## Chapter 4.4 Ocean acidification, projections of future state under two emission scenarios

**Lead Author:**

Ruben van Hooidonk[1,2,3]

[1]NOAA Atlantic Oceanographic and Meteorological Laboratory, 4301 Rickenbacker Causeway, Miami, FL 33149, USA,
[2]Cooperative Institute of Marine and Atmospheric Sciences, Rosenstiel School of Marine & Atmospheric Science,
University of Miami, 4600 Rickenbacker Causeway, Miami, FL 33149, USA
[3]Ruben van Hooidonk was supported by NOAA's Coral Reef Conservation Program and the projections were made possible by a grant from the Pacific Islands Climate Change Cooperative via the IRCP, based at the CRIOBE research station in Moorea, French Polynesia.

## 4.4 Ocean acidification, projections of future state under two emission scenarios

### 4.4.1 Summary and Key Messages

Roughly a third of the carbon dioxide ($CO_2$) released into the atmosphere since the 'Industrial Revolution' has been absorbed by the ocean (Sabine et al. 2004). This uptake of $CO_2$ is causing an ongoing change in oceanic carbonate chemistry. Oceanic pH is declining, a phenomenon commonly referred to as ocean acidification (OA). OA is causing a decline in the saturation state of calcium carbonate ($CaCO_3$) minerals such as aragonite (Doney et al. 2009). The skeletons or shells of many economically and/or ecologically important oceanic species are built from aragonite. A decline in aragonite saturation state ($\Omega$arag) can slow down calcification and negatively impact these organisms (Kroeker et al. 2013). For example, stony corals show declined calcification with decreasing $\Omega$arag, making them more vulnerable to damage by tropical storms and more prone to erosion (Chan and Connolly, 2013; van Hooidonk et al. 2014). Pteropods present at higher latitudes are projected to be affected severely by OA. Their distribution might be limited because of their inability to grow a shell or their shell being too weak as a defensive mechanism (Orr et al. 2005).

To project OA impacts on these and other important organisms, accurate projections of $\Omega$arag are needed. Here $\Omega$arag was modelled using state-of-the-art global circulation models included in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (Taylor et al. 2012). Aragonite saturation state was computed by adopting standard routines from the Matlab program $CO_2$SYS (http://cdiac.ornl. gov/oceans/ $CO_2$rprt.html). To calculate $\Omega$arag and compute all variables in the carbonate system sea surface temperature (SST), salinity and two of the following five variables are required: total alkalinity, total carbon dioxide, pH, and partial pressure of carbon dioxide or fugacity of carbon dioxide (see: Zeebe and Wolf-Gladrow, 2001). Here, SST, salinity, surface pressure of $CO_2$ and pH are used to calculate all the other parameters of the carbonate system. Two projections were made, one with the relative concentration pathway (RCP) 4.5, which is a scenario of rapid initial growth of greenhouse gas (GHG) concentrations, but stabilizing concentrations from 2070 onward (Thomson et al. 2011). The $CO_2$ equivalent concentration in 2100 is 580 ppm including all forcing agents. This pathway results in a total forcing of 4.5 W/m$^2$ in 2100.

The second projection was made using the RCP 8.5: a pathway of continuing growth of GHG concentrations in the atmosphere (Figure 4.39) and one that results in an additional forcing of 8.5 W/m$^2$ in 2100 at a $CO_2$ (equivalent, including all forcing agents) concentration of 1230 ppm (Riahi et al. 2011).

Currently ,emissions track above the RCP 8.5 scenario. In all four previous generations of emission scenarios employed by the IPCC for their Assessment Reports, emissions always exceeded the worst-case scenario (Peters et al. 2012). Both pathways project a 395 ppm $CO_2$ concentration in 2013 as a mid-year average, which is lower than measurements of $CO_2$ concentration for that year (http:// www.esrl.noaa.gov/gmd/ccgg/trends/). Measurements of $CO_2$ in 2014 at Mauna Loa peaked above 400 ppm (http:// www.esrl.noaa.gov/gmd/ccgg/trends/).

