Understanding Climate Change and How it Contributes to Nutrient/HAB/Dead Zone Problems in Lake Erie and Other Waters

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A. Introduction

Our goal in writing this paper is to provide a brief, easy to read, and easy to understand summary of a great deal of scientific information to help non-scientists and students understand global warming and climate change, and how they impact nutrient loading, harmful algal blooms (HABs) and dead zones. We want to return to some of the very basic science related to weather, climate and water quality—things that some of us learned many years ago and may have forgotten. And, we want to supplement that information with new information developed more recently as our scientific capabilities have advanced—things that students are studying today in middle school and high school, and new research results from scientists all over the world.

We have used data from Lake Erie and Midwest, but the information could easily be extended to many other locations around the United States and the world. We have also included many related topics in this discussion to broaden the reader's understanding of the issues. At the end of the paper we summarize what has been discussed and explain what we can do today to improve conditions in the future for our children and grandchildren. Along the way the reader should gain an increased appreciation for the complexities and interrelatedness of the issues and the many ways humans can impact them.

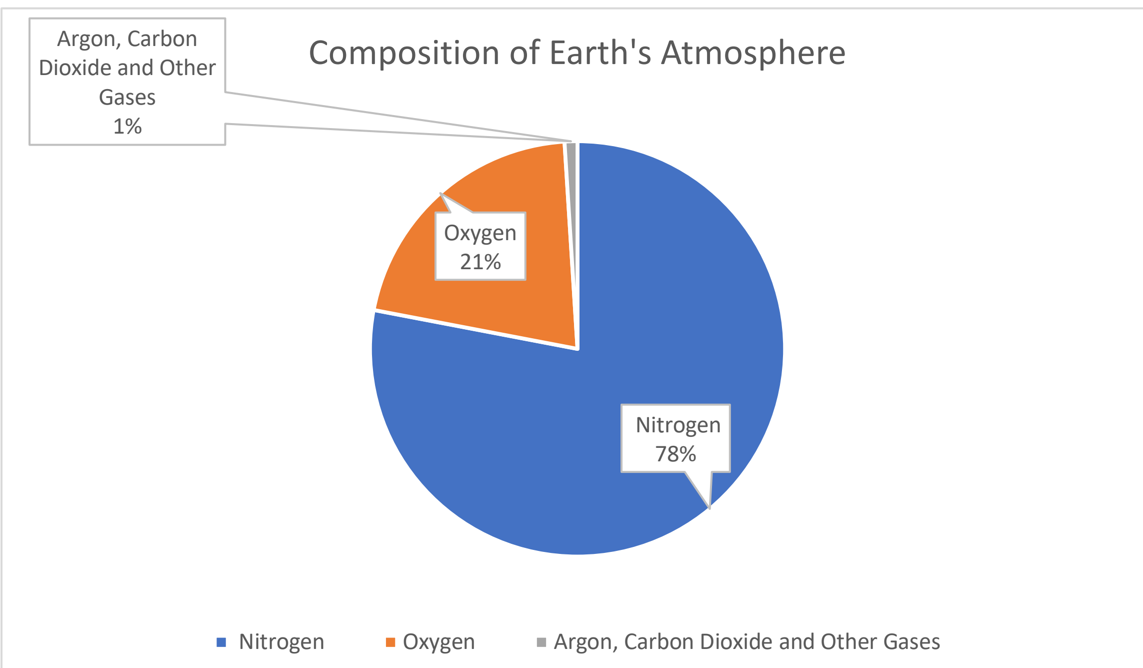
To make it easier to read and understand, we have not written it as a scientific publication. We have attempted to eliminate most of the scientific jargon and primary references at the end of each statement, we have included Fahrenheit readings with Celsius for temperature, and we have included a short list of reference materials for additional reading at the end. We found these reference materials particularly useful and also relatively easy to read and understand. NOAA's Climate.gov website is particularly good and worth following for up to date information and simple answers to commonly asked questions. We apologize to our scientific colleagues where we have omitted or provided too much abbreviation of your particular piece of research or your particular area of emphasis. Much more could have been written about each issue covered in this paper.

B. Understanding Global Warming and Climate Change

To understand global warming and climate change you have to have a basic knowledge about the Earth's atmosphere and its impact on sunlight. Our atmosphere is composed of the following gases:

- Nitrogen (N_2)— 78 percent
- Oxygen (O_2)— 21 percent
- Argon (Ar)— 0.93 percent
- Carbon dioxide (CO_2)— 0.04 percent
- Trace amounts of neon (Ne), helium (He), methane (CH_4), krypton (Kr) and hydrogen (H_2), ozone (O_3), as well as water vapor (H_2O) and more.

