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Reef Climate Adaptation Research and Technology

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Abstract: The authors describe research into technological means for addressing two consequences of climate change for coral ocean acidity and increasing sea surface temperatures leading to coral bleaching. Technology for a multi- integrated response is proposed. Sea surface temperatures can be monitored via satellite and on-line telemetry. Technology for moderating sea surface temperature spikes is based on pumping deeper cool seawater over coral reefs. The technology proposed includes plastic collapsible pipelines that can be deployed like oil spill booms with flat disc pumps and renewable energy devices (tidal turbines) to power the pumps. The technology for counteracting increasing ocean acidity on coral reefs is based on the Accelerated Weathering of Limestone (AWL). It is proposed that an acceleration of the natural process that restores the carbon balance, can be realized using a modified electrolyzer powered by renewable energy. The AWL process sequesters CO_2 and produces H_2 while generating a buffer solution that increases reef pH and also provides alkalinity to feed reef and shellfish calcification. The AWL buffer solution will be distributed where required using the same renewable energy powered pumps and pipelines as used to mitigate sea surface temperature spikes. The AWL process will operate continuously but can be interrupted whenever the pumps and collapsible pipes are required to avoid potential coral thermal bleaching events. Dual use improves affordability.

Keywords: Climate Change, Climate Change Adaptation, Climate Change Counter-measures, Sea Surface Temperature, Ocean Acidity

1. Introduction

THE PROPOSAL OUTLINED here is aimed at developing the capacity for cost effective preservation of coral reefs with an emphasis on the protection of the Great Barrier Reef against temperature and acidity changes. Elevated sea temperatures are known to contribute to coral bleaching (Wilkinson, 2004) [1.1].

The Great Barrier Reef is a World Heritage Area and the basis of tourism, fishing and other industries worth AUD$6.8 billion per annum employing 66,000 people in 2005-6 (Access Economics, 2007). Coral Reef ecosystems are of intrinsic value and major repositories of biodiversity (Garrett, 2007). The greatest coral diversity in the world, with over 500 species, occurs in the “Coral Triangle” with over 20,000 islands and a population of 300 million people dependent on the productivity of these reefs.

The proposal is based on technology to:

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1. detect and monitor temperature, salinity and flow conditions on the reef
   -extends the previous ReefTemp and FAIMMS projects
2. model shallow water solar radiant heating and ‘hot’ ocean currents
   -requires shallow inshore tidal and ocean current modelling
3. model fresh water and mineral influx from rivers and ocean CO_2 adsorption
   -requires rainfall and ocean chemistry modelling
4. moderate temperature extremes by pumping cooler water over reefs [CoolReef]
   -includes generation of on-site marine renewable energy
5. reduce ocean acidity by accelerating natural bicarbonate production [Reef-pH]
   -requires the diffusion of bicarbonate using the CoolReef system
6. economic modelling to show that coral habitat protection is viable
   -requires 1 to 5 to be developed to at least a demonstration stage

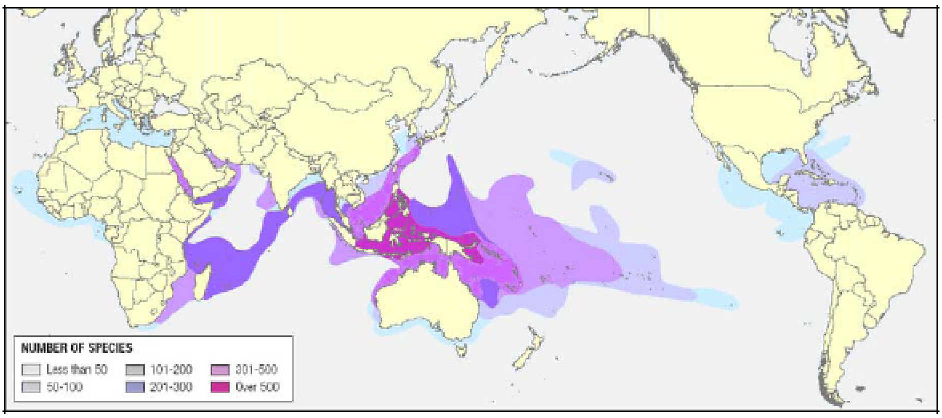

Figure 1.1: Distribution and Diversity of Reef-Building Scleractinian Corals (Vernon, 2000)

This paper will address technical aspects (sections 1-5) of the proposal and describe the technology that has already been deployed and technology yet to be developed and deployed. The proposed means for each stage of the integrated response will be discussed. These stages include monitoring, planning, deploying and managing the responses.