**Key Messages**

- Aragonite is a calcium carbonate mineral that is an important component of shells and skeletons of marine species;
- Ocean acidification can lead to aragonite dissolution, leading to significant weakening of the shells and skeleton of many marine species;
- Global oceanic pH is expected to decrease 0.12 units by 2099 in RCP4.5; for RCP8.5 the decline is projected to be 0.32 units;
- Globally averaged aragonite saturation state is projected to decline 0.55 and 1.14 units for RCP4.5 and RCP8.5 respectively;

**Figure 4.39.** Concentrations of greenhouse gases in the atmosphere expressed as $CO_2$ equivalents including all forcing agents for the Relative Concentration Pathways RCP 4.5 (blue) and 8.5 (red).



*Source: http://tntcat.iiasa.ac.at:8787*
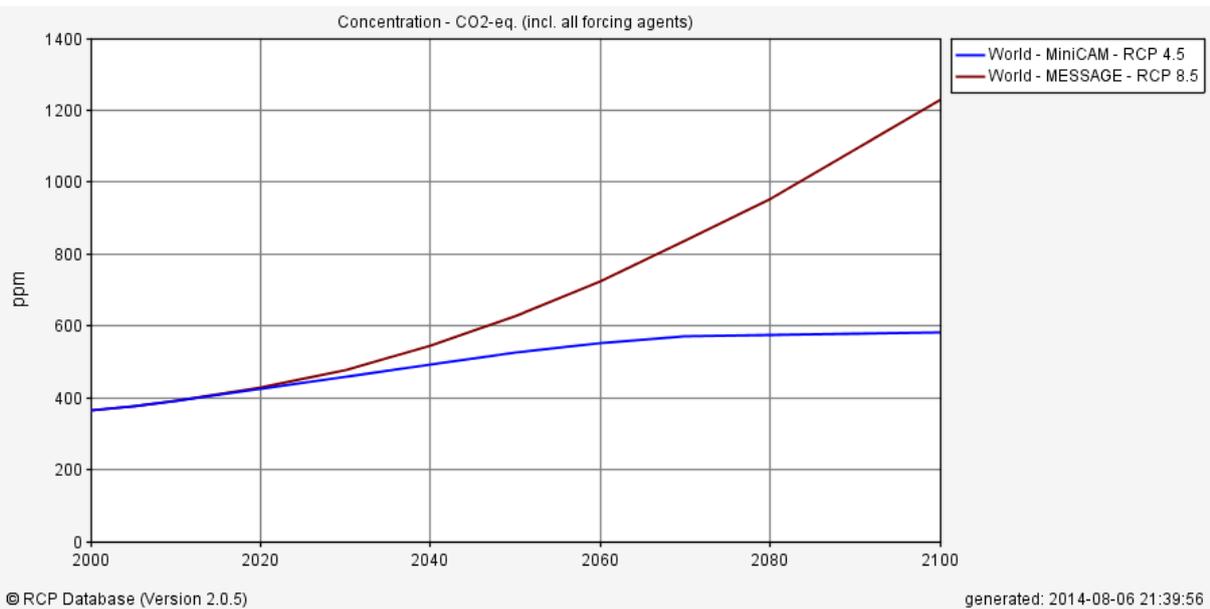
- There is a latitudinal gradient in reduction of aragonite saturation state: near the equator the reduction is largest; and
- Due to a projected weakening of easterly trade winds in the Pacific and consequently causing higher rates of SST increases in the region, aragonite saturation state is projected to decrease less in this region than surrounding areas.

### 4.4.2   Main Findings, Discussion and Conclusion

Global oceanic pH in the model ensembles decreases from 8.06 in the 2006-2015 period to 7.94 in the period 2090-2099 for the stabilization scenario (RCP4.5). In the scenario that is more consistent with the current increase in greenhouse gas emissions (RCP8.5), global oceanic pH drops from 8.06 in 2006 to 7.74 in 2090-2099. Globally averaged aragonite saturation state drops from 2.75 to 2.20 in RCP4.5. Averaged over just the tropics, aragonite saturation state is projected to decline from 3.46 to 2.91 in RCP4.5. In the 'Business As Usual' scenario (RCP8.5) the reduction in the aragonite saturation state is larger, from 2.71 to 1.57 globally, and 3.43 to 2.13, in the tropics.
The reductions in aragonite saturation state are not distributed evenly across the globe: there is a clear latitudinal gradient.

