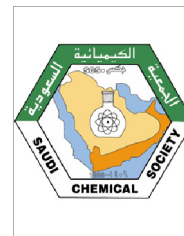




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**SPECIAL ISSUE: ENVIRONMENTAL CHEMISTRY**

# Climate change and our responsibilities as chemists

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**Abstract** For almost all of 4.5 billion years, natural forces have shaped Earth's environment. But, during the past century, as a result of the Industrial Revolution, which has had enormous benefits for humans, the effects of human activities have become the main driver for climate change. The increase of atmospheric carbon dioxide caused by burning fossil fuels for energy to power the revolution causes an energy imbalance between incoming solar radiation and outgoing planetary emission. The imbalance is warming the planet and causing the atmosphere and oceans to warm, ice to melt, sea level to rise, and weather extremes to increase. In addition, dissolution of part of the carbon dioxide in the oceans is causing them to acidify, with possible negative effects on marine biota. As citizens of an interconnected global society and scientists who have the background to understand climate change, we have a responsibility first to understand the science. One resource that is available to help is the American Chemical Society Climate Science Toolkit, [www.acs.org/climatescience](http://www.acs.org/climatescience). With this understanding our further responsibility as citizen scientists is to engage others in deliberative discussions on the science, to take actions ourselves to adapt to and mitigate human-caused climate change, and urge others to follow our example.

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## 1. Introduction

The Earth's environment has changed naturally and dramatically many times during its 4.5 billion year history. Humans have been changing the environment for the last few thousand years. We domesticated animals for food, transportation, and labor. We invented agriculture that changed the surface of the planet and reduced the percentage of the population required

to produce food. This, in turn, allowed the rise of towns and cities and the development of crafts and manufacturing and civilization, as we know it. During most of this period of human history, environmental changes were largely local. In some areas, for example, deforestation occurred to create more agricultural land and to provide firewood for heating and cooking and in others animals were driven to extinction by overhunting for food. But human impacts had not reached a global level.

This changed about 250 years ago with James Watt's invention of the steam engine that initiated the Industrial Revolution. Suddenly, enormous amounts of power that did not depend upon human, animal, or water power, were available essentially anywhere, including for transportation (the steam locomotive). All that was required for these engines was an energy source and burning readily available coal satisfied this

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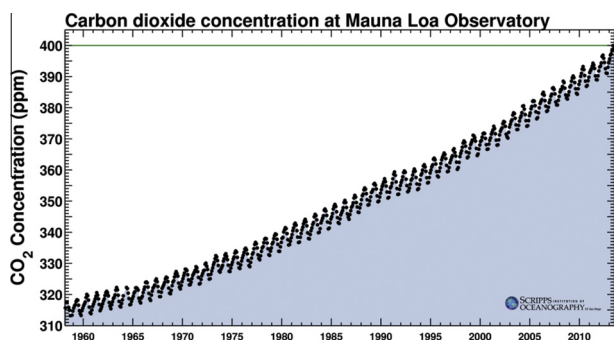
need. About a century later, the discovery of fossil oil (and natural gas) and then the invention of the internal combustion engine added an even more convenient source of power, especially for transportation (the automobile and airplane). The availability of this power and new raw materials, especially oil, transformed the world. From pharmaceuticals and synthetic polymeric goods to pesticides that make much modern agriculture possible, human ingenuity has capitalized on these resources.

More profoundly, our knowledge of the world has deepened and provides us with a great deal more insight into its history and our place within it. Scientifically, our achievements have been aided by both conceptual and technical advances—atomic and quantum models, electromagnetic theory, and spectroscopy that bring these concepts together and provide an intimate view of the molecular world. These advancements help us know much about the natural environmental changes brought about for example by the interactions of the Earth with the sun and its sister planets. This knowledge also makes us aware of the ways human activities influence natural processes and what the consequences can be for the planet and our lives. As scientists, our responsibilities are not only to understand the natural and human-influenced processes, but to help others understand them, and work with them to adapt to and reduce any negative consequences.

