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Denial and Acceptance

Bolin, B. & Eriksson, E. (1958). Changes in the carbon dioxide content of the atmosphere and sea due to fossil fuel combustion. In *The Atmosphere and the Sea in Motion: Scientific Contributions to the Rossby Memorial Volume* (ed. B. Bolin), pp. 130–142. Rockefeller Institute Press, New York.

Revelle, R. & Suess, H.E. (1957). Carbon dioxide exchange between atmosphere and ocean and the question of an increase of atmospheric CO_2 during the past decades. *Tellus*, **9**, 18–27. 9 pages.

Callendar asserted in 1938 that the CO_2 concentration in the air had risen between the turn of the century and the early 1930s. He also argued that the average temperature of the Earth had risen in that time, as a result of this rising concentration of the greenhouse gas CO_2. One scientific response to this was to refine the calculations of the potential impact of CO_2 on the Earth's temperature, and it was Manabe and Hansen that ultimately got this right. Another was to measure the CO_2 concentration in the air more accurately, which David Keeling did. The third approach is exemplified by the following two papers, by Revelle and Suess in 1957 and Bolin in 1958, who tried to figure out whether the oceans would quickly mop up any CO_2 emission, preventing an atmospheric increase. A comparison of the two papers is interesting, in that Revelle and Suess seemed almost to be in a psychological state of denial, while Bolin looked at the same problem with greater sophistication in his analysis, but also with a mind that was open to the possibility that ocean uptake of CO_2 would be slow, leaving humans a strong potential impact on global climate.

Changes in the carbon-14 concentration of the atmosphere were taken as a starting point observation by both studies. Carbon-14 is produced in the upper atmosphere by a nuclear reaction driven by cosmic rays, the transmutation of nitrogen-14 to carbon. Carbon-14 is radioactive, decaying with a half-life of 5730 years. This lifetime is long enough that the carbon-14 finds its way into trees, soil carbon, and the oceans. As the carbon dissolves in the oceans, some of the carbon-14 decays, so on average the carbon-14 concentration of the surface ocean is lower than that of the atmosphere, equivalent to an apparent "age" of the surface water of about 400 years. From this observation, and a knowledge of the relative amounts of CO_2 in the atmosphere and the ocean, Revelle and Suess calculated that the average lifetime of a CO_2 molecule in the atmosphere before it can expect to dissolve in the ocean is about 7 years. On the face of it, it seems that a slug of new CO_2 to the atmosphere should dissolve in the oceans in 7 years, preventing any buildup in the atmosphere that would lead to global warming.

Revelle and Suess assumed that the ocean is well mixed. Our CO_2 slug may be important to the atmospheric concentration, but there is so much dissolved carbon in the ocean that if the slug is mixed in, the increase in the ocean concentration would be negligible. Therefore, the slug released to the atmosphere will increase the downward CO_2 flux, dissolving into the oceans, much more than it would change the upward flux of CO_2 evaporating from the oceans. However, in a point picked up by Bolin and Calendar but missed by Revelle, the ocean takes a long time to mix. The surface ocean concentration of CO_2 increases more than the average for the whole ocean, and the rate of CO_2 degassing to the atmosphere increases as the surface ocean

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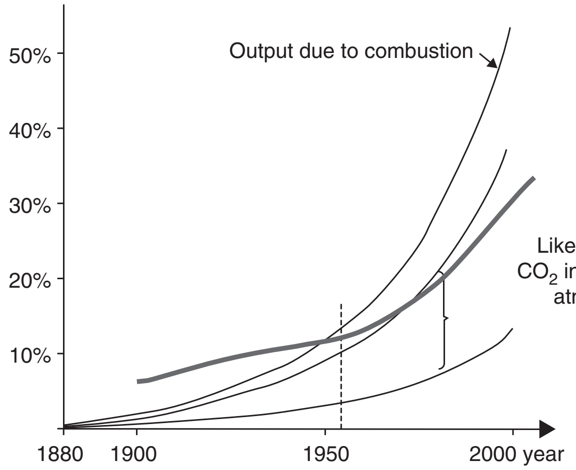

Fig 13.1 **Estimate of likely range for CO_2 increase int[illegible]tmosphere as a result of fossil fuel combustion according to UN estimatefs.**

concentration of CO_2 builds up, almost enough to counteract the invasion of the CO_2 slug into the ocean. There is a difference here between net invasion and CO_2 exchange; invasion draws down the atmospheric CO_2 concentration but exchange does not.

Another complicating factor seems to have come to Revelle and Suess at a late stage in the preparation of the manuscript; the paper reads as if it was pointed out by one of the reviewers. The way the carbon chemistry of seawater works, added CO_2 reacts with carbonate ion, CO_3^-, to form the pH-neutral bicarbonate ion, HCO_3^-. One might naively assume that doubling the CO_2 concentration in the air would double the concentrations of all of the forms of dissolved carbon in the seawater, including the bicarbonate and carbonate ions. This would be the case if the acidity, or pH, of the water were held constant by some external buffer. The reality is that the pH of seawater changes as the CO_2 invades, and the water only holds about a 10th of the naive expectation. This factor of 10 is called, perhaps a bit unfairly, the Revelle buffer factor.

Revelle and Suess' Fig. 1 is essentially a slide rule for calculating how much fossil fuel CO_2 there could be in the atmosphere, based on the lifetime of CO_2 and the observed changes in carbon-14 in the atmosphere, but it ignores the factor of 10 from the buffer chemistry, apparently because the model was already done, the figure already drafted, when the buffer chemistry effect was tacked on to the end of the manuscript as an afterthought. Figure 2 was added to illustrate what a factor of 10 slowdown in CO_2 uptake should look like, but it looks hastily drawn, with straight lines for the atmospheric CO_2 concentration with time instead of slower versions of the curved lines from their real solution. A further problem with their Fig. 2 is that they assume that CO_2 emissions will be constant with time, while their Table 1 shows clearly accelerating CO_2 emissions.

In every instance, Revelle and Suess seem to rebel against what their analysis wants to tell them, that the oceans will not control atmospheric CO_2 concentration quickly enough to prevent human-induced climate change. Based on the authors' prior and subsequent careers in science, we judge that their reluctance to see the results of their analysis stems from a psychological state of denial, rather than a deliberate effort to deceive. In contrast, the analysis of Bolin, 1 year later, is a breath of fresh air, brilliant in its clarity. The slow mixing time of the ocean, the impact of the buffer chemistry, and the acceleration of CO_2 emission with time are all accounted for, and the result is a prediction of future CO_2 concentration trends in the atmosphere, in Fig. 13.1, that looks stunningly like what actually turned out to happen.