The reduction in aragonite saturation state is larger near the equator and diminishes with increasing latitude (Figure 4.40), this is true for both emission scenarios. However, the equatorial eastern Pacific is an exception, where Ωarag decreases less than in surrounding waters of the Pacific. This is likely due to a projected weakening of easterly trade winds in the Pacific and consequential decreased upwelling, a flattening of the thermocline, and higher rates of SST increases in the region (Collins et al. 2010). With all else being equal, higher temperatures lead to higher Ωarag, explaining the difference seen in the equatorial eastern Pacific.

Expressed as a percentage change from 2006 values, lower latitudes experience a smaller decrease in aragonite saturation state then high latitude locations (Figure 4.41).

**Figure 4.40.** Absolute reduction in aragonite saturation state, projected using ensembles of GCMs. The top plot shows the reduction projected using RCP4.5, the bottom plot shows the projected reduction using the RCP8.5 scenario. Differences are calculated as the average of 2006-2015 minus the average for 2090-2099.
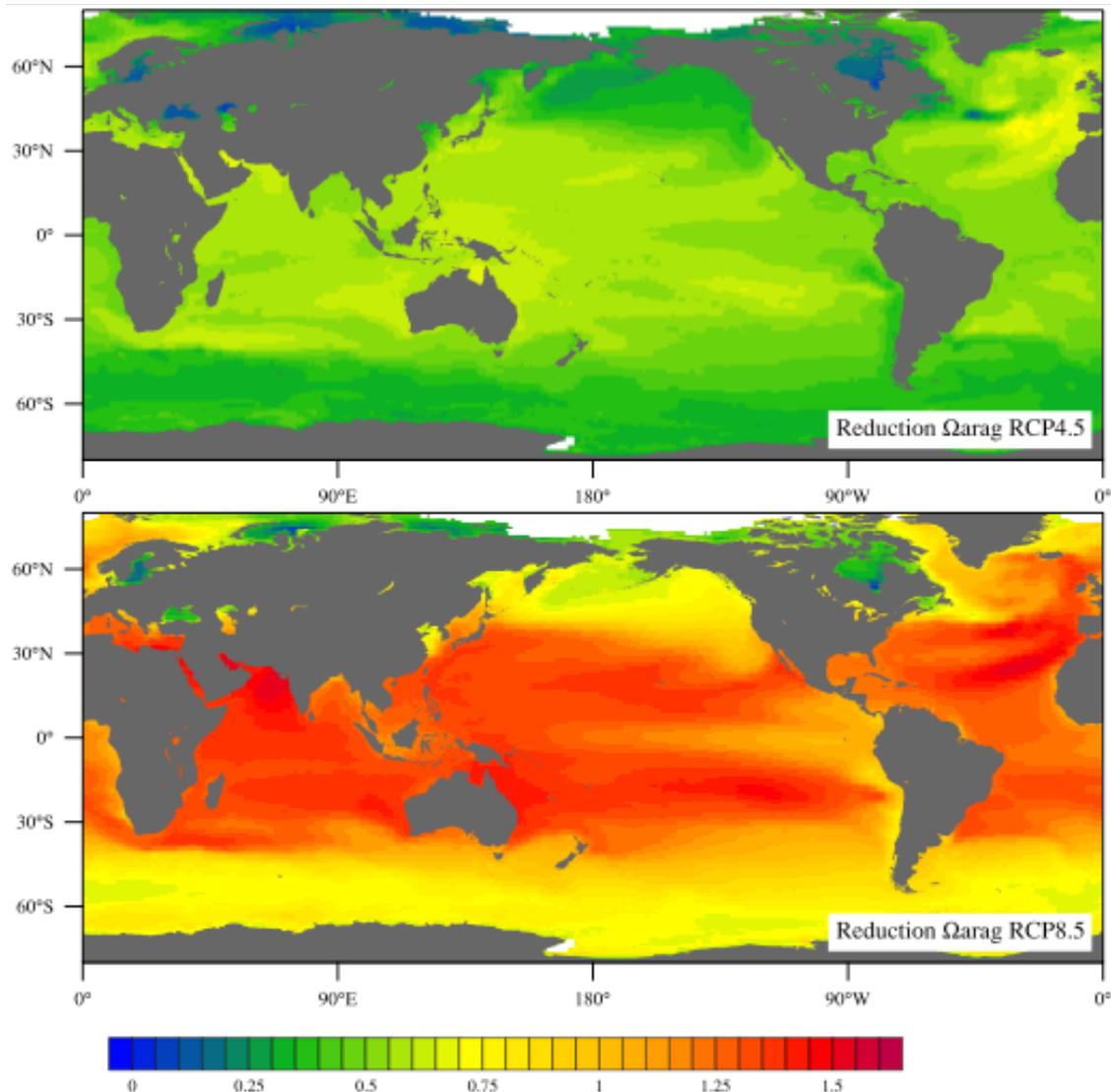