## 2. Climate change science

Accompanying all the knowledge and wonders made available by the Industrial Revolution is a large efflux of carbon dioxide to the atmosphere from the combustion of fossil fuels: coal, oil, and natural gas. Some of this gas dissolves relatively rapidly in the oceans or is taken up by photosynthesizing organisms and some enters the very long-term geochemical carbon cycle. The rest remains in the gas phase and is mixed fairly uniformly by convection and wind throughout the atmosphere. Evidence from air trapped in ice cores indicates that the pre-industrial level of carbon dioxide in the atmosphere was about 280 ppm. In mid-2013, the carbon dioxide level reached almost 400 ppm, (Fig. 1).

The human-caused release of carbon dioxide, mainly from burning fossil fuels, and its increasing concentration in the atmosphere and oceans are global phenomena with consequences for the environment of the entire planet. The basis



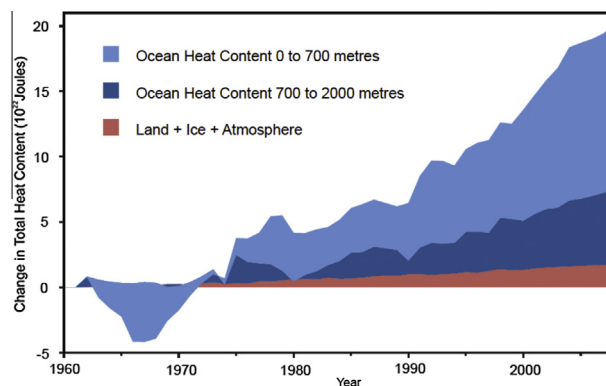
**Figure 1** The “Keeling curve,” the atmospheric concentration of carbon dioxide from the beginning of measurements in 1958 to mid-2013. (Institute of Oceanography).

of the consequences of concern here is interaction of atmospheric carbon dioxide with infrared radiation and the acid-base reactions of its aqueous solutions.

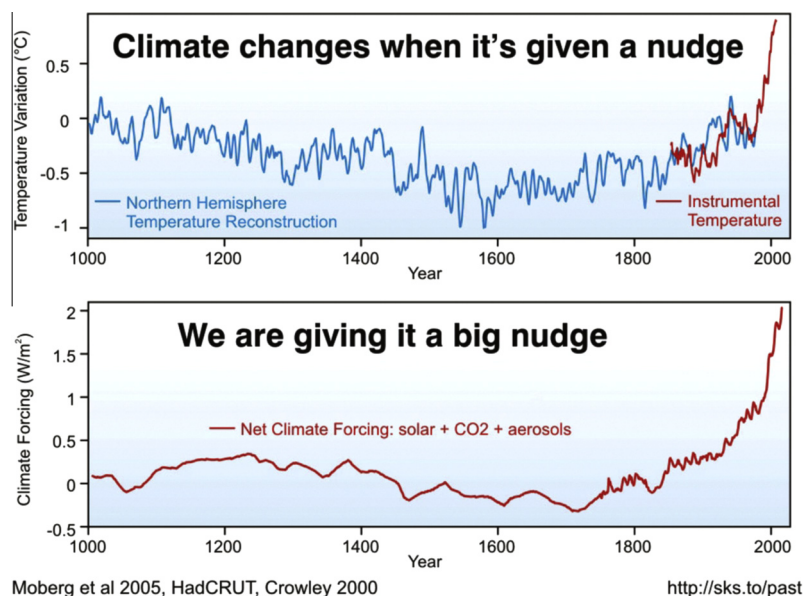
The Earth’s atmosphere is essential for maintaining a livable environment. Radiant energy from the sun, mainly in the visible region of the spectrum, where atmospheric gases are transparent, is absorbed by the Earth’s surface and warms it. The warmed surface radiates energy back into space, mainly in the infrared region of the spectrum. The balance between the incoming solar energy and the outgoing infrared energy determines the temperature of the planet. The presence of infrared absorbing gases in the atmosphere retains some of the infrared energy and requires a higher surface temperature to maintain the incoming-outgoing balance. This “greenhouse effect” keeps the planet warmer than it would be in the absence of infrared-absorbing gases and makes life, as we know it, possible.

Infrared absorption and emission by carbon dioxide are the major control mechanism for the atmospheric greenhouse effect. The increasing concentration of carbon dioxide increases the greenhouse effect, so the Earth retains more energy. Fig. 2 shows where this energy has gone over about the last half century—more than 90% into the oceans, which are an enormous, high heat capacity reservoir, with smaller amounts into melting ice (in glaciers and the polar regions), and warming the land and atmosphere.