2. Temperature Effects and Mechanism

The warm South Equatorial Current in the Pacific Ocean flows westwards until it meets the Australian continent in Northern Queensland where it splits into northern (Hiri Current) and southern (East Australia Current) currents. These currents carry heat into the Great Barrier Reef Region, particularly during El-Niño, leading to increased potential for coral bleaching.

The Great Barrier Reef includes an outer reef system which for long expanses is a partially continuous barrier to ocean currents but with many passages to the inner reef. The greatest influx of currents of warm equatorial water would most likely occur through these passages

(Callaghan et al 2007; Webb, 2000). Ocean currents are not the only mechanism heating coral reefs; they are further warmed by the shallow bay effect.

Figure 2.1: Natural Passages between Reefs of the Great Barrier Reef

Shallow inshore areas close to the coast, where there are no ocean currents, are warmed by a longer transit time near the surface so that the seawater absorbs more solar radiation. These inshore waters are not necessarily more stagnant and can have strong tidal currents moving the warmer water back and forth.

However the warmer surface water is shallow and the seawater just 10m below the surface is significantly cooler. Pumping cooler water to the surface will decrease the temperature of warmer surface waters. An astute observer may come to the conclusion that pumping could only create a quite small temperature difference. This is true, however the temperature change between dead and living coral reefs is only 1-2° [2.1]. The difference in sea temperature during El-Niño is also only 1-2° Celsius.

An ocean current turbine fence will deflect approximately one third of the water in an impinging current (Gorban et al 2001; Garrett and Cummins, 2005; Bryden and Scott, 2007).

We expect that pumping cooler water over a reef will be able to produce 1°–2° C of cooling, but it will depends on the temperature differential between surface and deeper water and the volume and duration of pumping.

