Climate Action can "Flip the Switch": Resourcing Climate Empowerment in Chemistry Education

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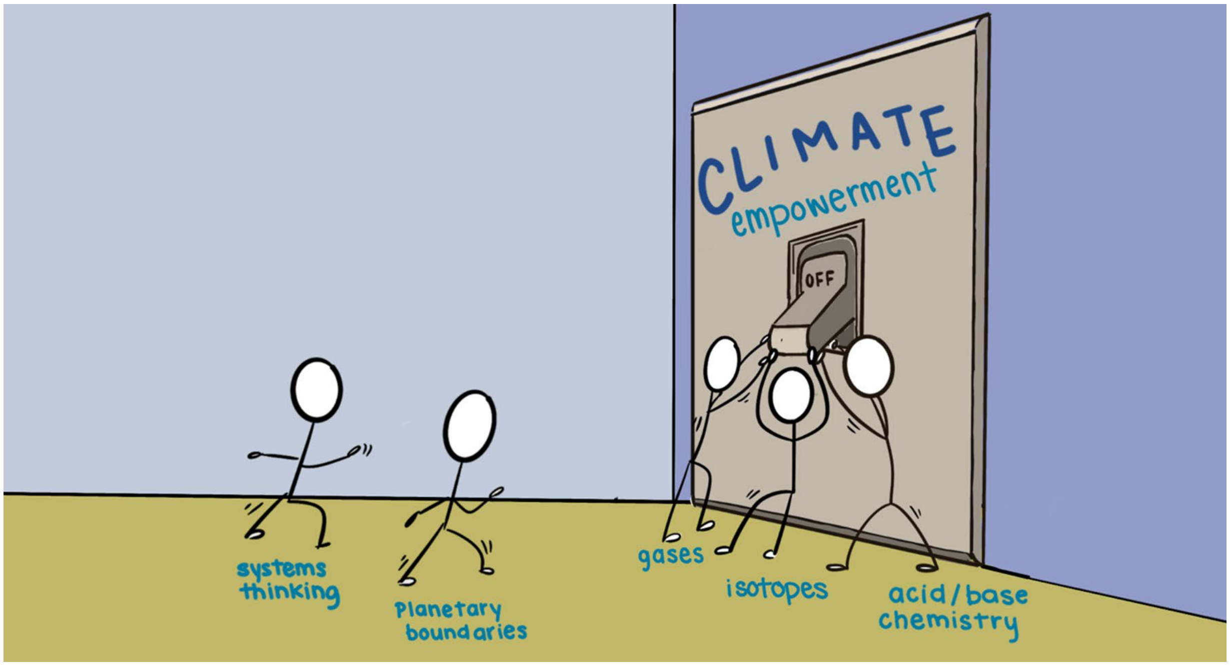
ABSTRACT

Traditional approaches to chemistry curriculum for undergraduate students prioritize coverage of fragmented individual topics rather than employing systems thinking to embed chemistry concepts in immersive holistic contexts vital to our planet's future, such as climate change. Many students are eager to understand and tackle climate change, drawing on political, socio-economic, sustainability and chemistry perspectives. However, educators face substantial barriers in resourcing climate empowerment through chemistry education. This paper outlines interactive resources and activities educators can use to help students engage with climate literacy and action, grounded in an emerging understanding of key concepts in chemistry. These resources draw from the work of 14 third- and fourth-year undergraduate students at The King's University who were learning about climate change in an environmental chemistry class. The students collaborated in small groups and as an entire class to develop learning activities, pilot activities created by others, articulate topics for educators, and perform several rounds of peer review. Topics chosen for this publication include systems thinking and Earth systems connections; the nature of and evidence for climate change; Earth's radiation balance, greenhouse gases, and climate engineering; models to forecast the future; and chemistry's role in solutions. Together, the students developed activities and learning outcomes they hope others will use to connect climate change to cognitive, affective, and kinesthetic learning in chemistry.

GRAPHICAL ABSTRACT



KEYWORDS

First-Year Undergraduate/General, Curriculum, Climate Change, Greenhouse Gases, Sustainability, Planetary Boundaries, Earth's Radiation Balance, Hydrogen, Models, Radiative Forcing, Systems Thinking

Introduction

> "Global heating is busting budgets, ballooning food prices, upending energy markets, and feeding a cost-of-living crisis…. Developing countries are being devastated by disasters they did not cause…. We are miles from the goals of the Paris Agreement – and minutes to midnight for the 1.5-degree limit…. Humanity's fate hangs in the balance…. But climate action can flip the switch." – *UN Secretary-General Antonio Guterres, opening the December 2023 UN World Climate Change Conference.*[1]

