The Science of Climate Change, Doug Hayhoe, February 2022

Climate change is a huge challenge, both now and for the next century. This essay explains the science of climate change and why we need to do something about it urgently.

Figure 1 Michael Faraday, holding his nose at the terrible smell coming from the sewage in the river

This cartoon from the British magazine *Punch* was published in 1855 (Figure 1). It depicts the famous physicist, Michael Faraday, out on the Thames River below London. He was so disgusted with the untreated sewage appearing in the river that he wrote a letter to the London authorities. *Punch* reprinted his letter, and drew the cartoon to illustrate it.

Faraday was the farthest I could imagine from a liberal-minded environmentalist. He was a devoted Christian who served as a lay elder in his local church, which discouraged worldly activities. Yet, here he was protesting about the environmental mess that the Industrial Revolution was causing around London and doing so because of his faith, not despite it. (See my essay, *Michael Faraday*.)

A brief survey of the scientific evidence

Most people know that the planet is warming and they are worried about it. Seasons are shifting, with winter coming later in the year and spring, earlier. Summer heat waves and heavy rainfall are becoming more frequent and more extreme. Hurricanes are intensifying faster and dumping much more rain. Droughts are stronger and longer, and wildfires are burning greater area. Around the world, glaciers that supply much of the worlds' fresh water are rapidly shrinking. Sea level is rising at an accelerating rate. Some of the giant ice sheets on Greenland and the Antarctic continent are in a precarious position, threatening a much greater sea level rise in the future.

Greenhouse Gases and Earth's Climate

In the 1820s, a French mathematician and scientist named Joseph Fourier calculated that, according to the amount of energy the Earth receives from the Sun, the Earth should be a frozen

ball of ice with an average global temperature of –18 ^{0}C (0 ^{0}F) – but it's not! Why not? The answer is because the Earth has an atmosphere with greenhouse gases in it. Instead, thanks to these gases, the Earth's average temperature is about 14 ^{0}C (57 ^{0}F).

There aren't a lot of greenhouse gases in the atmosphere. The most abundant is water vapor, which makes up only 0.4% of the atmosphere. The second most important greenhouse gas is carbon dioxide (CO_2), which makes up 0.04% of the atmosphere. So how do these "trace gases," as they're called, keep us more than 30^{o}C warmer than we would be otherwise?

It begins with the Sun's energy that heats the Earth up. As the Earth is heated by the sun, it gives off heat energy in the form of infrared radiation. Heat-trapping gases in the atmosphere trap the infrared radiation, sending some of it back to the earth. How? Greenhouse gases like water vapour and CO2 are triatomic molecules, with an extra degree of vibration, that the diatomic Nitrogen and Oxygen molecules don't have. This extra vibration allows the molecule to absorb infrared radiation and release it back out in all directions, including back to the earth. As my daughter often says, it's like the Earth, out in cold space, has a warm blanket over it that keeps it just the right temperature for life.

Understanding the scientific mechanisms

Scientists know climate has changed in the past and the Earth has been warmer and cooler than today. So why is it warming now, and how do scientists know humans are responsible?

Over the history of the Earth, the amount of greenhouse gases in the atmosphere have gone up and down naturally. During ice ages, levels are lower. During warm periods like we are in today, levels are higher. But today, CO_2 levels in the atmosphere are far higher than they would be naturally: and humans are entirely responsible for this rise.

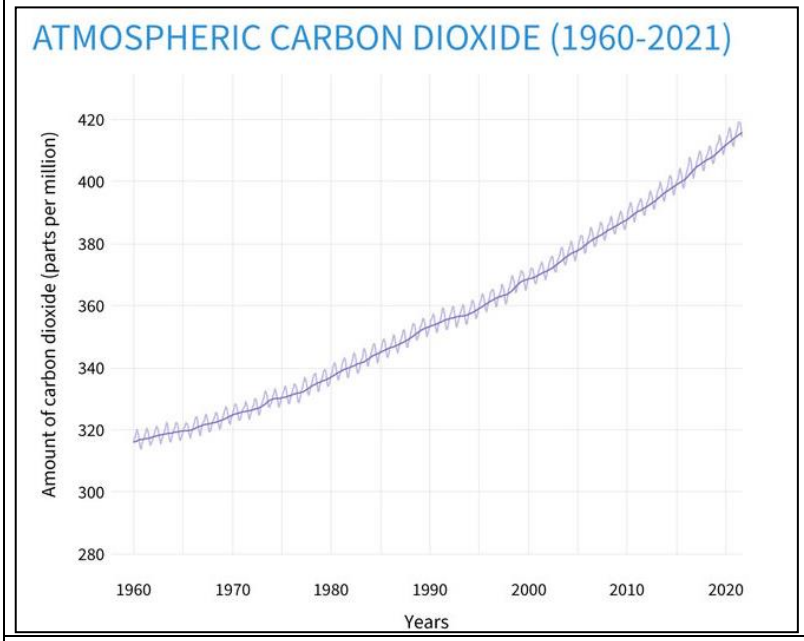

Figure 2 Atmospheric CO_2 has gone up from 316 ppm in 1960 to 412 ppm today.