3. Acidity Effects and Mechanism

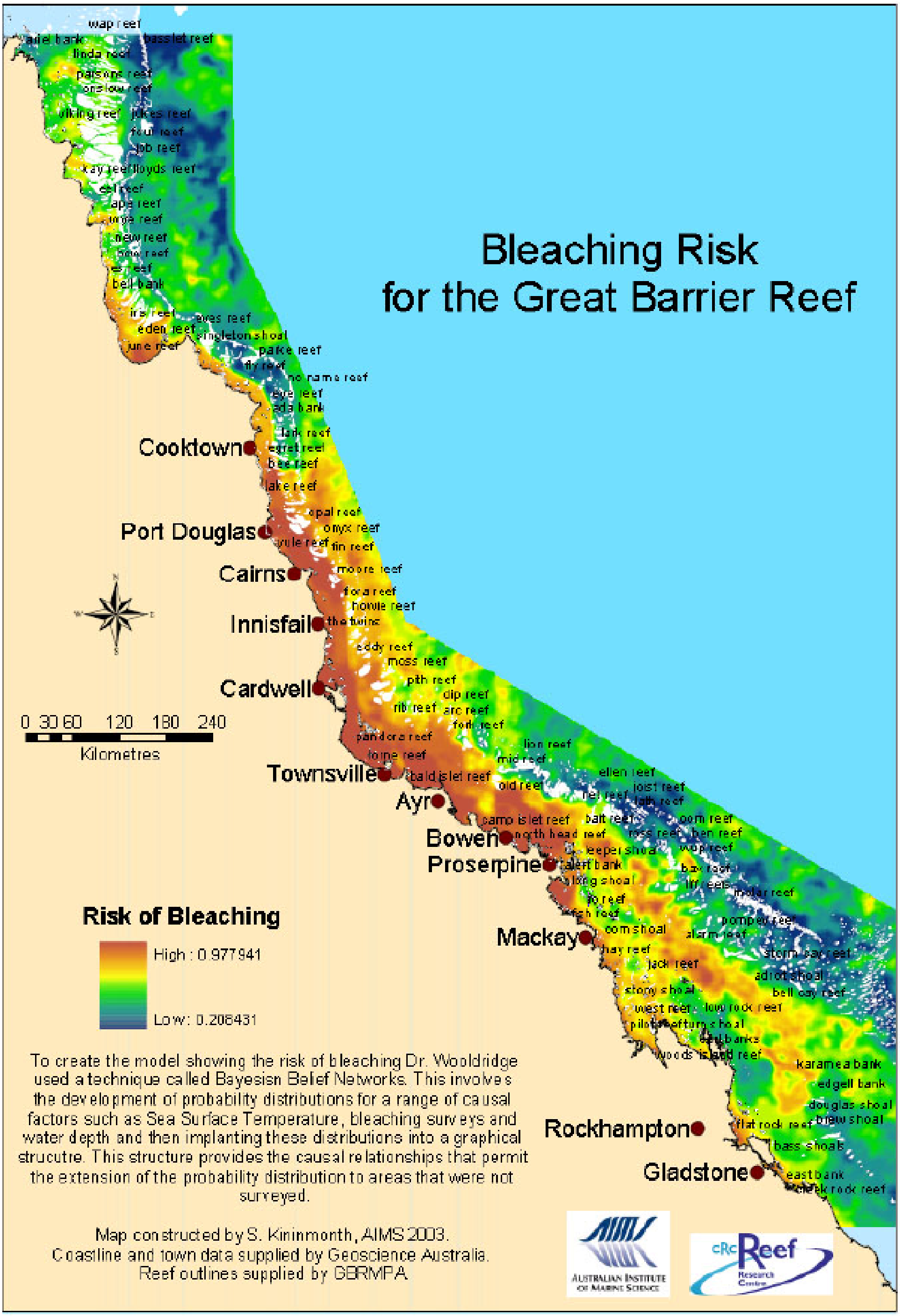

Figure 2.2: AIMS MAP - Bleaching Risk for the Great Barrier Reef

As anthropogenic CO_2 is added to the atmosphere, the resulting disequilibrium between air and ocean drives CO_2 into solution via diffusion, increasing the CO_2 concentration in seawater. However, most of this carbon does not remain as molecular CO_2, but is instead hydrated to form carbonic acid, H_2CO_3 $^-$ Carbonic acid subsequently dissociates into hydrogen ions (H^+) and bicarbonate ions (HCO_3 -). This increases ocean acidity (the H^+ concentration), lowering pH (= - $Log_{10}[H^+]$).

As a major controller of biogeochemical processes, changes in ocean acidity and pH can be expected to alter the structure and function of marine ecosystems. In particular, experiments have demonstrated that the addition of CO_2 and/or lowering of pH in seawater to levels anticipated to occur over the next century result in a dramatic diminution of calcification rates by corals and some shellfish (Kleypas et al, 2006; Doney et al., 2009).

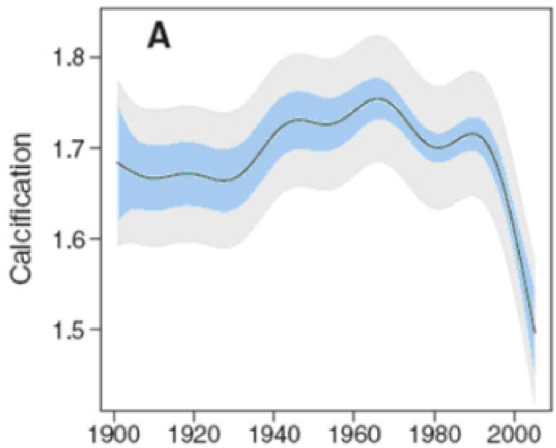

Figure 3.1: Declines in Coral Calcification Rate (De'ath, 2009) [3.1]

While the exact mechanisms of such an effect have yet to be fully elucidated, CO_2 acidification reduces the saturation state of dissolved calcium carbonate, as aragonite, in seawater ($CaCO_3$ is the primary structural material in shells and corals) and it appears to play a central role in determining the rate of shell formation (Marubini et al., 2008; Cohen and Holcomb, 2009). For this reason, in addition to the thermal effects discussed above, there is grave concern about the future health of coral reefs under a business-as-usual anthropogenic CO_2 emissions scenario (Doney et al., 2009). Ways of reducing CO_2 emissions, reducing atmospheric and ocean CO_2 concentrations, and mitigating the thermal and chemical effects of excess CO_2 all need to be seriously considered if impacts to marine ecosystems are to be avoided in the coming decades.

The decrease in coral calcification is likely to have resulted from a combination of increasing water temperatures and acidities – it is not yet possible to say which factor is more important.

- *Climate Scientists Australia*

4. ReefTemp

ReefTemp is a collaborative project between the Great Barrier Reef Marine Park Authority (GBRMPA), CSIRO Marine and Atmospheric Research and the Bureau of Meteorology to provide frequent (daily) monitoring of the risk of coral reef bleaching by satellite monitoring of sea-surface temperatures across the Great Barrier Reef [4.1]. This approach uses remote sensing imagery to identify times and locations that have surface water temperatures above the long term climatology. The resulting values are expressed as degree heat days or degree heat weeks.

