CO_2 Rising

The World's Greatest Environmental Challenge

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Introducing the CO_2 Molecule and Its Carbon Atom

My goal in writing this book is to provide essential information about what is surely the longest-term and most globally distributed environmental problem. I will aim for brevity, but I will lay out the essential inner workings of the global carbon cycle, concentrating on what I believe every global citizen should know.[1]

Carbon dioxide (CO_2) is the primary reason to be concerned about global warming and its consequences. The world appears locked in a certain direction. As CO_2 is increasing, so is civilization's dependence on fossil fuels, which creates ever-growing rates of CO_2 injection into the atmosphere. Climate effects will likely lead to serious disruptions in agriculture, coastal cities, human health, and the present web of life. Already, in the retreat of Arctic sea ice and mountain glaciers, and in shifts of the habitats of some species, we have warnings of change that will potentially be huge. But the issues are complicated. Not all the effects will be perceived everywhere as "negative." For instance, higher carbon dioxide, considered as an isolated factor, could enhance the growth of crops. However, the pertinent factors are interconnected, and they act as systems of feedback loops within the complex system of the biosphere.[2] I will unfold some of that complexity.

The CO_2 that goes into the air from combustion of fossil fuels does not stay there, but begins circulating throughout the biosphere. Furthermore, the fossil-fuel emissions are dwarfed by several natural inputs to the atmosphere, such as the constant releases of CO_2 from soil bacteria. Insofar as carbon dioxide is a perfectly natural gas that interacts with plants, algae, and the oceans—and indeed with everything in the biosphere—why doesn't nature just absorb the excess?

Understanding these and many more features that I feel are crucial for the drama's stage set is not particularly difficult, but the convoluted paths of carbon can stretch the imagination. Following those paths requires basic concepts, such as the presence of carbon in various chemical guises and magnitudes in distinct zones or regions. These zones usually are not separated geographically, as continents are—although they could be, depending on the focus of inquiry. More often they are distinguished by types of material and forms of carbon. Carbon-cycle scientists call the zones "pools." I will use that term, but I also like "bowls" (a more concrete metaphor). The four major bowls or pools of carbon in the system of the biosphere are the atmosphere, the soil, the ocean, and life taken as a collective bowl. The bowls are connected by a web of fluxes, which integrates the system and makes the dynamics of how carbon shifts around both tricky and exhilarating to follow. The scales of the fluxes and the bowls cross both space and time and vary from the minute to the gargantuan.

The human body is a complex system, too. When a doctor evaluates your condition and then discusses it with you, the doctor presumes that you know the basic facts about how your organs work: that the heart pumps blood, the lungs bring in oxygen, the stomach digests, the kidneys filter, the gonads make sex cells, the brain thinks, and so on. The same level of knowledge is not generally there about the organs of the planetary physiology. Thus, here I think of myself as an anatomy instructor. We are after the very anatomy of the biosphere, with its global metabolic pathways in and out and to and fro with the ocean, the soil, the air, and all living things. There are lots of people out there offering prescriptions for the ailing biosphere, from legitimate experts to snake oil salesmen. In reality, no one has the silver bullet solution yet. I believe that one quintessential component for hope is for citizens to become members of an adequately informed public able to digest and question the various debates on what to do, which will certainly rage over the coming years as increasingly serious prescriptions are put forward.

Doing nothing other than staying on the current course is equivalent to tossing dice for the future. Indeed, we have already entered an era of gambling with the global environment, and therefore it would be beneficial to at least understand the nature of the dice.

Here are the basics of why carbon dioxide is considered an environmental problem.

