the carbon dioxide balance than can change. First the oceans absorb more carbon dioxide to come to equilibrium with the larger atmospheric concentration. However, only the surface waters can absorb this gas and because of the slow circulation of the oceans, it probably takes at least ten thousand years for this process to come to equilibrium. Whenever the carbon dioxide amount is increasing an upper limit for the amount absorbed by the oceans can be found at any time by assuming the atmosphere-ocean system is always in equilibrium. The actual amount absorbed by the oceans will be considerably less than the amount calculated in this manner for at least several centuries after a sudden increase in the atmospheric carbon dioxide amount. In the first few centuries the surface ocean waters can absorb only a relatively small fraction of the additional carbon dioxide.

The second factor that can change is the amount used in photosynthesis. A higher level of photosynthetic activity can be supported by the increased carbon dioxide amount. As previously discussed, this process temporarily

Does Science Progress? Gilbert Plass Redux

Gavin Schmidt

Considering today's concerns about human-driven climate change and the need to cut carbon emissions, it's interesting to look back at a time (not that long ago) when the idea that carbon dioxide (CO_2) affected climate was very much a fringe concern. Gilbert N. Plass's 1956 article (reprinted in this issue of *American Scientist)* was only the start of a quite rocky road to modern respectability for an idea born in the 19th century; even he might be surprised to see how it has become completely mainstream (despite what one might read on the Internet!).

This paper, the insights it contained, and the calculations and forecasts it made actually constitute a great example of how, despite reaching bottom-line conclusions very similar to pronouncements made in the recent Intergovernmental Panel on Climate Change (IPCC) report, the science that underlies those conclusions has improved remarkably. It is also a great example of the role luck plays in determining one's role in scientific prosperity (but more on that below).

Before discussing the detail of what was in that paper, it is worth pointing out what Plass could not have known. He did not know how fast CO_2 was accumulating in the atmosphere—Charles Keeling would start his seminal measurements at Mauna Loa only in 1957. Neither did he know how CO_2 had varied in the past—the first ice core results only emerged in the 1980s. But he was still able, with his understanding of infrared spectroscopy, to write a paper that qualitatively predicted both these results—although with methods that we can now recognise as being incomplete—and correctly concluded that the impact of CO_2 on climate would be clear by the end of the 20th century. There are other things that we know now that he could not possibly have known—the importance of other greenhouse gases (methane in particular, which wasn't recognised as an important contributor to anthropogenic forcing until 1974, but also chlorofluorocarbons and N_2O, which have also increased dramatically because of human influence) and the role of human-emitted particulates and low-level ozone precursors.

To be sure, there is much that marks the paper out as a product of its era: There is an excessive focus on single-factor explanations of all climate changes and a penchant for what would now be considered naive back-of-the-envelope estimates of the impacts of small changes on very complex systems. And as befits publication in a popular science magazine, there is a lot of big-picture discussion, although perhaps in excess of what would be considered prudent today.

The paper revolves around three main themes: the modern day carbon cycle and the fate of human-produced CO_2, the calculation of the radiative impact of that CO_2 and the resulting temperature rise, and the possibilities for CO_2 playing a role in climate changes in the past. I'll review the first two of these themes and leave the far more speculative discussions about the cause of the ice ages for another time.

Plass knew that atmospheric levels of CO_2 were around 300 parts per million by volume (ppmv) and correctly noted (as had Guy Stewart Callendar almost 20 years earlier) that human use of fossil fuel would lead to an increase in atmospheric levels of CO_2. He was actually a little optimistic, though, in assuming that only 6×10^9 tons of CO_2 per year (equivalent to 1.5 gigatonnes of carbon per year, or GtC/yr) were being emitted. Current estimates suggest that emissions in 1956 were already almost 50 percent higher than that (8.8×10^9 tons CO_2 /yr or 2.2 GtC/yr).

He also understood enough of the terrestrial and oceanic carbon cycle to know that uptake of the anthropogenic carbon would be slow. He had two quite telling insights: First, although the residence time for carbon dioxide in the atmosphere (the total amount of CO_2 divided by the flux in and out of the ocean) is on the order of a few years, the perturbation time is much longer—even up to a few tens of thousands of years—because of the slow uptake in the deep ocean and the buffering effects of the ocean chemistry. Second, he realised that the added carbon in the ocean would cause increasing acidification with consequent impacts on marine life (although he did underestimate how big this effect would be).

Combining the rate of increase of fossil carbon and lack of uptake in the ocean, he estimated that the CO_2 levels might increase 30 percent in a century. Since 1850, CO_2 has actually increased by more than 100 ppmv (36 percent above pre-industrial values), and so this appears to be a reasonable prediction. However, Plass was lucky. In underestimating both the current anthropogenic emissions and the uptake by the ocean, his two errors roughly cancelled.