The process uses sea surface temperatures (SST) derived from the NOAA-15 and NOAA-17 satellites and using a 2km grid, it looks for areas that are more than 1 degree Celsius above the long term temperature average for that location and time of year. For each point on the grid the accumulated heat stress is summed as the number of days or weeks where that point is above the long term climatology, this value is represented as the Degree-Heating Days (DHD's). These values therefore represent the accumulated heat stress being experienced by corals and other organisms that live near the surface; the rate of change in DHD values indicates the rate of warming.

4.1 Satellite Monitoring

The base data for the ReefTemp project is Sea Surface Temperature (SST) data from the NOAA-15 and NOAA-17 set of satellites. Onboard the satellites are the Advanced Very High Resolution Radiometer (AVHRR) sensors that measure radiance from the earth in five bands or channels with 1.1 km resolution. Satellite estimates of SST's are made by converting the radiance measured in the infrared channels to brightness temperatures and then a multichannel technique to calculate SST to within ±0.5°C. Cloud identification masks are also created using visible and infrared channels with a series of spectral gradient, difference, and threshold tests [4.2]. The resulting data is a 1km grid of sea surface temperature values that can be directly compared to the long term climatology values.

From the satellite data and the long term climatology it becomes possible to identify areas that are 'hot-spots'; that is where the satellite measurements indicate the surface temperature is above the long term average. Work by Jokiel and Coles (1977) shows that corals are at risk of bleaching at only small increases from the average (two or more degrees Celsius) even though they experience daily changes far in excess of this. It seems that the cumulative thermal stress is more important than the absolute temperature and so the DHD measure looks to identify areas that are accumulating heat rather than just simply areas that are 'hot.'

4.2 Early Warning

The NOAA Coral Reef Watch product, that uses Degree Heat Weeks (DHW) instead of Degree Heat Days, has found that a value of 4 and above indicates areas of likely bleaching and values of 8 and above indicate a high probability of bleaching [4.3].

The Coral Reef Watch product uses the following scale:

Stress Level	Definition
No Stress	DHW <=0
Bleaching Warning	DHW > 0 and DHW <= 4
Bleaching Alert Level-1	DHW > 4 and DHW <= 8
Bleaching Alert Level-2	DHW > 8

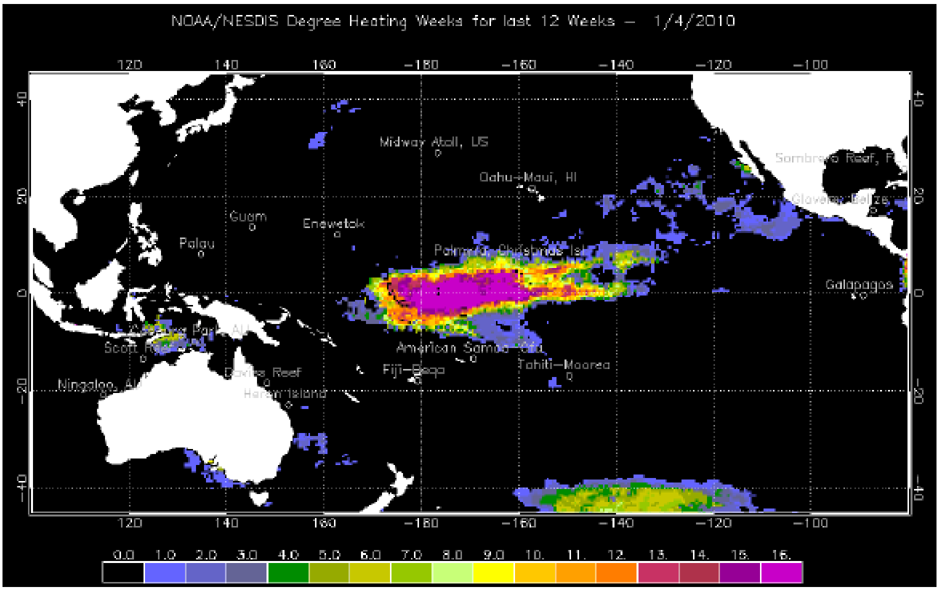

Figure 4.1: Degree Heat Week (DHW) Map for the Pacific as of January 2010 Showing a 'Hot-Spot' or Area of Accumulated Heat in the Central Pacific, Representing a Heat Load of 16 or more Degree Heat Weeks (NOAA)