Earth Warmer: The CO_2 Molecule

Molecules are, of course, made up of atoms. In a CO_2 molecule, a single carbon atom is bonded to two atoms of oxygen on either side. Often the atoms in molecules are depicted as hard little balls, somewhat spread apart and linked by Tinkertoy-like struts, or as touching.[3] Neither of these simple ways of picturing atoms is strictly true. In reality, atom balls are electrical whirlwinds, and the bonds that link them are strong electrical affinities. The bonds that carbon atoms enter into with other atoms are formed by shared electrons that sweep and swirl back and forth between and among the atoms. Some renderings show molecules that look like partially melted ice cubes in surreal shapes. That helps us picture the atoms blended together, emphasizing the fact that

The CO_2 Molecule and Its Carbon Atom

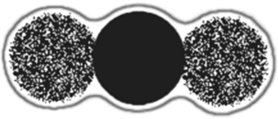

Figure 1.1 A CO_2 molecule, consisting of two oxygen atoms (shown in gray) and one carbon atom (shown in black).

the shared electrons form a truly new, higher-level entity: the molecule "above" the atoms. But no diagram can portray all the nuances of the reality, if only because the scale is below resolution by means of light (which is how we see objects that are close to our own scale).

In my diagrams, because I want to emphasize the individual atoms, I will draw simple balls, attached to one another and surrounded by an envelope to emphasize the reality of the molecule itself. Carbon atoms will always be black. Figure 1.1 shows the CO_2 molecule with its central atom of carbon.

The shared electrical bonds are not always exactly symmetrical. In the CO_2 molecule, the oxygen atoms are better at grabbing a portion of the shared electrical bonds than are the carbon atoms. That electrons have been pulled partially away from the carbon atom means that the carbon atom is in a relatively low energy state while in a CO_2 molecule. This has fundamental importance because we can burn fossil fuels, which before burning have their carbon atoms in higher energy states. The combustion that converts carbon from higher to lower energy states enables us to drive, to fly, to manufacture, to cook, to light our rooms, to heat our buildings, and to do many other things.

The story of fossil fuels and the rise in atmospheric CO_2 will unfold in the next few chapters, but first it is important to note how it is that this simple molecule possesses such powerful environmental effects.

CO_2 is a greenhouse gas. Molecules of greenhouse gases are capable of absorbing and re-emitting wavelengths of electromagnetic radiation that are in the infrared portion of the electromagnetic spectrum.

What is probably your most common experience with infrared waves occurs when you sit beside a fireplace or a campfire. Most of the air that is directly heated by the flames rushes straight up, so it is not this hot air itself that warms you; it is the copious flow of invisible infrared radiation, which is sent in all directions from the flames and the red embers.

Invisible to human eyes, infrared waves can be "seen" by sensors in the special facial hollows of pit vipers. This allows the vipers to detect temperature differences and thus to spot warmer prey (such as mice), even at night, against the background of the cooler soil. Military night-vision goggles take advantage of the difference in infrared emissions between the human body and cooler surroundings. Energy analysts who are hired to make buildings more efficient in winter often use cameras with special film or digital imaging to detect regions in a building's skin that are leaking heat.

What gives the CO_2 molecule its ability to absorb and (as a consequence of physics) re-radiate radiation in infrared wavelengths that are important to the atmosphere and the climate is its number of atoms: three.[4] "More than two" is the crucial concept here, because the other important infrared-capturing gases in the atmosphere also have three or more atoms in their molecules. When a gas has three or more atoms, it has modes of vibration inherent in its shape that can resonate with the frequencies of climate-affecting infrared waves. The matching enables the greenhouse molecules to intercept those waves and absorb their energy. Single atoms and two-atom molecules do not have those particular resonant modes. Just a few examples of other greenhouse gases make the point, if you count their atoms: water vapor (H_2O), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3).