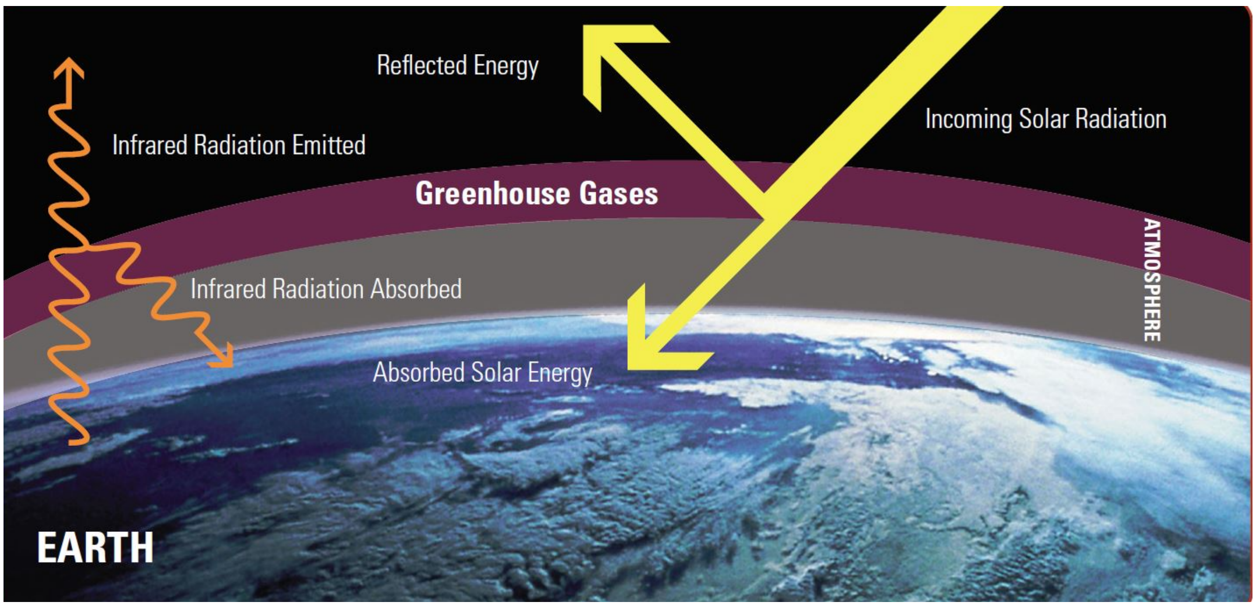
Figure 1



As sunlight passes through our atmosphere and reaches the Earth, some of the gases in our atmosphere block damaging ultraviolet light (very short wavelength light) before it reaches the surface. Oxygen and ozone, high up in the atmosphere, are very important in this regard. Some of you will remember the concerns about ozone depletion and the "ozone hole" over the arctic poles in the late 80s and 90s caused by chlorofluorohydrocarbons and hydrochlorofluorocarbons used in refrigerants (Freon) and in propellants in some spray cans. The loss of ozone causes more ultraviolet light to reach the Earth and increases the risk of skin cancer. The key point here is that the gases in our atmosphere are important—even those that occur in only trace amounts, like ozone.

Most of the sun's light passes through the Earth's atmosphere and hits the Earth, where it is absorbed and creates heat. Some of the heat is radiated from the Earth and passes back through our atmosphere into outer space, some of the heat is blocked and reflected back again to Earth by the atmosphere, and some of the heat is absorbed by gases in our atmosphere where it helps to keep the Earth warm enough for human life. We often call this the "greenhouse effect."

Figure 2. The Impact of the Earth's Atmosphere on Solar Radiation
(Source: Ohio Sea Grant)



Scientists have understood the physics of global warming for about 200 years and first demonstrated that carbon dioxide and other greenhouse gases contributed to the greenhouse effect in the 1850s. To a degree we experience examples of the greenhouse effect every winter—we expect it to be very cold on clear nights and warmer on cloudy nights because the clouds keep heat from radiating back into space, holding in the heat like a blanket. Gases in the atmosphere play this same role, holding in some of the heat even when we don't have clouds.

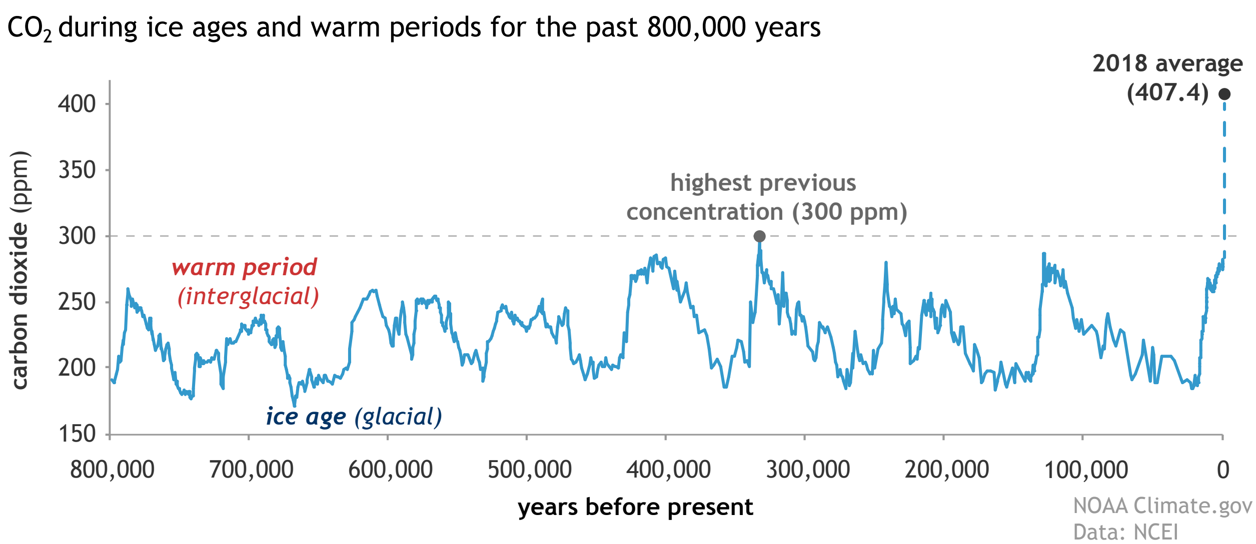
We have learned that certain gases in the atmosphere are better at absorbing heat than others. We call these gases, "greenhouse gases." The primary greenhouse gases in Earth's atmosphere are water vapor, carbon dioxide, methane, nitrous oxide (N_2O), and ozone. Without greenhouse gases, and they are all present in very small quantities, the Earth would be too cold for us to survive—the average surface temperature would be -18^{o}C (-0.4^{o}F). Having the right amount of these gases is very important and very helpful, but too much is a big problem as it causes the Earth to get warmer (global warming) and leads to significant changes in our weather. And, if the increased amount of the gases persists, it causes long-term changes in our climate and serious consequences on Earth.