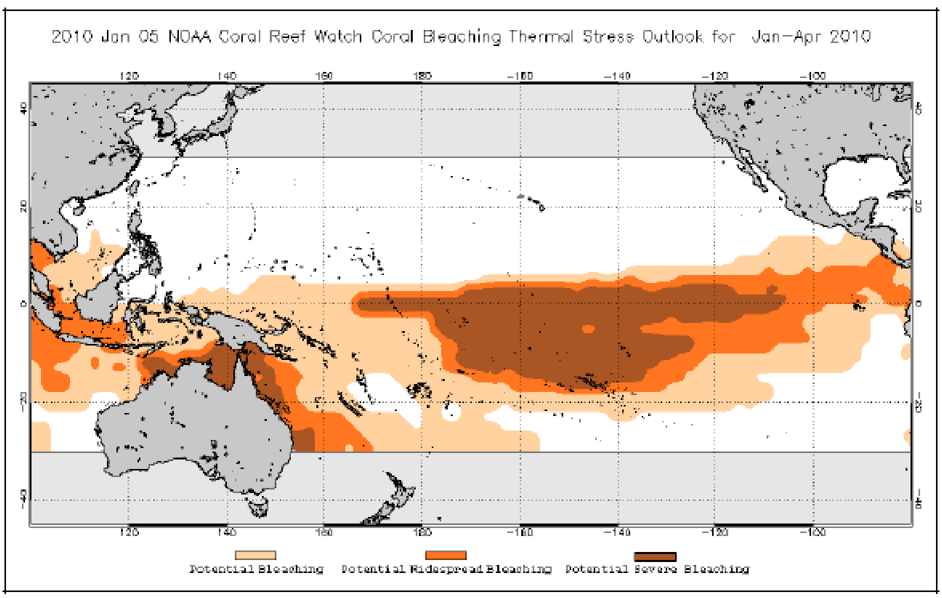

Figure 4.2: Experimental Coral Bleaching Outlook (forecast) Map Generated from the DHW Map for the Pacific Ocean for January to April 2010 (NOAA)

Using these values a risk map or DHW map can be produced (see Figure 4.1): using models of ocean circulation it is possible to produce forecast maps. These are currently in an experimental stage but the maps give up to three months warning of potential bleaching events and increased risk (see Figure 4.2).

The satellite derived measurements can be backed up with in-situ measurements to give a better understanding not only of the thermal stress at the surface but of the water actually around the coral. This not only gives a more accurate picture of the environment around the coral but also gives information about water mixing, heat flow, flushing and retention rates and processes that ultimately determine when and how corals respond to changes in climate.

5. ReefGrid - FAIMMS

The ReefGrid project pioneered in 2007 the use of the humidity layer above tropical seas to duct microwave signals over long distances. ReefGrid extended the Queensland internet infrastructure onto the Great Barrier Reef and proved the viability of establishing networked research facilities for real-time coral reef studies [5.1].

The Facility for Automated Intelligent Monitoring of Marine Systems (FAIMMS) is a facility within the Great Barrier Reef Ocean Observing System (GBROOS) node of the Australian Integrated Marine Observing System (IMOS) [5.2] project. The FAIMMS facility, run by the Australian Institute of Marine Science (AIMS), has deployed sensor networks on seven reefs along the Great Barrier Reef (GBR) that include high speed two way IP based remote communications, 'smart' controllers on each reef and a range of sensors deployed around the reef. The resulting system is the largest and most comprehensive coral reef sensor network in the world.

The project aims to provide real time spatially dense readings of major environmental variables around reefs to better understand and predict events such as bleaching, warm water events and destructive events such as cyclones and storms. The system also looks to measure fine scale events, such as the flushing of lagoons, and to link large scale ocean measurements from existing satellite and mooring systems with the smaller scale processes that impact the reef at the level of individual corals and coral bommies. This linkage across scales is essential to understand the impact of larger scale events at a scale relevant to the organisms being impacted and in turn to understand how they respond to such events.

6. CoolReef

The CoolReef program looks to extend the CSIRO ReefTemp collaboration with GBRMPA and AIMS beyond monitoring the risk of coral bleaching to active countermeasures and management and is an instance of Climate Change Adaptation. It is based on having technology to pump cooler water from the bottom of shallow coastal seas onto reefs when the seawater surface temperature is approaching bleaching conditions.