The Atlantic Ocean, of all oceans, shows the smallest reduction in $\Omega$arag, with the Caribbean Sea and the Gulf of Mexico projected to have a ~30% reduction by 2100 in the RCP8.5 scenario. The Pacific and Indian oceans are projected to decline 37-40% by 2100 in RCP8.5. During the modeled period 2006-2099, aragonite saturation state declines globally, but the latitudinal gradient can be seen through time as well (Figure 4.42).

## Discussion and Conclusion

There are assumptions and uncertainties that need to be considered when using global models to project $\Omega$arag. Even though the most advanced suite of models has been used, uncertainties still exist. Compared to the previous generation of models the projected changes in temperature and the patterns of change are exceptionally similar.

**Figure 4.41.** Projections of reductions in aragonite saturation state, computed from two ensembles of GCMs, one for RCP4.5, one for RCP8.5 expressed as a change in percentage from 2006 values.
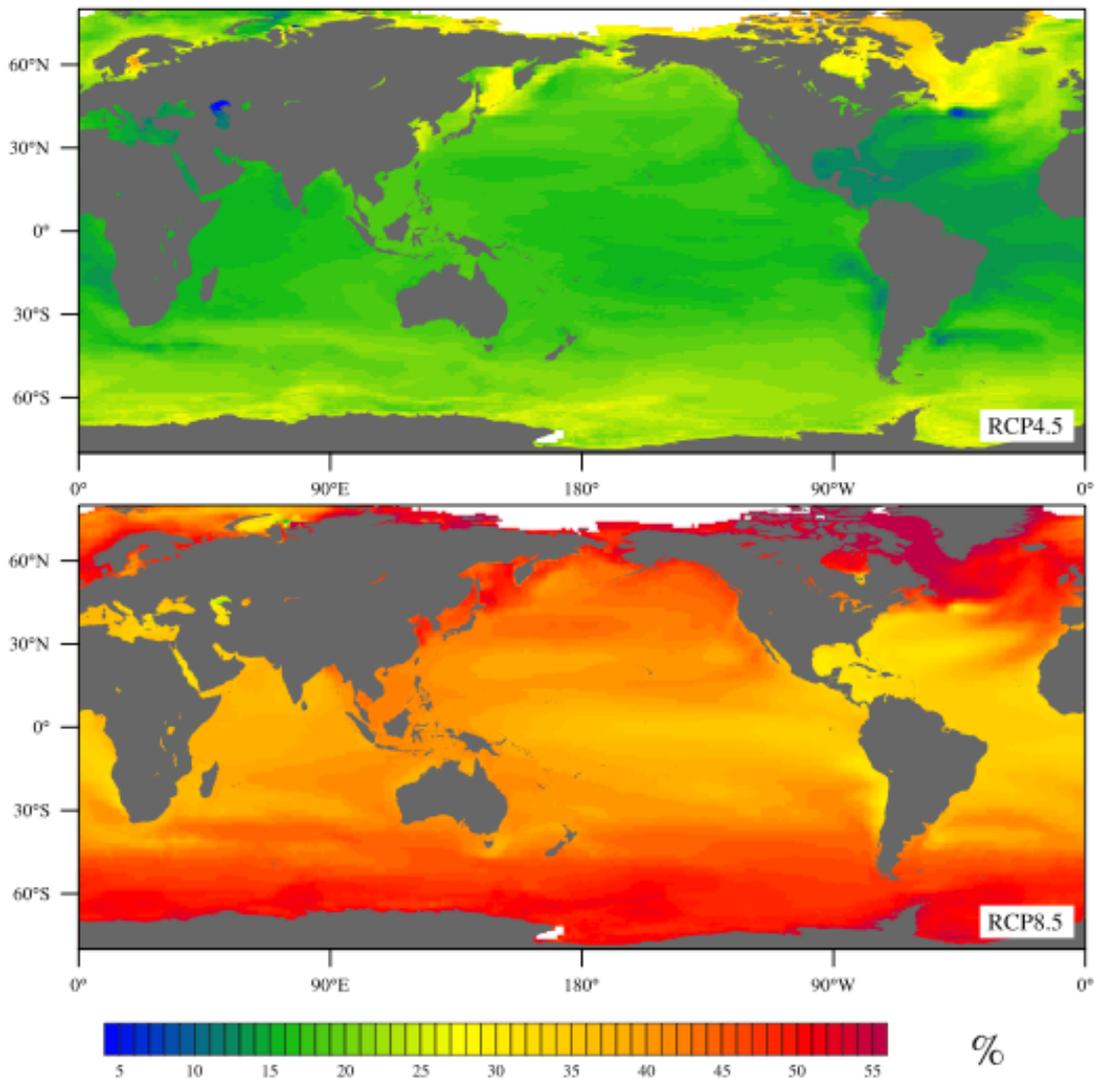
The current generation of models include vastly more complex and comprehensive representations of the processes that influence climate. Therefore, although the model spread has not decreased between generations, it is more *certain* that the important processes have been included and confidence in the models should increase (Knutti and Sedláček, 2012).