B.1. Carbon Dioxide and Other Greenhouse Gases

Carbon dioxide is the most important of Earth's long-lived greenhouse gases. It absorbs less heat per molecule than the greenhouse gases methane, nitrous oxide and water vapor, but it's more abundant (over 100 times more abundant than methane and nitrous oxide) and it stays in the atmosphere much longer. Increases in atmospheric carbon dioxide are responsible for about two-thirds of the total energy imbalance that is causing Earth's temperature to rise.

Drs. Lonnie Thompson and Ellen Mosley-Thompson, award-winning researchers at The Ohio State University's Byrd Polar Research Center, have been collecting ice cores from glaciers at the north and south poles and around the world. Some of these ice cores date back 800,000 years. By measuring the carbon dioxide in the bubbles in the ice (a process jointly developed in the late 1970s and early 1980s by two groups, one in Bern, Switzerland and one in Grenoble, France, working together and comparing their results over several years and publishing papers in Science and Nature), they can determine the amount of carbon dioxide in our atmosphere at the time the ice was formed. From this we know that for the last 800,000 years the amount of carbon dioxide in the atmosphere has averaged ~230 parts per million (ppm) and ranged from 160 ppm during multiple ice ages to almost 300 ppm during the multiple warm periods between ice ages.

Figure 3



Atmospheric carbon dioxide concentrations in parts per million (ppm) for the past 800,000 years, based on ice core data. The peaks and valleys in carbon dioxide levels track the coming and going of ice ages (low carbon dioxide) and warmer interglacial periods (higher levels). Throughout these cycles, atmospheric carbon dioxide was never higher than 300 ppm; in 2018, it reached 407.4 ppm (black dot).

NOAA's Mauna Loa Observatory in Hawaii is one of the premier laboratories in the world for measuring carbon dioxide concentrations in the atmosphere. When they first started measuring carbon dioxide levels in the atmosphere in 1958, the level stood at 315 ppm. In May 2019 it reached 415 ppm. Humans, *Homo sapiens*, have existed on Earth for only about 300,000 years. No human, until now, has ever seen the carbon dioxide level this high. The last time the atmospheric carbon dioxide level was this high was more than 3 million years ago, when the temperature was 2.0°-3.0°C (3.6°-5.4°F) higher than during the pre-industrial era, and sea level was 50–80 feet higher than today.

The rate of increase in carbon dioxide is accelerating. In the 1960s, the global growth rate of atmospheric carbon dioxide was roughly 0.6 ppm/year. Over the past decade, the growth rate has been approximately 2.3 ppm/year, and the increase from the 2018 average of 407.4 ppm (Figure 3) to the level observed in May 2019 is 7.6 ppm/year. The annual rate of increase in atmospheric carbon dioxide over the past 60 years is about 100 times faster than previous natural increases, such as those that occurred at the end of the last ice age 11,000-17,000 years ago. This carbon dioxide is coming primarily from human activities.

The **4th National Climate Assessment** notes that while there are natural factors that can impact climate and global temperatures, "greenhouse gas emissions from human activities (burning fossil fuels and, to a lesser extent, deforestation and land-use change) are the only factors that can account for the observed warming over the last century; there are no credible alternative human or natural explanations supported by the observational evidence. Without human activities, the influence of natural factors alone would actually have had a slight cooling effect on global climate over the last 50 years."

Another reason carbon dioxide is important in the Earth system is that it dissolves in water and into the ocean. It combines with water molecules, producing carbonic acid and lowering the ocean's pH. Since the start of the Industrial Revolution, the pH of the ocean's surface waters has dropped from 8.21 to 8.10. This drop in pH is called *ocean acidification*. The pH scale is a logarithmic scale, which means a pH of 4 is ten times more acidic than a pH of 5. The change of 8.21 to 8.10 means that ocean acidity has increased by about 30%. Increasing acidity interferes with the ability of marine life to extract calcium from the water to build their shells and skeletons and causes coral bleaching.

B.2. Photosynthesis

Photosynthesis is the process through which plants use sunlight, water and carbon dioxide to produce oxygen, water and their food (carbohydrates) to grow. The process occurs within the leaves of the plants. While noting that photosynthesis requires sunlight (it does not occur in the dark), scientists commonly write the process as: $6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$. This means that six carbon dioxide molecules and six water molecules are converted by light energy, which is captured by the green chlorophyll pigment in plants, into a sugar molecule and six oxygen molecules. One important take home message here is that carbon dioxide is not toxic. A small amount is very important for plant growth, and we even increase the concentration of carbon dioxide in some horticulture facilities to stimulate more rapid plant growth. So, a small amount of carbon dioxide is beneficial, but too much is a problem because it warms up and holds heat, and it stays in the system a very long time.

B.3. Respiration

When we breath, we take in oxygen and combine it with food we have eaten to produce energy for growth and movement, and we release carbon dioxide, water, and heat. All plants and animals that consume oxygen (aerobic plants and animals) do this. However, even though they respire, plants are net producers of oxygen and without them air would not be fit to breathe.