6.1 Temperature Gradient and Current Monitoring

The proposed program requires continuously monitoring seawater temperature throughout the water column, not just at the surface, while also monitoring water movement (currents). Thermistor curtains, made of multiple thermistor strings, can be stretched across channels between reefs and above reefs with acoustic current profilers positioned to measure seawater movement through the channel and across the reef (van Haren et al., 2001).

This temperature gradient and current data provides the basis for deciding when and from where to pump cooler bottom water. Initial testing should be sited adjacent to an existing ReefGrid node so that real-time data can then be obtained by connecting the thermistor curtain and current profiler to the ReefGrid on-line sensor network. The ReefGrid node will also provide weather information which together with precise bathymetric data can be combined with the sea temperature and current profile data in a shallow sea model (Gremmrich and van Haren, 2002).

6.2 Pumps and Pipelines

The response technology consists of submersible pumps and plastic pipelines that can be rapidly deployed from boats when required. The plastic pipe is flexible so that the pipe folds flat and can be stored on a drum and deployed and recovered in much the same fashion as fishing nets. Collapsible plastic pipe suitable for this purpose is already available and used to convert irrigation channels to pipelines to reduce evaporation losses. Lengths of this plastic collapsible pipeline are joined with metal collars to which the ends of the pipe are clamped.

The pipe joining collars could include propellers and electric motors to form a 'disc pump'. The electric power cable to provide power to these disc pumps could be incorporated within the pipeline. The pipeline would have near neutral buoyancy but the disc pump units would act as weights to keep the pipe where it was deployed.

6.3 Marine Current Turbines

Ideally the energy to pump cooling water should come from a renewable source. In this case tidal power is preferable due to its reliability and the accelerated currents through reef openings.

Tidal turbines can be moored as single units or strung together to form a "tidal fence" which need not entirely close a seaway (see Figure 6.1). A tidal fence can be used to slow a tidal flow creating sheltered waters and reducing the heat flux of "hot" currents, yet is open to marine life and the passage of boats so that seaways continue to function.

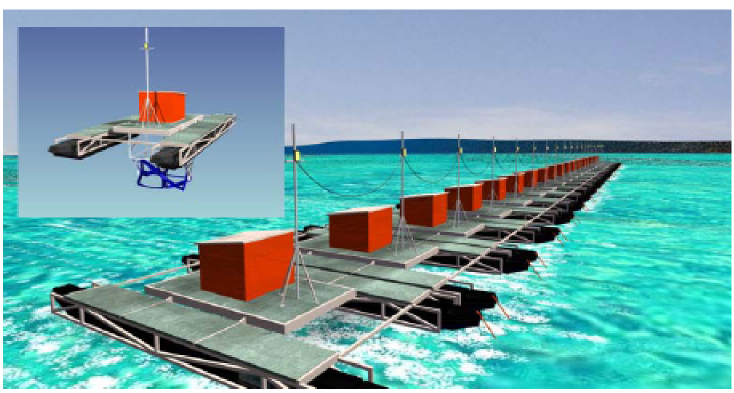

Figure 6.1: Relocatable Array of Pontoon Based Tidal Current Turbines

Marine current turbines are "open flow" like very slowly rotating wind turbines. While wind turbine aerofoils move at 8 to 18 times the wind speed tidal turbine hydrofoils move at 2 to 3 times the water speed (Gorlov, 1998). The velocity of tides is far lower than typical wind speeds. The hydrofoils have rounded leading edges and when cross-flow turbines are used there are no propeller tips.

Unlike earlier barrage dam tidal schemes, they do not cause sedimentation and are open to the migration of fish, marine mammals and other marine biota. There are no damaging large pressure gradients. The fixed structure around the hydrofoils is an artificial reef.

If it is necessary to run pumps at a high rate for an extended period this could be achieved by increasing the number of turbines that are deployed to produce renewable energy to power the CoolReef pumps.

7. Reef-pH

Given that coral communities are challenged by anthropogenic CO_2 induced acidification of their habitat (see above), one approach to mitigation is to chemically neutralize the acidity in situ with the addition of a chemical base: acid + base → salt (+ water). Indeed, the chemical reactivity of carbonates and hydroxides with CO_2 can be exploited to absorb excess, hydrated CO_2 and thus moderate or buffer pH excursions, e.g.,