Part of the model spread is inherent to internal variability in the climate system itself. Due to the coarse resolution of global models, near coastal and fine scale features such as local upwelling or run-off might not be represented accurately. Upwelling can influence the SST and run-off can alter the carbon chemistry of the surface water as well. Small local features that could influence the carbonate chemistry such as sea grass beds can also not be resolved by global models. Observations however show that these local features could have significant impact on projected functioning of ecosystems such as coral reefs (Manzello et al. 2012).

**Figure 4.42.** Trajectories of aragonite saturation state for the period 2006-2099 computed from the RCP8.5 ensemble. The panels show average (black solid line) and the model spread expressed as by 2100 in RCP8.5. The areas are the combination of the same latitudinal bands north and south of the equator, therefore panel a) represents from -5 to 5ºN, b) 5º to 10º on both sides of the equator, c) 10º to 20º, d) 20º to 30º, e) 30º to 40º and f) 40º to 60º on both sides of the equator.
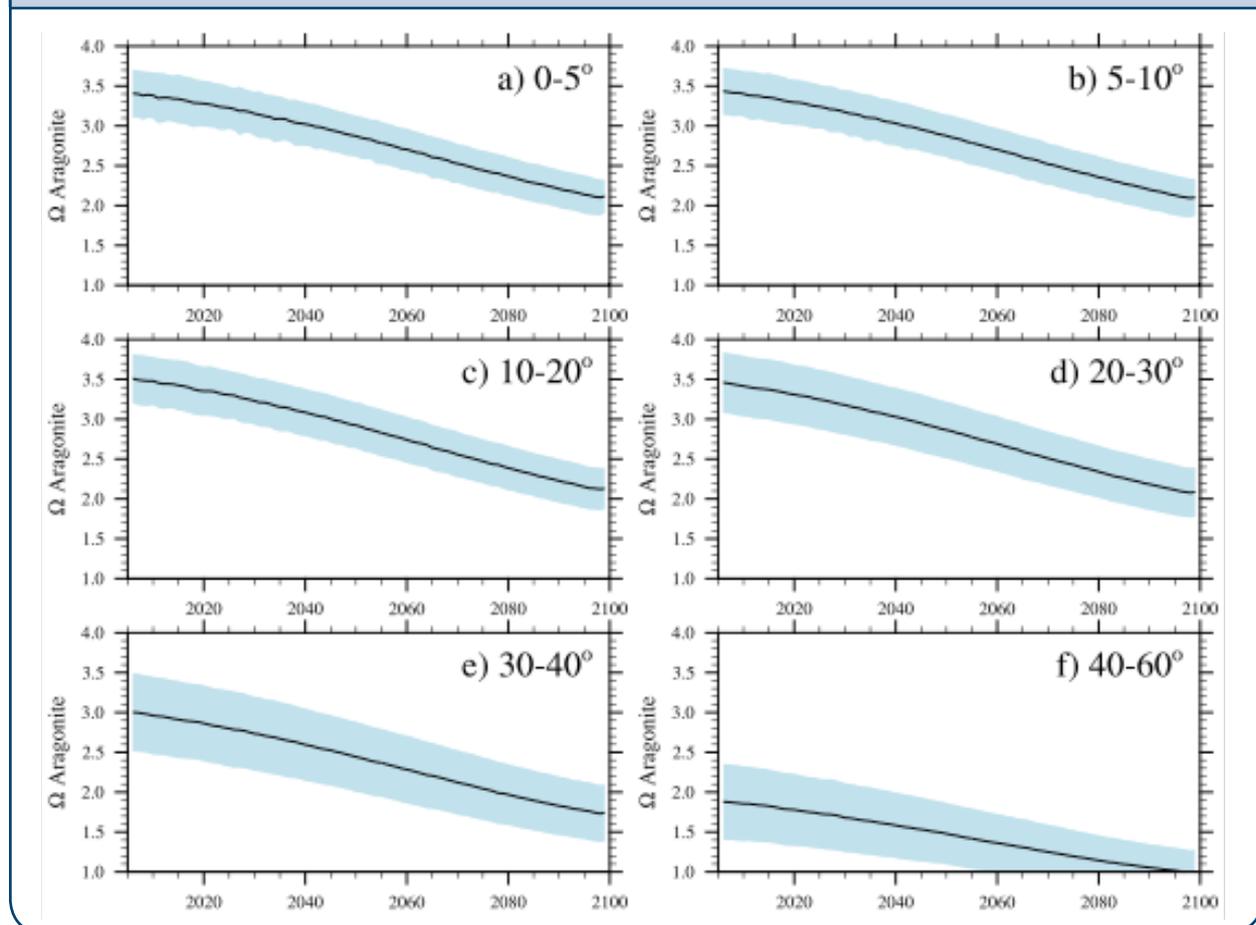


The models do not reflect higher frequency variabilities of $\Omega$arag, such as diurnal and weekly variability due to the monthly resolution of the outputs that are needed to compute $\Omega$arag. Global models still have some known and unknown biases and errors, for example the representation of the annual cycle of SSTs can be under or over represented (Wu et al. 2008; van Hooidonk and Huber, 2012), which influences $\Omega$arag considerably. A frequently used method to minimize biases and errors