The two most abundant greenhouse gases are water vapor and carbon dioxide, with water vapor the most important in terms of total global infrared absorption. But it is CO_2 that is the environmental driver of Earth's climate. Why? Because the open bodies of available water that we call oceans allow water vapor to adjust as an effect of the primary heating caused by CO_2. The amount of water vapor, which will increase in response to the increasing concentrations of CO_2, is therefore considered a climatic feedback to the primary greenhouse effect of CO_2.[5]

Besides water vapor, three other gases in the atmosphere are more abundant than CO_2. Argon is 25 times as abundant on a molecule-to-molecule comparison, but it travels alone as one atom (a "noble" gas that snubs its nose at relationships) and has no greenhouse effect. The other two are oxygen (O_2), more than 500 times as abundant as CO_2, and nitrogen (N_2), more than 2,000 times as abundant. With only two atoms to each molecule, they are not greenhouse gases.

There may not be much CO_2 in the atmosphere, but its effects on the climate are powerful. Infrared rays, which Earth uses to cool itself to space, are exactly what CO_2 is good at absorbing and re-radiating. It does not matter that CO_2 molecules are present in tiny amounts. What matters is what CO_2 molecules do to the rays emitted from Earth's surface. This is analogous to the way a few drops of food coloring can tint an entire glass of clear water. The colored drops, dispersed everywhere in tiny concentrations, still affect the light enough to alter the entire look of the water. Small can be potent.

Figure 1.2 shows, in a highly simplified sketch, how the greenhouse effect works. Crucial to this picture is the concept of the planetary energy balance. Earth's surface is warmed by the sun. But the surface does

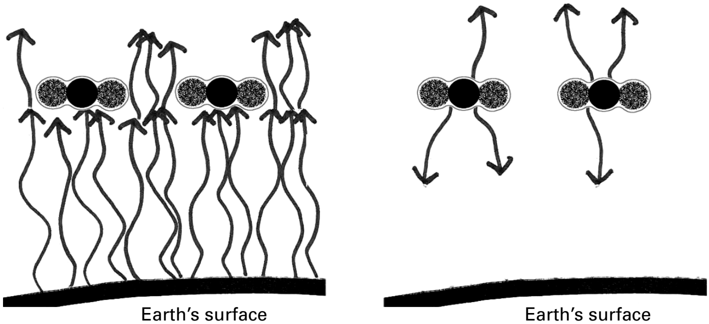

Figure 1.2 The greenhouse effect of CO_2. Left: To balance the energy absorbed from the sun (not shown), Earth's surface radiates rays of infrared waves to cool itself. Molecules of CO_2 in the atmosphere absorb some of the infrared rays. Right: Those same molecules, achieving their own micro-energy balances, then re-radiate new infrared rays in all directions. The re-radiated rays that happen to shoot downward exert an extra heating effect on the surface, which then will radiate even more infrared rays (not shown) to achieve a balance.

not get increasingly hot because the upper levels of the atmosphere radiate the cooling infrared wavelengths outward to the cold blackness of space. I have simplified the diagram to highlight the process of absorption and re-radiation of the infrared waves by the greenhouse gas.[6] In reality, the atmosphere becomes like a infinitely complex pinball machine for the rays, as they slowly work their way toward a net flow upward by a complex path, going up and then down, then up a bit more, then down not quite so far, then up some more, until eventually they get out free into space and the energy has left the biosphere. The greenhouse gases are like insulation in the walls of a home in winter. They block the exit of the heat. With the insulation, the heat stills gets out, but the inside temperature is higher as a result.

With the simplified picture and additional remarks, it logically follows that increasing the amount of any greenhouse gas results in higher temperatures (up to a saturation point of near-maximum effect of particular gases).

Without any greenhouse gases in the atmosphere, hypothetically assuming, say, that the CO_2 were reduced to zero and the water vapor as a feedback response dropped as well, calculations show that Earth's surface would be 60°F cooler (about 33°C cooler). With the average temperature of the surface now about 60°F (15°C), it is obvious that without its greenhouse gases Earth would be a frozen ball in space. The greenhouse gases are necessary for present-day life forms. They are why we have liquid water. Natural levels of CO_2 keep the planet from a permanent ice age. Yet rising levels of CO_2 threaten the future stability of the climate.