$$CaCO_3 + H_2CO_3 \dashrightarrow Ca(HCO_3)_{2aq} \qquad (1)$$

$$Ca(OH)_2 + 2H_2CO_3 \dashrightarrow Ca(HCO_3)_{2aq} + 2H_2O \qquad (2)$$

Such schemes have been previously proposed for marine CO_2 capture/storage (Kheshgi, 1995; Rau and Caldeira, 1999; Harvey, 2008), but it is also recognized that ocean acidity would be neutralized and/or its biological effects offset via the resulting addition of ocean alkalinity in the form of dissolved $Ca(HCO_3)_2$. A system of adding NaOH or $NaHCO_3$ to seawater has also been proposed (House et al, 2007). Coral calcification rates have been shown to be significantly enhanced with the addition of Ca or Na bicarbonate (e.g., Marubini and Thake, 1999; Langdon et al., 2000), probably because such addition elevates the carbonate (aragonite) saturation state known to be a critical factor in coral biocalcification (Marubini et 2008; Cohen and Holcomb, 2009).

However, there are a number of practical issues that limit the large-scale use of reactions 1 and 2 for coral reef preservation/restoration. First, reaction 1 can only be spontaneously driven to right under substantially elevated CO_2 (H_2CO_3); $CaCO_3$ is virtually insoluble in present-day, air-equilibrated surface seawater. Therefore, dissolution can only occur in the presence of high CO_2, and/or carbonate undersaturated conditions such as found in seawater equilibrated with power plant exhaust (Rau et al., 2007) or in the subsurface ocean (Harvey, 2008), neither of which may be in close proximity to affected corals. Secondly, since $Ca(OH)_2$ is not naturally abundant, use of reaction 2 would conventionally require hydroxide production via energy and carbon intensive calcination of limestone (Kleshgi, 1995).

7.1 AWL Technology and Performance

To address these issues, an electrochemically assisted version of reactions 1 and 2 has been demonstrated (Rau, 2008; 2009). This method takes advantage of the highly $CaCO_3$-undersaturated, low pH environment in the immediate vicinity of the anode of a functioning seawater water electrolysis cell to decompose calcium carbonate. The resulting ions, Ca^{2+} and $CO_3{}^{2-}$, then can migrate to the cathode and anode, respectively forming $Ca(OH)_2$ on the one hand and H_2CO_3 (or H_2O and CO_2) on the other. By maintaining a pH between 6 and 9, subsequent hydroxide reaction with CO_2 primarily produces dissolved calcium bicarbonate (reaction 2). Experiments have shown that: i) >4X more hydroxide is produced in electrolyzed seawater when $CaCO_3$ encases the anode, ii) this hydroxide is subsequently consumed via absorption of CO_2 from air (rather than a concentrated source), and, iii) the dissolved inorganic carbon content of the seawater is thus increased by some 30% (Rau, 2008). The proposed net reaction is:

$$CaCO_3 + 2H_2O + CO_2 + \text{DC electricity} \rightarrow 0.5O_2 + H_2 + Ca(HCO_3)_{2aq} \qquad (3)$$

with a minimum work requirement of 266 kJ per net mole $Ca(HCO_3)_2$ produced.

Even with inefficiencies, a realized net energy expenditure lower than the preceding quantity appears possible considering energy recovery via oxidation of the H_2 produced by the electrolysis. Otherwise, the market value of the H_2 produced and CO_2 mitigated (carbon credits) would help offset the cost of the simultaneous hydroxide/alkalinity production.

The carbon benefit of the process would be maximized via the use of electricity derived from non-fossil sources such as ocean wind, wave, tidal, or solar energy. Thus, floating or shore-based systems could be placed in close proximity to coral reefs, considering the abundance of the required electrolyte (seawater), $CaCO_3$ (carbonate sands), and ocean energy that are typically nearby.

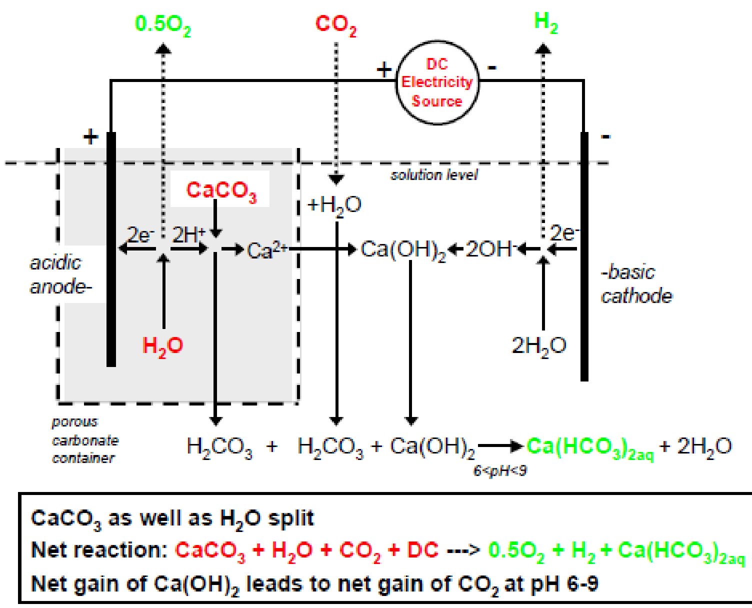

Figure 7.1: Electrolyser for Electrochemically Accelerated Weathering of Limestone (after Rau, 2008)