is to use a multi model ensemble (Tebaldi and Knutti, 2007). The spread of the models, expressed as standard deviation, can be considered as an approximation of the robust*ness of the results (Figure 4.42*). The standard deviation increases with latitude and is on the order of 0.25-0.5 units of $\Omega$arag. Both the standard deviations and the absolute values of $\Omega$arag are comparable to previously published results based on measured data fro*m cruises (Feely et al. 2009).*

### 4.4.3   Notes on Methods

To project future ocean acidification and aragonite saturation states, ensembles of fully coupled ocean atmosphere global circulation models were used. Monthly data for the following variables were obtained from 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): SST, surface pressure of $CO_2$ (sp $CO_2$), pH, and surface salinity. For this report only the results from RCP4.5 and RCP8.5 were used. For the impact of OA on tropical coral reefs under all four scenarios see van Hooidonk et al. (2014).

All modeled data were remapped to a 1x1° resolution grid. If there were multiple runs available for a model, these runs were averaged first before a multi-model ensemble was created by averaging all model outputs. Because many sites of interest are close to coastal boundaries, such as coral reef sites, missing data was filled in using an interpolation algorithm that solves Poisson's equation by relaxation. This function uses the existing data as boundaries and interpolates in the zonal direction. By filling in missing data this way, near coastal projections could be made. The models used in the RCP4.5 and RCP8.5 ensembles are documented in Table 4.1.