This, in a nutshell, is the physics of the environmental challenge we all must think about. As the CO_2 concentration rises, Earth is heading for a regime of greenhouse-gas levels and associated temperatures such as it has not experienced, as far as we know, in a very long geological time.

The Hero: The Carbon Atom

The carbon atom doesn't stay in the CO_2 molecule. Carbon dioxide is only one of the many molecules that contain carbon. Thus, to fully encompass what is going on with CO_2 we must expand the focus of understanding, gradually during the course of this book, to include the entire global, circuitous system of carbon in all its forms, in all places, and in many kinds of exchange. I have already hinted at this system, which is called the *carbon cycle*. The world travels of carbon atoms in the carbon cycle lead me to nominate a clear hero here: the carbon atom itself.

Carbon is the backbone of all biological molecules. Our bodies are carbon-burning machines fed by crops. Carbon fuels cooking fires in many developing nations. It also fuels most industrial energy systems. Civilization would collapse without the conversion of fossil forms of organic carbon into the waste gas CO_2. Biologically and technologically, we depend on carbon.

The same carbon atom can be in different kinds of molecules. A carbon atom, by breaking the electrical bonds to other atoms in one molecule and then forging new bonds with new neighboring atoms in new molecules, travels, in a sense, throughout the various "pools" of the biosphere. To make this clear, I will single out one carbon atom and give it a name.

The most famous scientist of the global carbon cycle was C. David Keeling, who dedicated his life to monitoring CO_2, starting half a century ago, and who discovered its rising levels in the atmosphere. In his honor, I give the name Dave to the main carbon atom we will follow.

Wherever Dave is right now, recently he was in an airborne CO_2 molecule. A few years before that, he was in the equatorial belt of the Pacific Ocean, in the type of molecule that holds (because of its total numbers in the vast ocean) the most carbon of any kind of molecule in biosphere: the bicarbonate ion, HCO_3^- (figure 1.3).

Furthermore, Dave recently was also in another kind of carbon-containing molecule that is widely abundant: a cellulose molecule in the trunk of a tree.

A cellulose molecule has an almost web-like appearance (figure 1.4). Other kinds of "organic" molecules have their carbon atoms in linear rows, such as the tadpole-like tails of lipids molecules in all cell

Figure 1.3 A molecule of bicarbonate ion, consisting of three oxygen atoms (shown in gray), one hydrogen atom (the smallest, also shown in gray), and one carbon atom (here labeled D for Dave, the primary atom whose path this book traces, which is often in a bicarbonate ion when in the ocean). The ion has a net single negative charge.

membranes. The cells and fluids of our bodies are filled with tens of thousands of kinds of proteins, among them the enzymes hemoglobin and insulin and the brain neurotransmitter dopamine. As molecules go, the enzymes are giants. Dave has been in all the types—in the lipid molecule of a membrane inside a little swimming copepod crustacean in the highly productive Bay of Bengal of Indian Ocean, in a humus molecule in the soil cast out an earthworm's rear end in the moist soil of Ireland, in the dopamine in the brain of a giant tortoise of the Galapagos Islands, and so on.

Clearly, Dave gets around. And he doesn't travel alone; he always takes up residence with other atoms, temporarily and for varying amounts of time that are not under his control. Sometimes his neighbors are the oxygen atoms in CO_2 and in the bicarbonate ion; sometimes his neighbors are other carbon atoms and hydrogen atoms, as in the cellulose and lipid molecules; sometimes he binds with nitrogen and sulfur atoms in protein molecules. Furthermore, his partners are different during these cycles. Every time he is in a CO_2 molecule, the