B.4. Transpiration

Transpiration is the process by which water is taken up by the roots of a plant, carried to the leaves, and released as water vapor through small openings, called “stomata,” on the underside of the leaves. Up to 90% of the water taken up by a tree’s roots is released to the atmosphere as water vapor through the process of transpiration.

B.5. The Importance of Trees and Other Plants

Trees remove carbon dioxide from the atmosphere and release oxygen by photosynthesis, as described above. Some of the carbon in the carbon dioxide they consume is held in the woody material of the tree as it grows and in the roots of the tree beneath the surface of the ground. Therefore, while planting trees is a great way to reduce carbon dioxide in the atmosphere, deforestation and forest fires are huge problems. They eliminate the trees that were removing carbon dioxide and producing oxygen, and the carbon that was stored in the woody material of the tree is released to the atmosphere as the tree burns. This should help to explain some of the concern over the loss of the rain forest in Brazil and forest fires in Australia.

B.6. Acceleration of the Warming Process

The warming cycle tends to accelerate over time for many reasons, but one of the most obvious and easy to understand reasons is that snow and ice are white and reflect the sun’s rays. The rays go back through our atmosphere and into space as light waves. Soil, rock, and water are less reflective, however, and they absorb the sun’s rays and radiate heat that is trapped by our atmosphere. For example, we are cooler wearing white on a hot sunny day than wearing black because the white clothing reflects the sunlight while the dark clothing absorbs it. So, as the earth warms up, we have less snow and ice (white materials), we absorb more of the sun’s light as heat, more ice and snow melt, and the warming process accelerates.

The interested reader may want to compare the 4th National Climate Assessment, noted above to earlier versions. Scientists are clearly becoming much more alarmed at the rate of change they are observing and concerns over future changes that could accelerate the process even more. For example, as the Arctic warms, the permafrost (land that had been permanently frozen) is melting and releasing large amounts of methane, which can greatly accelerate the warming process.

B.7. Understanding the Increase in the Frequency of Severe Storms

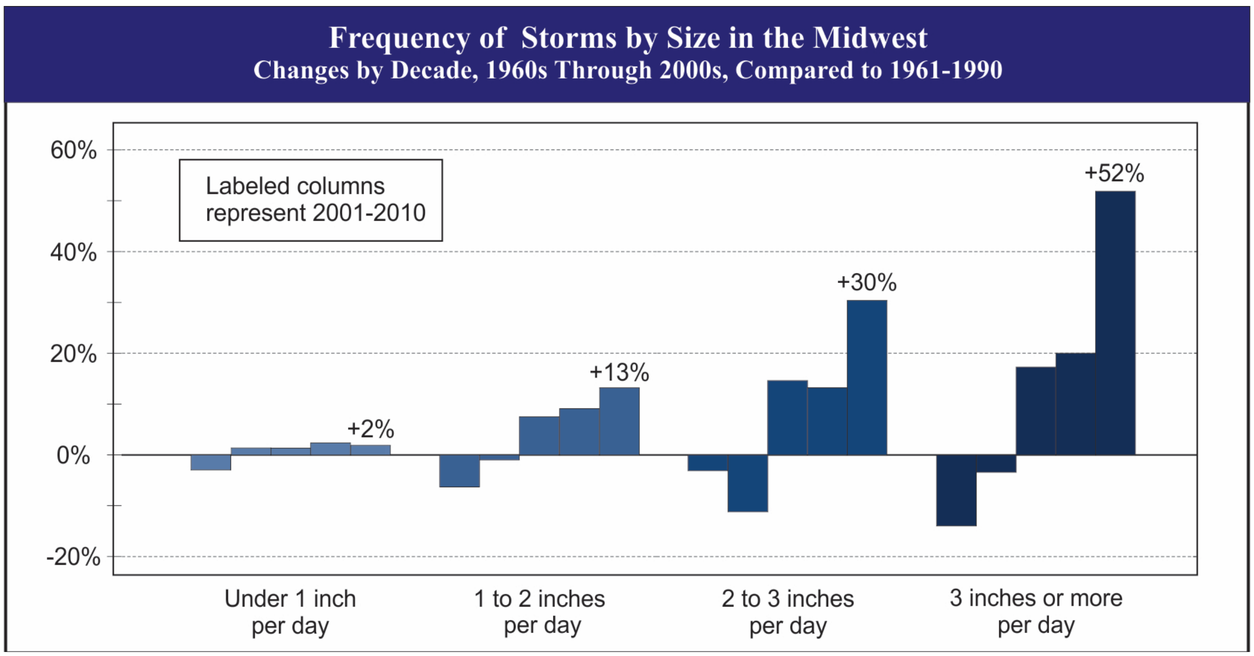
One of the biggest problems caused by warming the Earth, its water, and its atmosphere even a degree or 2 Celsius (1.8 to 3.6°F), is that the severity of storms greatly increases. The “specific heat” of a substance is the amount of heat required to raise the temperature of a specific quantity of that substance by 1.0°C (1.8°F). The specific heat of water is higher than just about any other common substance. This means that it takes a lot of heat, or energy, to raise the temperature of water, and water releases a lot of heat when it cools. Those living around the Great Lakes feel this every year as the lakes hold onto the heat in the fall providing warm and beautiful weather, but we have really cold and sometimes miserable springs as it takes a lot of heat to warm the lakes up.