Over the last two centuries, people have been burning more and more fossil fuels (coal, oil, and gas) to produce energy. Fossil fuels contain carbon that, when burned, combines with oxygen to create CO_2. Before the Industrial Revolution, the atmospheric concentration of CO_2 was 280 ppm. Today, it is nearly 420 ppm, one and a half times greater (Figure 2). While the initial amount of CO_2 in our atmosphere was just right, the perfect blanket

that the earth needed to support life, we have now added an extra blanket, and the earth is beginning to run a fever. Over the history of human civilization on this planet, the average temperature varied by just a few tenths of a degree, the same amount human body temperature varies over the day. Over the last hundred years, though, average global temperature increased by 1.1 ^{0}C. That might not sound like much; but imagine if your body were constantly a degree warmer. You'd feel feverish and tired as the impacts of the warming started to affect you. The same thing is happening to the Earth.

Comparing the extra atmospheric CO_2 with that produced by humans

How do we know that humans are mainly responsible for the additional CO_2 in our atmosphere? There are at least two ways they can tell. First, the isotopic signature of carbon from burning fossil fuels is very different than the signature of carbon produced by natural processes such as emissions from the ocean or biosphere. Scientists can easily tell the difference between naturally occurring carbon in the atmosphere versus carbon that comes from burning coal, gas or oil. And second, every major company and country has kept careful records of how much coal, oil, and natural gas it has produced and burned. It's straightforward, then, to compare how CO_2 in the atmosphere has increased over the past century with the CO2 produced by burning fossil fuels. How do they compare? Very closely! The concentration of CO_2 in the atmosphere (blue line) increases in direct proportion to the emissions of CO_2 from human activity (black line).

Other Factors contributing to Climate Change

Burning fossil fuels is responsible for 75% of the observed warming over the last century. Deforestation and large-scale industrial agriculture are responsible for the remaining 25%. When trees are burned, they also release carbon into the atmosphere, and disappearing forests no longer absorb the extra CO_2 we produce. That's why the destruction of the Amazon rainforest is so serious. Agriculture's contributions mainly come from two other gases, CH4 and N2O. CH4 is produced by belches from ruminants (cows, sheep, goats, etc.), by the decomposition of food, manure, and other organic material, and by rice paddies. N2O is produced by fertilizer use. Although the actual emissions of these gases are relatively small compared to human emissions of CO2, these gases' ability to trap heat is much more powerful.

Are Scientists Sure?

A common argument you may have heard is that not all scientists agree with the science I've described above. In my essay *Why Trust Science?* I mention how science builds trust by the collaborative way it works, building consensus among many scientists who are expert in the same area. Climate change is no exception. The overwhelming majority of climate scientists agree that the climate is changing, that this change is caused primarily by humans, and that its effects will be catastrophic. The number of scientists who agree are in the thousands. But, as with vaccines, so with this topic, there are a small handful of scientists who oppose this consensus. Most of these scientists are not climate scientists, and they don't do research in the field. Instead, they spread their opinions through YouTube videos and books.

One of these, Richard Lindzen, is a physicist who, years ago, denied that smoking causes lung cancer – something everyone accepts now. In fact, he has a track record of disagreeing with science that contradicts the positions of wealthy industries such as the tobacco and fossil fuel companies. Another physicist who often contradicts the scientific consensus on climate change is Steven Koonin. He frequently highlights how he worked for the Department of Energy under President Obama (as did thousands of other scientists who agree with the scientific consensus) as evidence for his views.

Over the last decade, there have been hundreds of thousands of scientific studies published showing that climate change is real, human-caused, and serious. There have also been 38 studies published over that time, claiming that climate is not changing and/or humans are not responsible. However, an analysis of these 38 studies found errors in each that, if corrected, would bring them in line with the scientific consensus: and this is no surprise. The science explaining how heat-trapping gases affect the Earth's temperature has been well understood for over a century. That's why there are so few who disagree with the consensus that climate change is human-caused and serious.

Conclusion

Michael Faraday's example demonstrates the belief of Christians that we have a responsibility to care for the environment, as we see it as part of God's creation. While Faraday was concerned about visible pollution in his time, today we face more complex environmental issues, including invisible carbon dioxide pollution, which is causing warming and affecting the entire planet. The evidence of human-induced climate change is clear and overwhelming, and it can be seen in nature through various ways, such as trees budding earlier, glaciers melting faster, and species moving poleward. As Christians, we have a responsibility to care for God's creation, and we must ensure that future generations can enjoy the same beauty and abundance that we have been blessed with.

Credits

Thanks to my daughter Katharine who corrected errors in my draft and brought clarity to the key points.