From SST, sp $CO_2$, pH and surface salinity aragonite saturation state was computed at each 1x1º pixel at each monthly timestep from 2006 until 2099. To compute aragonite saturation state, $CO_2$SYS Matlab routines (http://cdiac.ornl.gov/oceans/$CO_2$rprt.html) were ported to the NCAR Command Language (NCL 6.2.0), with K1 and K2 constants used from Mehrbach (1973), refit by Dickson and Millero (1987).

**Table 4.1 Models used to compute aragonite saturation state**

|  | **RCP45** | **RCP85** |
|---|---|---|
| 1.  CanESM2 | 2.  1 | 3.  1 |
| 4.  CMCC-CESM |  | 5.  1 |
| 6.  GFDL-ESM2G | 7.  1 | 8.  1 |
| 9.  GFDL-ESM2M | 10. 1 | 11. 1 |
| 12. HadGEM2-CC | 13. 1 | 14. 1 |
| 15. HadGEM2-ES | 16. 1 | 17. 1 |
| 18. MPI-ESM-LR | 19. 1 | 20. 1 |
| 21. MPI-ESM-MR | 22. 1 | 23. 1 |
| 24. NorESM1-ME | 25. 1 | 26. 1 |
| 27. Total | 28. 8 | 29. 9 |

# References:

Beerling DJ, Royer DL (2011) Convergent Cenozoic CO. *Nature Geoscience*, **4**, 418–420.

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.

Doney SC, Fabry VJ, Feely RA, Kleypas JA (2009) Ocean Acidification: The Other CO 2Problem. *Annual Review of Marine Science*, **1**, 169–192.

Feely RA, Doney SC, Cooley SR (2009) Ocean acidification: present conditions and future changes in a high- $CO_2$ world.

Knutti R, Sedláček J (2012) Robustness and uncertainties in the new CMIP5 climate model projections. *Nature Climate Change*, –.

Kroeker KJ, Kordas RL, Crim R et al. (2013) Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming. *Global Change Biology*, n/a–n/a.

Manzello DP, Enochs IC, Melo N, Gledhill DK, Johns EM (2012) Ocean Acidification Refugia of the Florida Reef Tract. *PLoS ONE*, **7**, e41715–10.

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.

The NCAR Command Language (Version 6.2.0) [Software]. (2013). Boulder, Colorado: UCAR/NCAR/CISL/VETS. http://dx.doi. org/10.5065/D6WD3XH5

Orr JC, Fabry VJ, Aumont O et al. (2005) Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature*, **437**, 681–686.

Peters GP, Andrew RM, Boden T et al. (2012) The challenge to keep global warming below 2ºC. *Nature Climate Change*, **3**, 4–6.

Riahi K, Rao S, Krey V et al. (2011) RCP 8.5—A scenario of comparatively high greenhouse gas emissions. *Climatic Change*, **109**, 33–57.

Sabine CL, Feely RA, Gruber N et al. (2004) The oceanic sink for anthropogenic $CO_2$. *Science*, **305**, 367–371.

Taylor KE, Stouffer RJ, Meehl GA (2012) An Overview of CMIP5 and the Experiment Design. *Bulletin of the American Meteorological Society*, **93**, 485–498.

Tebaldi C, Knutti R (2007) The use of the multi-model ensemble in probabilistic climate projections. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **365**, 2053–2075.

Thomson AM, Calvin KV, Smith SJ et al. (2011) RCP4.5: a pathway for stabilization of radiative forcing by 2100. *Climatic Change*, **109**, 77–94.

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 RJ, Maynard JA, Manzello D, Planes S (2014) Opposite latitudinal gradients in projected ocean acidification and bleaching impacts on coral reefs. *Global Change Biology*, **20**, 103–112.

Wu Q, Karoly D, North G (2008) Role of water vapor feedback on the amplitude of season cycle in the global mean surface air temperature. *Geophysical Research Letters*, **35**.

Zeebe RE, Wolf-Gladrow D (2001) $CO_2$ *in Seawater: Equilibrium, Kinetics, Isotopes: Equilibrium, Kinetics, Isotopes*. Elsevier.