The observed environmental changes include increasing sea level as the oceans warm and expand and more water is added from melting land ice, increasing loss of Arctic sea ice affecting the atmospheric jet stream and northern hemisphere weather patterns, and increasing average temperature of the Earth’s surface – usually characterized as “global warming.” This surface warming is shown on the upper plot in Fig. 3 while the lower plot shows the Earth’s imbalance in retention of solar energy in terms of climate forcing, the amount of the energy imbalance at the top of the atmosphere. (See the American Chemical Society Climate Science Toolkit for discussions of planetary energy balance, mechanism of the greenhouse effect, energy imbalance, and radiative forcing.) (American Chemical Society Climate Science Toolkit) Note that the forcing and temperature had a modest downward trend for the first 800 years of the past millennium, but both started an upward trajectory that became ever steeper during the 200 years



**Figure 2** Distribution of the Earth’s annual thermal energy content change due to the increased greenhouse effect during the past half century. (Nuccitelli et al., 2012).



**Figure 3** Upper graph: Surface temperature variations from proxy data (sea and lake sediments and tree rings) in blue and the instrumental record in red. Lower graph: Top-of-atmosphere radiative energy forcing (imbalance) taking account of variations in solar input and atmospheric carbon dioxide and aerosols. (Moberg et al., 2005).

following the Industrial Revolution as atmospheric carbon dioxide from fossil fuel burning increased, Fig. 1. As fossil fuels continue to be burned, both these curves are very likely to continue their upward climb producing an ever-warmer Earth and its consequences for the environment.

For example, rising seas could inundate low-lying islands and coastal areas such as the Maldives and the Mississippi, Nile, Tigris-Euphrates, and Ganges-Brahmaputra deltas that are home to millions of people. Furthermore, predictions from climate modeling and, increasingly, from observations, include further increases in extreme weather events such as more intense cyclonic storms, wet regions getting wetter, and, ironically, dry regions getting drier and expanding. In dry areas, the problem is exacerbated because aquifers in, for example, the central plains of the United States and the Middle East, are already greatly depleted. (Commitments by Middle Eastern countries to greatly expand water desalination using solar in place of fossil fuel power can help mitigate both greenhouse warming and water shortages.)

In addition to its primary role in greenhouse warming, the chemistry of carbon dioxide also has a large environmental impact. As fossil fuels are burned, a substantial fraction of the carbon dioxide produced dissolves in the Earth's oceans. The upper plot in Fig. 4 shows the increase in dissolved carbon dioxide that accompanies the increase in its atmospheric concentration – a consequence of Henry's law. The reaction of dissolved carbon dioxide with water produces hydronium and bicarbonate ions. The increase in hydronium ion concentration produces the decreasing ocean pH shown on the middle plot in Fig. 4, that is, the ocean is acidifying. In this lower pH medium, calcium carbonate is more soluble, or, looked at from the opposite point of view, its saturation decreases, as shown on the lower plot in Fig. 4. The consequences could be dire for many of the marine organisms that depend on the deposition of calcium carbonate to build their structures. In