It also takes a lot of heat to change water from ice to liquid and from liquid to vapor, and water releases a lot of heat when it goes from a vapor to a liquid and liquid to ice. When water evaporates, it absorbs a lot of heat (high heat of vaporization) and changes from a liquid to a gas. The water that is left behind is a little cooler and warm water vapor goes into the atmosphere. That vapor is a very potent greenhouse gas (it is a gas capable of absorbing lots of heat). The percentage of water vapor in surface air varies from 0.01% at -42°C (-44°F) to 4.24% when the dew point is 30°C (86°F). This is important, as the higher temperatures from global warming lead to higher ocean and lake evaporation rates and increase the amount of moisture in the air.

During a thunderstorm, warm, moisture-rich air rises, or is forced up, in an updraft. Eventually it rises into colder regions and the moisture in the air condenses into droplets in clouds. If the upward convection currents continue to move more moisture-rich air up, the cloud grows and rises into even colder air where ice can form. And, as noted above, the condensation process (going from a gas to a liquid or droplet) in water and the process of freezing from a droplet into an ice crystal, releases a lot of heat. This heat can contribute to the updrafts in the thunderstorm and can lift the droplets and ice crystals even higher and allow them to grow larger. Eventually the water droplets or ice crystals begin to fall creating a downdraft that overpowers the updraft and we have rain and hail falling to the ground. In a nutshell, the high levels of water vapor in the air, driven by warming even during the winter, create conditions for very heavy precipitation in the form of intense rain and snow storms.

Hurricanes and other tropical storms get their energy from warm ocean water. It might help to think of hurricanes as ocean air conditioners. These storms tend to form over warm ocean areas and their circulation above the ocean surface reduces the temperature of the water as it evaporates—and we know from the above discussion that a lot of heat comes out of the water as the water temperature is reduced. When ocean temperatures are warmer, hurricanes and other tropical storms grow stronger, with faster winds, more evaporation, greater amounts of water vapor, and heavier rain and hail. Because of higher temperatures and increased evaporation, climate change causes thunderstorms and tornadoes to get stronger and become more frequent, too. In the Midwest, since 1961, we have experienced a 30% increase in the frequency of storms that produce over 2 inches of rain and a 24-hour period and a 52% increase in the frequency of storms that produce more than 3 inches of rain in a 24-hour period.

Figure 4



Changes in frequencies of storms in the Midwest, by category of storm size for five decades, 1961-1970 through 2001-2010. Labeled changes are for the last decade. Comparisons are to frequencies in 1961-1990. Source: Rocky Mountain Climate Organization and Natural Resources Defense Council 2012 Report.

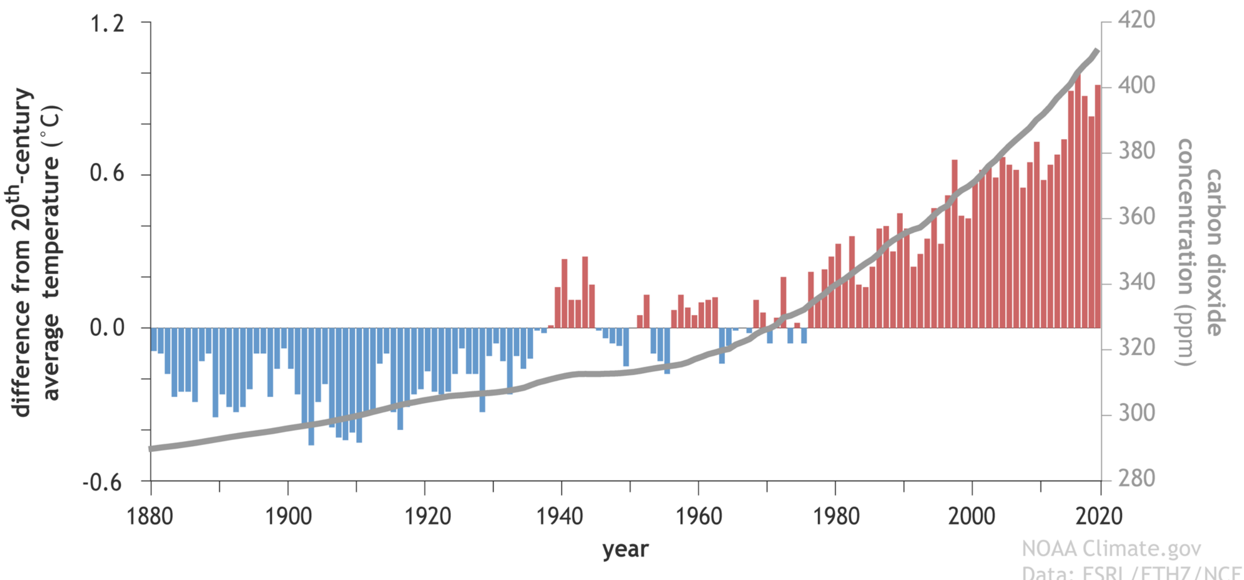
C. Evidence That the Climate is Changing and the Earth is Getting Warmer

To get a complete picture of Earth's temperature and trends over time, scientists combine lots of measurements of the air above land and above the ocean surface, and use four major datasets to understand the global temperature of the Earth. The UK Met Office Hadley Centre and the University of East Anglia's Climatic Research Unit jointly produce HadCRUT4. In the US, the GISTEMP series comes via the NASA Goddard Institute for Space Sciences (GISS), while the National Oceanic and Atmospheric Administration (NOAA) creates the MLOST record. The Japan Meteorological Agency (JMA) produces a fourth dataset. Scientists then compare the global temperature from each year to the average global temperature from the twentieth century (1900-1999). The following points are worth noting:

- Global temperature has been on a steady upward trend since about 1960.
- Starting with 1977, the average global temperature of every year has been above the twentieth century average.
- Nine out of 10 of the warmest years on record have occurred since 2005.
- From 1900-1980, a new record high for global temperature was set on average of once every 13.5 years. Since 1981, a new record high for global temperature has been set on average of every 3 years.
- The Arctic appears to be warming more than twice as fast as the global average.
- The world's glaciers are melting and shrinking and sea level is rising.

