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In the last section we examined the primary reason why there's so much carbon in the world's oceans. That is, the fact that carbon dioxide doesn't simply dissolve in the ocean as a gas, but reacts to form many different species, which allows the ocean to hold a good deal more carbon than it otherwise would be able to. There are other reasons though, that the ocean holds more carbon than one might expect.

We can see this by looking at profiles of dissolved inorganic carbon in the world's oceans. First a note about what we're looking at. So these are vertical profiles with depth on the vertical axis in meters, and on the horizontal axis is latitude. So this is like taking a slice out of the Atlantic Ocean on the top and the Pacific Ocean on the bottom, and then just plotting the observed concentrations of dissolved inorganic carbon in the contours and colors.

You see very quickly that at the top you have the lowest concentrations of dissolved inorganic carbon, and toward the bottom you have much higher concentrations of dissolved inorganic carbon, or DIC. And this is particularly true in the Pacific Ocean. We also see these lateral gradients in DIC that are observed at depth. And so the question for both of these is, why does this occur?

The importance of these vertical gradients is that by having lower DIC near the surface of the ocean and higher DIC at depth, the ocean is able to hold more carbon than one might otherwise expect. The atmosphere only equilibrates with the DIC that's in the surface ocean and not that at depth. And so if you have lower DIC in the surface ocean, you have a greater propensity for CO2 to move from the atmosphere into the ocean.

It's also worth noting that it's somewhat surprising that a liquid like the ocean would maintain gradients. It's of course constantly mixing, and so in order to maintain gradients such as this, you have to have processes that are pumping carbon from lower concentrations to higher concentrations. There are three of these so-called pumps, and I'll briefly review them here.

The first of the pumps has to do with the fact that the deep ocean is much colder than most of the surface ocean. You see here contours of temperature. It's expressed as theta because it's been corrected for the effect of increasing pressure on temperature. So it's known as potential temperature. The important point is that the surface of the ocean is much warmer than at depth. The only places where deep ocean temperatures are actually observed at the surfaces are in the polar regions. This reflects the fact that high latitude waters are the waters that get dense enough to sink to depth, and these waters resupply the abyss.

The importance of this temperature gradient is that carbon is more soluble in cold waters. This is a plot of equilibrium DIC concentrations versus temperature, holding all other things constant. And what we see is that at high temperatures characteristic of tropical waters, you have about 10% less DIC than at very cold temperatures.

As a result, the ocean's circulation maintains a gradient in DIC. Near the poles, in the high latitudes, the ocean loses heat, and as a result it has a greater solubility for carbon dioxide. And so carbon dioxide moves from the atmosphere into high latitude waters. Those high latitude water sink and move into the deep ocean. Those deep waters up-well primarily a lower latitudes where the ocean gains heat, it gets warmer. And as a result, carbon solubility decreases. This carbon dioxide then moves into the atmosphere. But the overall effect of this circulation is to maintain a gradient where you have lower DIC at the surface, and higher DIC at depth.

You can see this in this map of annual mean carbon dioxide flux into and out of the ocean. Positive values are places where carbon dioxide is moving into the ocean from the atmosphere, and negative values are the opposite. So we see that at higher latitudes carbon dioxide is primarily moving into the ocean, sinking to depth with deep waters. And at lower latitudes where cool waters are upwelling and warming up CO2 is moving out of the ocean and into the atmosphere. Changes in these patterns of upwelling and down-welling will affect how anthropogenic CO2 moves into the ocean in decades and centuries to come. In addition, the overall warming of the ocean will decrease CO2 solubility in the ocean.

The second two pumps are both known as biological pumps. And the first of these biological pumps is the soft tissue pump. In the world's oceans phytoplankton live in the photic zone, that is the upper reaches of the ocean where light penetrates. These phytoplankton grow, they fix carbon into organic matter, they're consumed by higher organisms, and some of this organic matter sinks to depth in the ocean. As it sinks it's broken down and forms inorganic carbon, or CO2. This biological activity of taking carbon dioxide, turning it into organic matter that sinks, and pulls carbon into the deep ocean, acts as a second pump that maintains low DIC near the surface and higher DIC at depth.

You can see this nicely in this plot of sinking particle flux from the North Pacific Ocean that was measured in the 1980s. It is fairly representative of what goes on in the world's oceans at large. You see very high particle fluxes near the surface, and decreasing particle fluxes at depth. As most of these particles are biological matter, what's happening is that you have a lot of biological matter being produced near the surface. It's starting to sink, but then as it sinks it's getting broken down and turned into dissolved carbon and nutrients.

The last of these pumps, and the second biological pump, is the so-called carbonate pump. Some phytoplankton create calcium carbonate shells which sink very efficiently too deep waters. These deep waters are more corrosive to calcium carbonate. Calcium carbonate dissolves. Calcium carbonate dissolves and returns that DIC back into solution, again maintaining higher DIC at depth.

The point of all this is that these pumps, the solubility pump, the soft tissue biological pump, and the carbonate biological pump act to move carbon from the atmosphere into the surface ocean, and from the surface ocean into the deep ocean. And these processes will act to take CO2 out of the atmosphere and move it into the ocean with time.

What's shown on this plot is a comparison of different models in which 1,000 petagrams of carbon were instantaneously added to the atmosphere, and then natural processes were allowed to remove this carbon from the atmosphere over time. You see that over the first 1,000 years following the pulse, something like 80% of the carbon is removed from the atmosphere. This primarily reflects carbon moving from the atmosphere into the ocean.

Over longer time scales carbon continues to decrease in the world's atmosphere. And over time scales of 100,000 to a million years CO2 concentrations in the atmosphere eventually return to their baseline values. So the ocean primarily determines the time scale of this response, this decline in CO2 concentrations from initial values to lower values in the first 1,000 years. Because that's the approximate time scale of the ocean circulation. What about these longer time scales? Why does carbon dioxide continue to decrease after it's already equilibrated with the ocean?