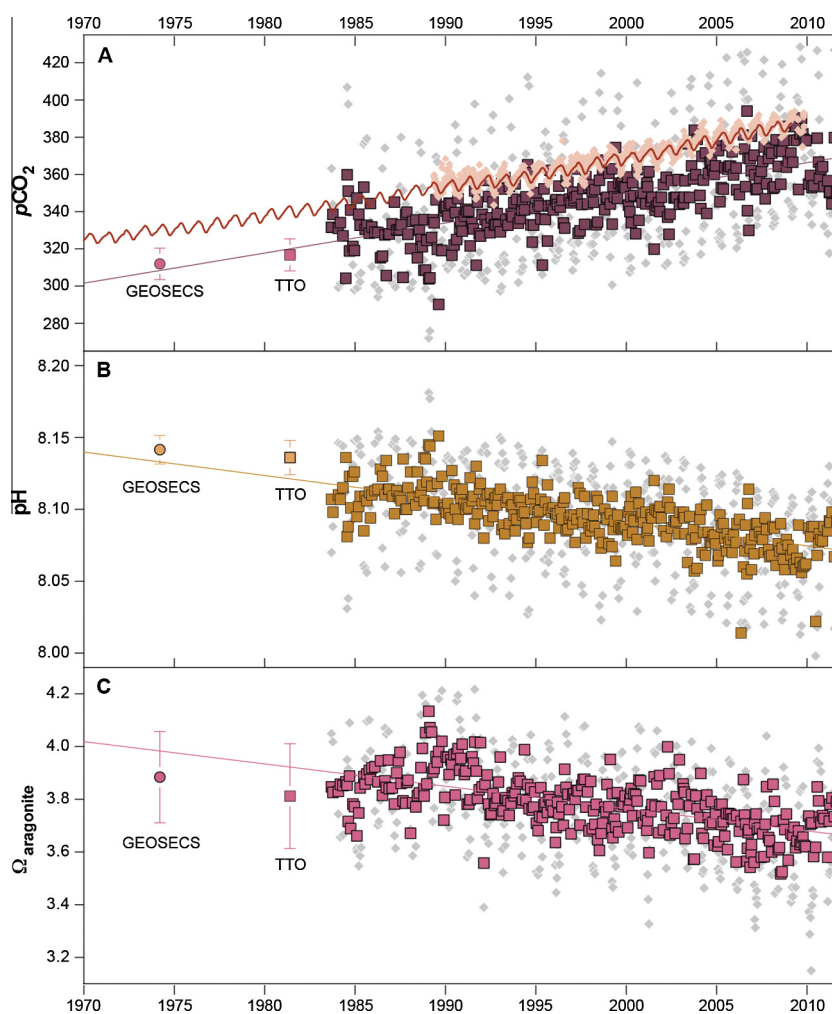
particular, these include photosynthesizing phytoplankton, such as coccolithophores, that are the basis of the oceanic food chain and responsible for perhaps half of Earth's photosynthesis. As decreasing pH decreases calcium carbonate saturation, the survival of these vital organisms and, hence, other marine life may be at risk.

### 3. Our responsibilities as chemists

Science and technology are the engines that drive our economy. Advances in both have given us a higher standard of living, accompanied by wonderful conveniences and have created new jobs. Our professional work in the chemical sciences contributes significantly to the well-being of society. Pharmaceuticals, agriculture, desalination and other water treatments, heightened awareness for protecting the environment.

Chemistry and chemists are central to sustaining the Earth and all its denizens in the face of the many challenges of a finite world. Our research and our technology can provide clean water and nutritious food, meet energy demands and reduce pollution, and help lead the way to sustainable development everywhere. Just as important, we can help society develop the will to improve the quality of life on the planet and to advance the human condition everywhere around the globe.

One of these challenges, climate change, was highlighted by the United States President Barack Obama in his second inaugural address on January 21, 2013. "We, the people, still believe that our obligations as Americans are not just to ourselves, but to all posterity. We will respond to the threat of climate change, knowing that the failure to do so would betray our children and future generations. Some may still deny the overwhelming judgment of science, but none can avoid the devastating impact of raging fires, and crippling drought, and more powerful storms." (Full Text of President Barack Obama's Second Inaugural Address) We have seen above that



**Figure 4** Time series of atmospheric (sawtooth curve) and ocean  $p\text{CO}_2$  (upper), pH (middle), and calcium carbonate (aragonite) saturation (lower) at a marine laboratory near Bermuda. (Bates et al., 2012).

climate change is a global problem, not unique to the United States, but one that the citizens of every country must face and respond to. In facing this challenge, we are all citizens of the world.

As citizens, chemists share in the responsibility to take and support actions to mitigate the causes of climate change and adapt to the changes that have already occurred and will increase in a warming world. As scientists, we have a special responsibility to help our fellow citizens, including the decision makers, understand why the climate is changing and what it means for them, their children, and generations to follow.

Polls suggest that much of the world's population is aware of recent climate change, think it is an important issue, and understand that it is mainly human caused, but there is too little sense of urgency or motivation to directly confront the causes. Climate scientists have spoken out forcefully in print (Hansen, 2009; Mann, 2012) and electronic media (RealClimate; Skeptical Science) in an effort to alert us to the inevitability of continuing and worsening climate changes from emissions we have already made and how continuing inaction exacerbates the effects. But there are relatively few climate scientists and people also hear messages from those who still deny the overwhelming judgment of science. As scientist-citizens, we must add our voices to support the science.