Figure 5

Atmospheric carbon dioxide and Earth's surface temperature (1880-2019)



This plot shows temperature on the left and carbon dioxide concentration on the right. The zero line for temperature is the average global temperature for the 20th century. Blue lines are years with below average temperature, and red lines are years with above average temperature from 1880-2019, based on data from NOAA NCEI. The gray line shows the carbon dioxide concentrations from 1880-2019: 1880-1958 from IAC, 1959-2019 from NOAA ESRL. Original graph by Dr. Howard Diamond (NOAA ARL), and adapted by NOAA Climate.gov.

D. Understanding Harmful Algal Blooms, Dead Zones, and Nutrient Loading

D.1. Harmful Algal Blooms

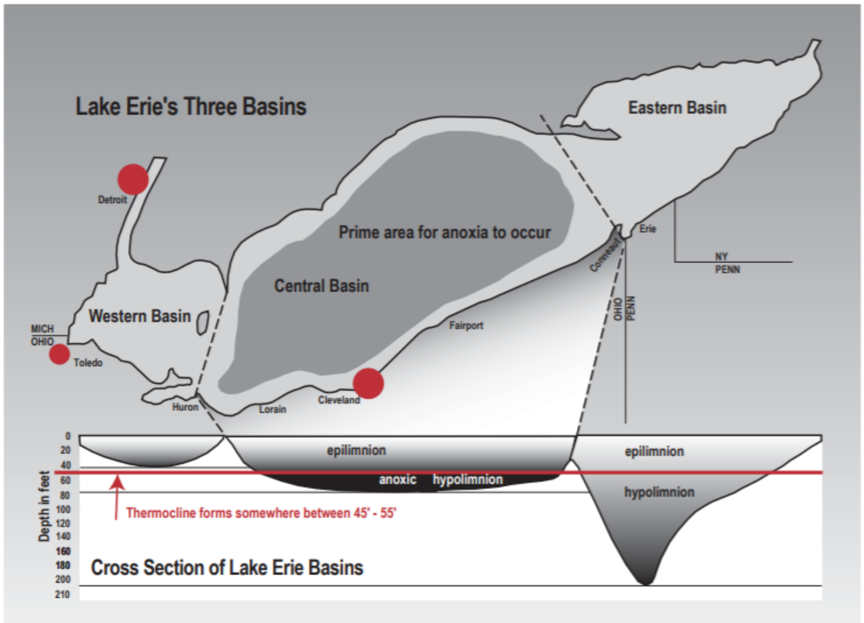
The three major groups of algae in Lake Erie are diatoms (cold water forms), green algae (cool water forms), and blue-green algae or, more accurately, cyanobacteria (warm water forms). Diatoms and green algae are important to the food chain in Lake Erie and all lakes. However, cyanobacteria are capable of producing very potent toxins that are dangerous to people and animals, and they are of little value to the food chain.

In addition to being found most commonly in warm water, cyanobacteria require high concentrations of nutrients (primarily phosphorus), and are capable of forming incredibly dense blooms. Because of their ability to produce toxins, large blooms of cyanobacteria are referred to as harmful algal blooms (HABs). The four primary algal toxins are all more toxic than cyanide. Some of the toxins attack the nervous system and some attack the liver. Research by Dr. Jiyoung Lee at The Ohio State University, shows that increases in non-alcoholic liver cancer rates are linked to the presence of harmful algal blooms.

D.2. Dead Zones

Many lakes and ponds stratify during the summer with warm water on the top and cold water on the bottom. The line separating the warm surface layer (epilimnion) from the cold bottom layer (hypolimnion) is called the thermocline. The thermocline normally forms in late spring or early summer and lasts until late summer or early fall when the temperature of the warm surface layer cools to the temperature of the cold bottom layer, and the thermocline disappears. The warm surface layer normally has plenty of dissolved oxygen because it is in contact with the air and it normally has plenty of light from the sun allowing the algae to produce oxygen by the process of photosynthesis. While the thermocline is in place, the cold bottom layer does not come in contact with the air, and it is often too dark for a significant amount of photosynthesis to occur. Therefore, over time, the amount of dissolved oxygen in the cold bottom layer goes down as fish and other organisms living there consume the oxygen through respiration. If the demand for oxygen is great enough, all of the oxygen in the cold bottom layer can be used up before the thermocline disappears. When the oxygen in the cold bottom layer becomes very low (2.0 ppm or less), scientists call it hypoxic. When all of the oxygen in the cold bottom layer is consumed, the area is called "anoxic (meaning: without oxygen)," or an "area of anoxia," or more commonly, a "Dead Zone," because oxygen breathing organisms cannot live there. Bacterial decomposition of organic matter (bacteria eating dead algae and other organic matter) is normally the largest consumer of oxygen in the cold bottom layer. Therefore, if we reduce the amount of algae sinking to the bottom, there will be less demand for oxygen, and we are less likely to have a dead zone. When all of the oxygen is consumed, only bacteria that do not need oxygen can live there. We call them anaerobic bacteria, and they release lots of methane as they grow, which, as noted above, is a greenhouse gas 25 times more potent than carbon dioxide. Therefore, improving water quality and eliminating dead zones will also reduce the amount of greenhouse gases going into the atmosphere.