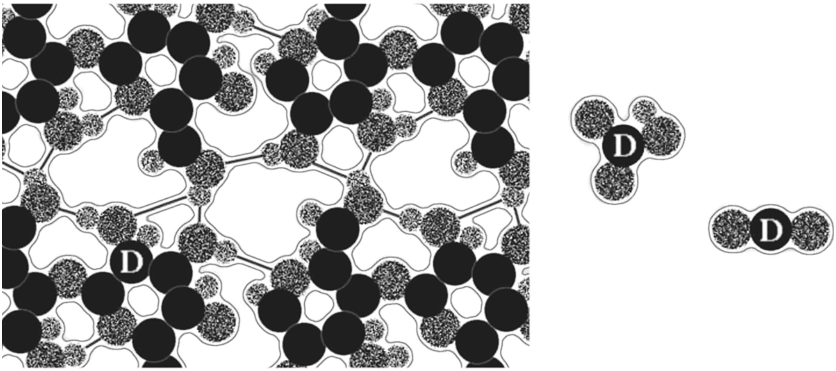

Figure 1.4 From left to right: Only a small portion of the huge network of the cellulose molecular system is shown, relative to the bicarbonate ion (middle) and CO_2 (far right). Carbon atoms, as is the custom in this book, are shown in black. Carbon atom Dave (D) has been in all these molecules and in others at various times; his location here in cellulose is arbitrary.

oxygen neighbors are different specific atoms of oxygen. Dave passes in and out of different molecular forms. And he can revisit those forms, creating sub-cycles within the global carbon cycle. Most trips among the pools for molecules traveling in the biosphere are not limited by one-way tickets.

The Sizes of Atoms and Molecules

Keep in mind when following the travels of Dave and the other carbon atoms that the scales are nearly inconceivably small.

Consider the CO_2 you exhale. It is a waste gas from your body's metabolism. And the concentration of CO_2 in your exhaled air is about 100 times that in the air that you inhale with each breath taken from the atmosphere. You, therefore, are a source of CO_2 to the atmosphere

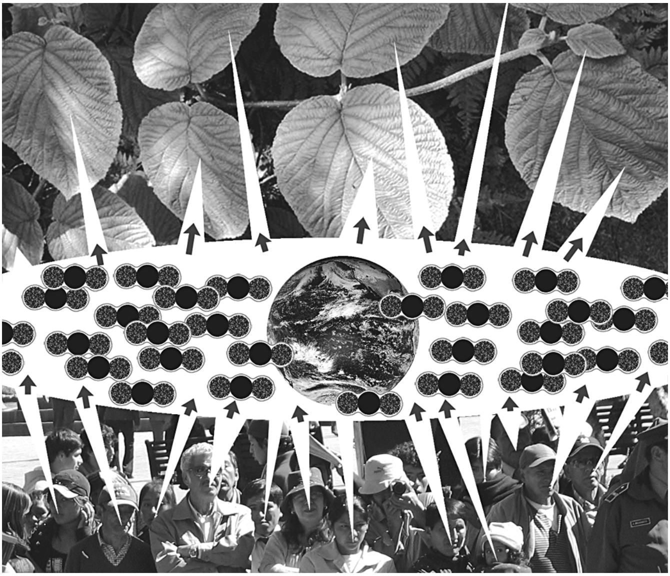

Figure 1.5 "New" molecules of CO_2 are born from each human breath. These circulate in the atmosphere, and soon each leaf that grows incorporates some molecules from each breath.

(figure 1.5). The numbers work out to about 5×10^{20} molecules of CO_2 per exhalation.

When these new CO_2 molecules leave your mouth, they begin dispersing in the air. The entire atmosphere, from the North Pole to the South Pole, is stirred in about a year, so within that year the molecules you added from each exhalation are evenly distributed into the very air you will later breathe back in. To put the number 5×10^{20} in perspective, assume that you live in the mid latitudes of the northern hemisphere and that you exhaled at the end of the summer's growing season, say in

October. By the start of the next spring, the mixing in the atmosphere is essentially complete within the hemisphere. The green leaves that grow in the spring draw on CO_2 from the atmosphere as their source of carbon for the organic molecules they make, including cellulose and thousands of other kinds of molecules. Each and every leaf that grows will incorporate into its body a few dozen atoms of carbon that came from one particular exhalation you made during the previous fall.