We mean this literally. Research (and common experience) indicates that people tend to be influenced most favorably by faith and by members of the groups with whom they identify and whose commitments they share. (Kahan, 2010) We scientist-citizens belong to a large number of groups – our colleagues, students, neighbors, schools, political organizations, and others. Our interactions in any of these represent opportunities to engage in respectful and deliberative conversations on the reality of climate change, its present and future effects, and policies and actions individuals, communities, and nations may take to mitigate and adapt.

#### 4. Resources for action

But many of us may be reluctant to begin this conversation or to know where to go with it. We have a responsibility to develop a command of the large and varied body of knowledge encompassed by climate science and a level of comfort with communicating it. To assist in this responsibility, the American Chemical Society Climate Science Toolkit, [www.acs.org/climatescience](http://www.acs.org/climatescience), (American Chemical Society Climate Science Toolkit) provides a concise introduction to the fundamentals of climate science at an undergraduate science level. It should take no more than a few hours for you to work through its

four basic content modules – Energy Balance and Planetary Temperatures, Atmospheric Warming, Greenhouse Gases, and Oceans, Ice & Rocks – to provide a robust intellectual foundation for exploration of the Toolkit’s references and resources and for conversations on climate change.

To aid in communicating about climate science and climate change, both informally and formally, the Toolkit provides a series of brief narratives that are designed for you to use or adapt in conversations with fellow scientists and with nonscientists. You might, of course, have opportunities to make presentations on climate science and climate change and the Toolkit provides a few examples of slide shows (with their narratives) as models. These examples feature climate changes that are already being observed and are familiar to many people and they draw attention to their causal relationships to climate science.

Implicit in these narratives and slide shows is the message that it is necessary to make adaptations to changes that have already occurred and will continue. And, further, that the changes will be more extreme if the emission of carbon dioxide goes on unabated. Thus, mitigation, reducing emissions, is also necessary to begin to decrease the further negative consequences of an ever-warmer world with rising and more acidic oceans. As a scientist-citizen conversing with others, you need to stress how personal lifestyle decisions that lower energy use are consequential first steps toward mitigation. Among these decisions are conscious choices to purchase goods and services from companies that share these goals. Supporting political leaders at all levels who promote policies aimed at mitigation is another step that individuals and citizens’ groups should take.

We know that joining in these conversations on global climate change will be hard for many scientist-citizens who are not used to this role. But keep in mind the future for the children and grandchildren of those in the conversation, including yours. Also keep in mind the enormous importance of your responsibilities and obligations as a scientist-citizen.

An exemplary model of the scientist-citizen is Professor Ahmed H. Zewail, the 1990 Nobel Laureate for his work on developing femtosecond spectroscopy to follow reaction dynamics. Professor Zewail, who holds dual citizenship from his native Egypt and adopted United States, has taken seriously the responsibility to use his standing in the scientific community as a way to help build bridges between these two nations. To explain the basis of his scientist-citizen activity he quotes the Arabic phrase, *al-ilm nur*, “knowledge (science) is light.” (Jacoby, 2012) We must emulate this teaching as we use our knowledge of climate change science to illuminate our actions and our conversations with fellow citizens.

Here are actions to pursue. Use the ACS Climate Science Toolkit, to review or learn the basic concepts of climate science and expand your knowledge of climate science areas of special interest to you. Use your knowledge to engage your friends and colleagues in deliberative discussion on the science of global climate change and its consequences. Set an example and encourage others to adopt personal choices that decrease the

undesired consequences of climate change. Take a public stand on the issues related to the undesired consequences of climate change and the need for adaptation to these changes and mitigation of their sources. Take advantage of opportunities to make formal presentations on the science of climate change when invited to do so. Encourage and support your local, regional, and national decision makers to adopt policies that are aimed at adaptation to and mitigation of human-caused climate change.

It is a responsibility of scientists who have knowledge of something that can affect the environment to shed enough light on it, so that action actually takes place. If not us, who? If not now, when? (Nobel Laureate) Please take action now.

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