Figure 6. The Area of Anoxia or Dead Zone in Lake Erie (Source: Ohio Sea Grant)



D.3. Why Are Phosphorus and Nitrogen Important?

Cyanobacteria, the grass in our lawns, and common crops like corn, soybeans, and wheat, need nitrogen, phosphorus, and potassium (N:P:K). We call these three nutrients: essential nutrients. Without an essential nutrient, cyanobacteria, our grass, and our crops, cease to grow. During a HAB, the cyanobacteria continue to grow and multiply until one of the essential nutrients is used up. In fresh water, the essential nutrient in the shortest supply is almost always phosphorus. In salt water it is almost always nitrogen. Therefore, to reduce the size of HABs in fresh water, we try to reduce the amount of phosphorus (the essential nutrient in the shortest supply). However, nitrogen should also be reduced in fresh water as the toxins the cyanobacteria produce are 14% nitrogen by weight. Therefore, reducing the amount of nitrogen can prevent cyanobacteria from producing toxins.

D.4. How Much Do We Have to Reduce Phosphorus Loading?

In March 2013, the Ohio Phosphorus Task Force recommended a 40% reduction in phosphorus loading to Lake Erie to address HABs. The International Joint Commission endorsed the 40% reduction in October 2013. In May 2015, the binational (US and Canada) Objectives and Targets Task Team of the Nutrient Annex (Annex 4) of the Great Lakes Water Quality Agreement recommended a 40% reduction in spring phosphorus loading to address HABs in the western basin of Lake Erie and a 40% reduction in annual phosphorus loading to address the Dead Zone in the central basin. The US and Canadian governments endorsed the Annex 4 reduction targets in February 2016. The target reductions will not eliminate HABs or the Dead Zone. Instead the goal is to produce HABs like the small HABs of 2004 and 2012 or smaller, nine years out of ten, and to raise the average dissolved oxygen level in the hypolimnion of the central basin to above 2.0 ppm.

Total phosphorus (TP) is a combination of particulate phosphorus (PP), phosphorus attached to sediment particles, and dissolved reactive phosphorus (DRP), phosphorus dissolved in water. PP is approximately 26% bioavailable (usable by plants and algae), and DRP is 100% bioavailable.

The annual load of TP to Lake Erie has not changed much since the early 1980s, but the amount of DRP in that load began increasing in the mid-90s and has increased by 132 percent. This is the primary driver for the current algal blooms on Lake Erie. The Annex 4 recommendations call for reductions in both TP and DRP.

Satellite observations have shown that HABs in the western basin have grown rapidly since 2002 with the worst blooms occurring in 2011 and 2015, and the six worst blooms all occurring since 2011. Unfortunately, USEPA's National Lakes Assessment in 2012 showed that the excessive nutrient loading and HAB problem was quite pervasive: approximately 40 percent of the lakes and ponds in the US have excess phosphorus, more than 35 percent have excess nitrogen, and algal toxins were detected in 39 percent of the lakes. The report also showed that the problem got worse from 2007 to 2012.

D.5. Where Does the Phosphorus Come From?

The Cuyahoga River in Cleveland, Ohio, burned in June 1969. Lake Erie became the posterchild for pollution problems in the world. The next year USEPA and NOAA were formed and we celebrated the first Earth Day. In the late 1960s and early 1970s, Lake Erie was clogged with algae and many toxic substances, and the media called it a "dead lake." At that time, about 70% of the phosphorus causing the algae blooms in Lake Erie was coming from poor sewage treatment. The problem was solved by improving sewage treatment plants and reducing phosphorus loads from sewage treatment by 75-90%. Today, the biggest source of phosphorus is agricultural runoff of fertilizer and manure to the Maumee River, which drains about 4 million acres of agricultural land. Sewage loads represent 9% of the total, failing septic tanks account for 4% of the total, and combined sewer overflows make up 1% of the total. Effective 1 January 2013, Scotts Miracle-Gro removed phosphorus from its lawncare products, and we estimate that 95% of the market followed Scotts lead. The most recent estimate indicates that agricultural runoff now accounts for over 85% of the load.

D.6. The Impact of More Frequent Severe Storms and Higher Temperatures

Excessive phosphorus from agricultural runoff is the primary driver of harmful algal blooms in the western basin of Lake Erie and the dead zone in the central basin. Severe storms produce the greatest amount of agricultural runoff. Of the total amount of phosphorus going into Lake Erie from the Maumee River annually, 70-90% goes in during the 10 largest storms each year. Higher water and air temperatures exacerbate this problem because most cyanobacteria grow best at temperatures above 15.5^oC (60^oF) and most other forms of algae prefer lower temperatures.

E. The Solutions

E.1. Global Warming and Climate Change

National Climate Assessments were published in 2000, 2009, 2014, and 2017/18. As one might expect, we have learned a lot about global warming and climate change in the last 20 years. Our observations and our ability to model, predict and forecast changes have improved every year. As a result, each report is able to make stronger and more well-informed statements about global warming and climate change and what the future will look like. It is also worth noting that the more we learn about global warming and climate change, the more alarmed we become about both the rate of change and the impact of that change on future generations.

To protect future generations, the United States needs to join the majority of the countries in the world and work to reduce the concentrations of greenhouse gases in the atmosphere. Actions to take:

- Improve the energy efficiency of our buildings and homes.
- Move away from fossil fuels as an energy source and convert to renewable energy sources, e.g., wind and solar.
- Improve the efficiency of our various modes of transportation.
- Reduce our meat consumption. Animals, especially cows, produce a huge amount of methane.
- Plant trees.
- Stop deforestation.
- Live our lives sustainably.
- Support policies and leaders that help to promote these actions.