Note that in-situ electrolysis of seawater has been previously proposed as a method of reef building (Hilbertz, 1992). However, while enhancing $CaCO_3$ precipitation, this method does so at the expense of net ocean carbon and alkalinity removal, in contrast to the net carbon and alkalinity addition offered by the method above. A critical issue for both methods is Cl_2 generation common in seawater electrolysis. This hazardous emission might be avoided via the use of high or low current densities, O_2-selective anodes, or ion-selective membranes (Rau, 2008). Further research is needed to better determine the potential scale, and monetary and environmental cost/benefit of such systems.

8. Reef Environment Management

We have described four technology systems ReefTemp, ReefGrid - FAIMMS, CoolReef and Reef-pH. In this section we consider how they can be linked to provide a reef management authority (eg. GBRMPA) with a capacity to avoid coral bleaching and locally reduce ocean acidification.

ReefTemp provides whole of coast monitoring and early warning (say 1 month) of locations where bleaching event conditions are developing. Early warning is the trigger to establish more detailed monitoring.

ReefGrid-FAIMMS provide the communications capability for the reef management authority to monitor in real-time through-the-water-column temperatures and profile local currents. This data stream would be processed by computer modelling software that will predict temperature rises and current movements. If coral bleaching conditions continue to develop then CoolReef units could be deployed to the locations identified by the analysis software.

CoolReef units can be dispatched from response centres and deployed either from charter or volunteer boats or from a trailerable “hub” boat sent with the equipment. Local response centres could operate from ports or marinas and be staffed by trained volunteers interested in preserving their local environment and livelihoods. The reef management authority would provide the volunteer training and a deployment plan for each event based on information from the modelling and analysis software.

CoolReef plastic pipelines and pumps would be deployed and connected to the “hub” boat anchored nearby which has the power supply hub and radio data communications to the FAIMMS node already at the site. A string of tidal turbines could be deployed so that their influence on tidal and/or ocean currents would direct hot surface flows away from the endangered reef. The turbines produce DC power, which would be fed to the power supply hub which controls the various pumps as directed by an onboard controller which receives instructions via the radio link and FAIMMS node. This operational plan is similar to the strategies employed to respond to bush fires or oil spills.

Reef-pH is more akin to farming operations such as irrigating and fertilizing crops. The decline in the health and strength of coral reefs due to increasing ocean acidity can be reversed locally by the special purpose electrolyser which processes limestone or marine carbonate aggregate/sand to produce bicarbonate. The facility needs to be supplied with the such calcium carbonate particles together with electricity (preferably renewable) and seawater, and should be located up-current and in close proximity to reefs, on or off shore.

The solution from the facility needs to be distributed at regular intervals in appropriate concentrations and rates to the reefs being managed. This requires continuously updated detailed knowledge of the pH, temperature and currents around coral reefs. These requirements can be met by the same FAIMMS nodes and instrumentation as used for CoolReef with the addition of pH sensors.

The solution can be distributed using the trailerable "hub" boats and deployable pipelines and pumps of the CoolReef equipment. Alternatively this dual use may justify permanently installed facilities which can then perform both the temperature regulation and PH regulation/reef feeding operations. These facilities could be powered by a tidal turbine "fence" along the outer reef.

9. Conclusion

The measures described above may be viewed as intrusive to some in the marine conservation communit – like seeing a loved one on life support. However, such courses of action may be necessary with the continued absence of effective measures to stabilize, if not reduce, atmospheric CO_2. It is therefore time to consider that, in addition to monitoring and forecasting environmental impacts, science and engineering can also provide a safe and cost effective alternative to the crisis facing marine ecosystems. The urgency and magnitude of the excess CO_2 problem demands we work together to solicit and evaluate all options for saving coral reefs. Evaluating potential methods of mitigating thermal and acidification effects on corals should be incorporated into ocean research and management policies going forward.

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