Plass's real contribution, however, is in his assessment of what that ex-

withdraws some of the additional carbon dioxide from the atmosphere into the organic world. However, in a relatively few years the increased rates of respiration and decay bring this process back into equilibrium and only a relatively small amount of carbon dioxide is permanently lost from the atmosphere. Thus it appears that a major fraction of the additional carbon dioxide that is released into the atmosphere remains there for at least several centuries.

Even if there may be some question as to whether or not the general amelioration of the climate in the last fifty years has really been caused by increased industrial activity, there can be no doubt that this will become an increasingly serious problem as the level of industrial activity increases. In a few centuries the amount of carbon dioxide released into the atmosphere will have become so large that it will have a profound influence on our climate.

After making allowance for industrial growth, a conservative estimate shows that the known reserves of coal and oil will be used up in about 1,000 years. If this occurs, nearly 4×10^{13} tons

tra CO_2 would do to the climate. His calculations included the fact that you have to consider the whole atmospheric column, and that despite the large amount of water vapor near the surface, there are always large parts of the atmosphere where CO_2 is a very important absorber and emitter. This meant that the impact of changing CO_2 would not be as negligible as had been thought over previous decades. These calculations require good knowledge of how all the various wavelengths are absorbed by each component in the atmosphere (including clouds), and how that changes as a function of temperature and (most importantly) pressure. The data for these absorption spectra have improved enormously in the past 50 years as has the capacity to do all these calculations, so one might anticipate that this is where Plass would have been most overtaken by scientific progress. However, Plass actually did a pretty good job. Converting to more modern units and doing a little publication archaeology, we can see that he estimated the radiative forcing by a doubling of CO_2 in clear sky conditions at 8.3 watts per square meter (W/m^2) and that in cloudy conditions it would be 5.8 W/m^2. The accepted value for the global average today is around 4 W/m^2 with about a 10 percent uncertainty (including both cloudy and clear-sky conditions). Thus while his numbers were a little large, they were within a factor of two of the right answer, and much closer than the near-zero impact that had been previously considered to be the best estimate.

To convert the radiative forcing into a temperature change, Plass relied on a conversion factor of about 0.43°C/(W/m^2) (again, updated to more modern units). This was not independently calculated by him and referred only to the "no-feedback" case where all other atmospheric components (for example, water vapor and clouds) stayed the same. Modern estimates for the no-feedback sensitivity are a little lower (around 0.3°C/(W/m^2)). The basis of his 3.6°C change for a doubling of CO_2 is then seen as a combination of his over estimated forcing and a slightly high no-feedback sensitivity. Modern estimates of this number are around 1.2°C. Plass was aware of the potential for amplifying feedbacks, particularly via water vapor and cloud changes, but the quantification of these effects would have to wait another 10 years for the work of Fritz Möller and subsequently Suki Manabe and colleagues.

Thus even though the headline number in the Plass article is well within the range of the modern IPCC reports (which give a total sensitivity of between 2 to 4.5°C for a doubling of CO_2), it isn't quite fair to give him full credit since his number doesn't include many important factors that he was not able to quantify. Nonetheless, he realized full well the importance of numerical computation for these estimates but was working at the edge of what was then possible.

Similarly, his estimate for the temperature change for the 20th century of 1.1°C was uncannily close to the actual change of roughly 0.7°C. However, as he himself admits, this "could merely be coincidence," and unfortunately I have to confirm that. Two other factors that he was not really aware of complicate this estimate dramatically. The first is the thermal lag of the system due to the heat capacity of the oceans. This delays substantially (by decades to centuries) the full impact of a change in greenhouse gases, as it takes a long time for the ocean surface temperatures to equilibrate with the new radiation balance. Secondly, he probably wasn't aware that other aspects of atmospheric composition—as mentioned above—were being greatly affected by human activity as well.

Nonetheless, a number of conclusions that he drew were almost prophetic. He was correct in assuming (against the conventional wisdom of his time) that moves towards nuclear energy would not make a substantial difference to carbon emissions. He was also correct in thinking that the price of removing the carbon from the air would be prohibitively expensive (as it has turned out, although some progress is being made).

So does science progress? Yes, of course. Gilbert Plass had the right framework for this problem and foresaw most of the issues, but the detailed rendering of the calculations—for the carbon cycle, for the radiative transfer, for the existence of feedbacks, for the temperature response—have all become much more sophisticated and complete. What once were rough estimates have been much more tightly constrained. Speculations about growth rates and past behavior have been confirmed by multiple observations.

Nonetheless, the coincidences of some of his numbers and the ones we know today are just that, coincidences, and so some part of the high regard in which we hold Plass today may simply be due to luck. Indeed, Lewis Kaplan, the author of a subsequent and more accurate calculation, has been all but forgotten since he incorrectly concluded that CO_2 could not play a role in climate change. In 50 years time if someone reviews my work, I would hope to have been as lucky as Gilbert Plass.

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