E.2. Excessive Nutrient Loading, HABs and Dead Zones

The four most important immediate actions for all farmers to reduce nutrient runoff from their fields are:

1. Do not apply more phosphorus (commercial fertilizer and manure) than is needed.
2. When applying commercial fertilizer and/or manure, do not simply broadcast it across the surface of the soil and leave it. Instead, insert the commercial fertilizer and manure 3-5 inches below the surface so that it is readily available to the seed and not likely to runoff the surface during rain events.
3. Work to reduce erosion from agricultural fields.
4. Work to reduce the amount of water leaving your fields by improving soil health, using drainage water management, and diverting runoff water through wetlands.

Numbers 1 and 2 above are most important. If all farmers did just the first two actions we would reduce phosphorus loading significantly and could potentially solve the problem. More information on suggested actions for farmers and possible policies to improve the situation will be included in a future supplement to this paper.

While we have learned that most phosphorus comes from agricultural runoff, there are still actions we can all take to reduce our contributions, and every little bit helps.

- Be sure your septic tank is working properly.
- Work with your city to improve the city sewage system.
- Use lawncare products that do not contain phosphorus.
- Use low phosphate cleaning products.
- Reduce the amount of water you send to your city sewage treatment plant.
    - Install rain barrels and rain gardens.
    - Separate sanitary and storm sewers.
    - Install low-flow toilets and showerheads.

F. Summary

- We have learned how greenhouse gases (water vapor, carbon dioxide, methane, nitrous oxide, and ozone) work (the greenhouse effect) to hold in solar radiation from the sun and warm the surface of the Earth.
- While greenhouse gases constitute a very small percentage of the gases in Earth's atmosphere, and without them Earth would be too cold to accommodate life as we know it. However, if their concentrations are too high, it causes big problems.
- Carbon dioxide is by far the most abundant of the greenhouse gases and the most long-lasting in the atmosphere.
- Concentrations of carbon dioxide in the atmosphere are on a very steep upward trajectory and are currently more than 33% higher than at any point in the last 800,000 years.
- Carbon dioxide dissolves easily in water, creates carbonic acid, and causes ocean acidification and harms ocean life.
- Global temperature has been on a steady upward trend since about 1960.
- Starting with 1977, the average global temperature of every year has been above the twentieth century average.
- Nine out of 10 of the warmest years on record have occurred since 2005.
- From 1900-1980, a new record high for global temperature was set on average of once every 13.5 years. Since 1981, a new record high for global temperature has been set on average once every 3 years.
- The Arctic appears to be warming more than twice as fast as the global average.
- The world's glaciers are melting and shrinking and sea level is rising.
- The warming process is accelerating.
- The **4th National Climate Assessment** notes that while there are natural factors that can impact climate and global temperatures, "greenhouse gas emissions

from human activities (burning fossil fuels and, to a lesser extent, deforestation and land-use change) are the only factors that can account for the observed warming over the last century; there are no credible alternative human or natural explanations supported by the observational evidence. Without human activities, the influence of natural factors alone would actually have had a slight cooling effect on global climate over the last 50 years."

- Plants and trees can store carbon in their tissues, remove carbon dioxide from the atmosphere by photosynthesis, and produce oxygen and carbohydrates.
- Warmer temperatures increase the evaporation rate of water, which adds water vapor to the atmosphere, and leads to an increased frequency of severe storms.
- Warm-water forms of algae, or cyanobacteria, are blooming. We call these blooms harmful algal blooms (HABs) because they are capable of producing toxins that are more toxic than cyanide.
- HABs need high concentrations of phosphorus. That phosphorus can come from any source. In Lake Erie, more than 85% of the phosphorus comes from agricultural runoff, and 70-90% of that comes in during the 10 largest storm events each year. More severe storm events driven by climate change leads to more phosphorus and larger HABs.
- Approximately 40 percent of the lakes and ponds in the US have excess phosphorus, more than 35 percent have excess nitrogen, algal toxins were detected in 39 percent of the lakes, and the problem is getting worse.
- To solve the HAB and dead zone issues in Lake Erie, we need to reduce the amount of phosphorus going into the Lake by 40%.
- To protect future generations, the United States needs to join the majority of the countries in the world and work to reduce the concentrations of greenhouse gases in the atmosphere.

G. Related Reading

National Oceanic and Atmospheric Administration's (NOAA) Climate Change Website
http://www.climate.gov/

National Climate Assessments
https://en.wikipedia.org/wiki/National_Climate_Assessment

"Fourth National Climate Assessment Report"
https://nca2018.globalchange.gov/

"Greenhouse Effect: Atmosphere Energy Absorption"
http://www.soest.hawaii.edu/mguidry/Unnamed_Site_2/Chapter%202/Chapter2B2.html

"Climate Change: Atmospheric Carbon Dioxide"
https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide

"The Discovery of Global Warming"
https://www.scientificamerican.com/article/discovery-of-global-warming/

"Lake Erie: Past, Present and Future" in the "Encyclopedia of Water":
https://doi.org/10.1002/9781119300762.wsts0085?

"Summary of Findings and Strategies to Move Toward a 40% Phosphorus Reduction"
http://go.osu.edu/habswhitepaper

"Commentary: Achieving phosphorus reduction targets for Lake Erie"
https://doi.org/10.1016/j.jglr.2018.11.004

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