1-BGC | | 1 | | 1 |
| CESM1-CAM5 | 1 | 1 | 1 | 1 |
| CESM1-WACCM | | 1 | | 1 |
| CMCC-CESM | | | | 1 |
| CMCC-CM | | 1 | | 1 |
| CMCC-CMS | | 1 | | 1 |
| CNRM-CM5 | 1 | 1 | | 1 |
| CSIRO-Mk3-6-0 | 1 | 1 | | 1 |
| EC-EARTH | 1 | 1 | | 1 |
| FGOALS-s2 | 1 | | | |
| FIO-ESM | 1 | 1 | 1 | 1 |
| GFDL-CM3 | 1 | 1 | 1 | 1 |
| GFDL-ESM2G | 1 | 1 | 1 | 1 |
| GFDL-ESM2M | 1 | 1 | 1 | 1 |
| GISS-E2-H-CC | | 1 | | |
| GISS-E2-H | 1 | 1 | 1 | |
| GISS-E2-R-CC | | 1 | | |
| GISS-E2-R | 1 | 1 | 1 | 1 |
| HadGEM2-AO | 1 | 1 | 1 | 1 |

| | | | | |
|---|---|---|---|---|
| HadGEM2-CC | | 1 | | 1 |
| HadGEM2-ES | 1 | 1 | 1 | 1 |
| inmcm4 | | 1 | | 1 |
| IPSL-CM5A-LR | 1 | 1 | 1 | 1 |
| IPSL-CM5A-MR | 1 | 1 | | 1 |
| IPSL-CM5B-LR | | 1 | | 1 |
| MIROC5 | 1 | 1 | 1 | 1 |
| MPI-ESM-LR | 1 | 1 | | 1 |
| MPI-ESM-MR | 1 | 1 | | 1 |
| MRI-CGCM3 | 1 | 1 | 1 | 1 |
| NorESM1-ME | 1 | 1 | 1 | 1 |
| NorESM1-M | 1 | 1 | 1 | 1 |
| **Total:** | 25 | 35 | 17 | 33 |

Table 2. Models used to calculate aragonite saturation state.

| | **RCP26** | **RCP45** | **RCP60** | **RCP85** |
|---|---|---|---|---|
| CanESM2 | 1 | 1 | | 1 |
| CMCC-CESM | | | | 1 |
| GFDL-ESM2G | 1 | 1 | 1 | 1 |
| GFDL-ESM2M | 1 | 1 | 1 | 1 |
| HadGEM2-CC | | 1 | | 1 |
| HadGEM2-ES | 1 | 1 | 1 | 1 |
| MPI-ESM-LR | 1 | 1 | | 1 |
| MPI-ESM-MR | 1 | 1 | | 1 |
| NorESM1-ME | 1 | 1 | 1 | 1 |
| Total | 7 | 8 | 4 | 9 |

**References**


Chan NCS, Connolly SR (2013) Sensitivity of coral calcification to ocean acidification: a meta-analysis. Global Change Biology, 19, 282–290.

Dickson AG, Millero FJ (1987) A comparison of the equilibrium constants for the dissociation of carbonic acid in seawater media. Deep Sea Research Part A. Oceanographic Research Papers, 34, 1733–1743.

Donner S, Skirving W, Little C, Oppenheimer M, Hoegh-Guldberg O (2005) Global assessment of coral bleaching and required rates of adaptation under climate change. Global Change Biology, 11, 2251–2265.

Mehrbach C, Culberson CH, Hawley JE, Pytkowicz RM (1973) Measurement of the apparent dissociation constants of carbonic acid in seawater at atmospheric pressure. Limnology and Oceanography, 18, 897–907.

Moss RH, Edmonds JA, Hibbard KA, et al. (2010) The next generation of scenarios for climate change research and assessment. Nature, 463, 747–756.
Reynolds R, Rayner N, Smith T, Stokes D, Wang W (2002) An improved in situ and satellite SST analysis for climate. Journal of Climate, 15, 1609–1625.
van Hooidonk R, Huber M (2012) Effects of modeled tropical sea surface temperature variability on coral reef bleaching predictions. Coral Reefs, 31, 121–131.
van Hooidonk R, Maynard JA, Planes S (2013) Temporary refugia for coral reefs in a warming world. Nature Climate Change, 3, 1–4.