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### Carbon Dioxide Removal (CDR) and Ocean Alkalinity

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First, I would like to just thank my sponsor, which is the UK Research Council's program on greenhouse gas control. I would also like to thank my coauthors on this. But, of course, any of the views I express are my own.

[Slide] The idea of increasing ocean alkalinity is essentially a way of using a process that happens within nature, and that is the process of weathering, but enhancing that on a time scale that is relevant for the problem that we are talking about.

I have put on the screen there one weathering reaction, and that is the weathering of a mineral called forsterite or olivine. What is happening there is on the left-hand side of the arrow you have your weathering reaction, the olivine is dissolving; and on the right-hand side of the arrow you have the weathering products, which are magnesium ions that are dissolved in water and you have bicarbonate ions that are dissolved in water.

And it is those bicarbonate ions that are essentially the storage reservoir for this carbon. So we are not talking in this case of precipitating any minerals to store the carbon but we want to keep the carbon dissolved as bicarbonate.

[Slide] The benefit of storing the carbon as bicarbonate is that you get essentially two-for-one in terms of carbon to magnesium or calcium when you are talking about dissolving a silicate mineral, so something like forsterite. When that dissolves, you capture two carbons for every magnesium.

Storing it using bicarbonate is the historic mechanism. You also open up the possibility of using carbonate minerals to store carbon. We know that they weather a lot quicker than the silicate minerals.

There is a problem here, though, and that is that the carbonate minerals — in this case calcite — do not spontaneously dissolve.

[Slide] What I have shown here is an alkalinity profile through the Pacific Ocean. You can see that alkalinity changes with depth. But the important point in this image is that the black line represents the saturation horizon for carbonate minerals, for aragonite or calcite, and above that line we know that carbonate minerals are not going to dissolve in the ocean.

So we cannot just put carbonate minerals into the ocean and expect them to dissolve because above that line they are supersaturated.

[Slide] To get your carbonate mineral to dissolve we need to do some work to it. We could either change the environment in which the carbonate mineral is dissolving and increase the CO<sub>2</sub> concentration. This is the idea called the "accelerated weathering of limestone," where you put your carbonate into a reactor with high CO<sub>2</sub>, and that forces dissolution.

[Slide] We can also create our own highly reactive minerals. We can create more reactive minerals by putting carbonate minerals into a lime kiln and creating a mineral like portlandite, and we know that that rapidly dissolves at ambient conditions.

Just a plug for another project I am involved in. I am looking at material streams from different industries where these sorts of minerals are produced. The iron and steel industry is an example of that.

[Slide] This is quite a complicated slide. The dynamics of carbon in the ocean are quite complex. The important point I want you to take away from this slide is that the concentration of carbon in the oceans is large. It is about 40 times the carbon concentration in the atmosphere.

But you can see the two arrows going out of the ocean are really quite small. That means that the carbon residence time in the ocean is something on the order of a million years, so it is really long-lived within the ocean.

The big question, I suppose, with increasing ocean alkalinity is the carbon store: If we increase carbon in the oceans, does that increase the rate at which it flow out of the oceans? That is a big unknown within this field. The question is: Well, if it is a million years residence time and that decreases to half a million years — then that is still a relevant permanent carbon store for what we need.

[Slide] There is a whole range of different proposals — I would not call them technologies — that have been put forward to increase ocean alkalinity. There are things like enhanced weathering, which is dissolving minerals on the land surface, or enhanced weathering, adding minerals to the coast or directly to the ocean; and there are more industrial-type technologies of dissolving minerals in reactors, like the accelerated weathering of limestone, electrochemical weathering, or turning your carbonate into lime and putting that into the oceans.

I do not have time to go into all of these technologies and all the caveats behind those. But what I wanted to do with this talk is just focus on the shared environmental impacts that these technologies have on the oceans, and that is increasing ocean bicarbonate.

All of these technologies have the same essentially underlying carbon storage mechanism, and that is creating bicarbonates within the ocean. That is what this talk is going to focus on.

[Slide] Just as a quick overview, this is just a review of some of the costs that have been forward for these ideas. While I would not expect these costs to be particularly accurate per se, they do show that the range of costs might be comparable to some of the other ideas that have been put forward to draw CO<sub>2</sub> out of the atmosphere. Just on a cost basis, this is not something that we should discard at the moment. It is certainly something that seems reasonably competitive.

[Slide] You have probably seen the top panel in this diagram before, showing the CO<sub>2</sub> concentration through time, for the past 800,000 years, and that shows the fluctuations of CO<sub>2</sub> between glacial and interglacial cycles.

The bottom panel may be something you have not seen before. That is a recreation of the saturation state of carbonate within the oceans over the same time period. You see that fluctuates within that time period between 6 and 8.

[Slide] Going down on the omega calcite axis, the Y axis on that graph, is essentially what ocean acidification is, and it is bad news for shell-forming organisms within the ocean. We might want to essentially be somewhere within the historic data points if we want to protect marine organisms.

[Slide] Of course, going over that might end up having a negative environmental impact as well, so there is potentially within this diagram a boundary for us to aim for.

[Slide] This is some modeling work I did where I looked at a business-as-usual emissions scenario, and that is the red line on both of those graphs. You can see that the CO<sub>2</sub> increases potentially over the next 100 years. The red line in the bottom right-hand pane is what would happen to the carbonate saturation state in the oceans, and that is essentially ocean acidification.

The blue line represents if all we did was increase ocean alkalinity to counteract that — and I am not suggesting that as a potential option — we would end up with essentially a saturation state in the ocean that was restored to what preindustrial levels were. In the worst-case scenario, we would be restoring saturation states to the preindustrial level; and probably in a more realistic scenario, we would be mitigating the effects of ocean acidification.

This is essentially the broad-scale, very fundamental, intrinsic environmental impact of each of these technologies.

[Slide] Of course, it is not as simple as that. This image was produced by modeling the impact on the ocean, the spatial distribution of that impact, if you only added the alkalinity in one or two places. So, if we do not spread out the addition, we might end up with hot spots.

[Slide] I do not want to give you the impression that all of these impacts are benign, but essentially the intrinsic impact behind all of these seems to be relatively benign, and they all have their own potential impacts. To understand the impact of any of these on the environment, we would need to go up to higher resolution and look at the technologies individually.