That stark assessment of the state of our planet as a result of anthropogenic climate change echoes global scientific findings, including the 2023 Intergovernmental Panel on Climate Change Synthesis Report and the recent update to the Planetary Boundaries Framework, which concludes Earth is now beyond six of nine planetary boundaries and well outside of the safe operating space for humanity.[1,2]

As the effects of rapidly changing climate become impossible to ignore across the globe, educators are increasingly incorporating climate education into the curriculum to better prepare students for responsible citizenship and emerging transformations in the labor market.[3] Professional programs in law and medicine and undergraduate courses in the humanities, arts, and social sciences more frequently include climate literacy and climate change impacts – in some cases pushing students to think beyond the boundaries of their disciplines.[3] But what about chemistry education? Does the current scope of chemistry curricula contribute meaningfully to equipping students to flip the switch towards just and equitable transitions in sectors needed for climate sustainability?

Grounded as it is in the molecular basis of sustainability, chemistry is crucial to both understanding climate change and finding solutions for mitigation and adaptation.[4] Yet to flip the (climate) switch, chemistry educators need to flip the (learning) switch, adopting new approaches that help students move beyond learning clusters of isolated concepts disconnected from their lives – and from pressing global challenges.[5] Interactive climate literacy tools are readily available, yet mainstream chemistry course syllabi and required textbooks fall short of integrating climate and chemistry content. A recent analysis of coverage of climate change in general chemistry textbooks found that most leading textbooks used in North America either omit climate change or relegate coverage to peripheral regions such as margin notes and end-of-chapter questions.[7] The switch to new approaches to chemistry curriculum has proven notoriously difficult to flip, yet literature suggests several frameworks that can help educators flip the (learning) switch to accelerate the move to curriculum and pedagogies that better equip students to understand and manage complexity, change, uncertainty, resilience, and vulnerability.[6]

Resourcing climate empowerment through chemistry education is addressed in this paper from the perspective of 14 third- and fourth-year undergraduate students at The King's University who were actively learning about climate change in an environmental chemistry course focused on atmospheric processes. The course made extensive use of several dozen climate-related interactive learning tools created by The King's Centre for Visualization of Science (KCVS), including two comprehensive KCVS sites for connecting climate change to chemistry: ExplainingClimateChange.com (Figure 1) and Visualizing the Chemistry of Climate Change (VC3Chem.com).[8,9]

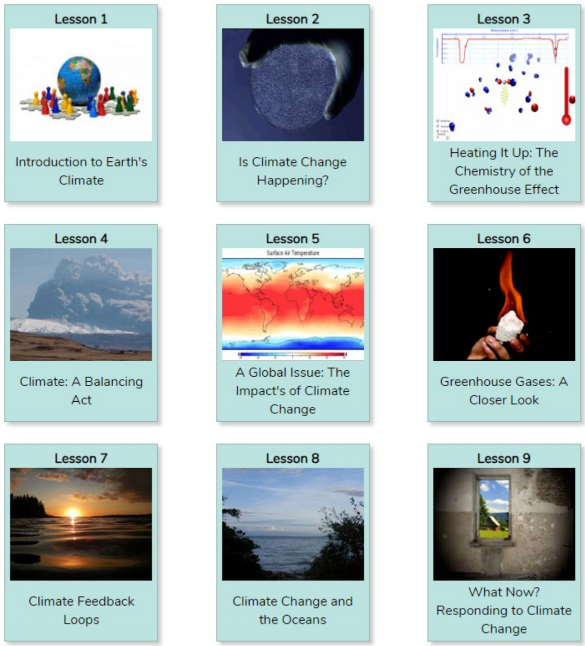


Figure 1: Screen capture from the KCVS ExplainingClimateChange.com interactive learning tool.

Students reflected on their learning and created activities based on KCVS and other interactive learning tools they felt might help equip chemistry educators and students to understand the fundamental science of climate change and explore how chemistry can contribute to solutions. In each of six groups, chemistry majors were paired with environmental studies students to tap broad perspectives and knowledge. After brainstorming a list of topics and KCVS resources connecting chemistry and climate change, each group was assigned a topic related to core understandings of the chemistry of climate change and/or the role chemistry plays in solutions (Table 1).

Each group articulated learning outcomes for its topic and developed an outline as well as a system concept map showing possible interconnections within chemistry and climate concerns. They also developed one or two activities suitable for undergraduate students. The learning outcomes, outline, and activities were presented to the class, followed by discussion and peer review by other groups. A chemistry course for non-majors (Sustainability and the Flow of Matter and Energy) tried out three of the activities and provided peer feedback to the authors. Each group then drafted a topic and activities for the manuscript and reviewed manuscript contents. To fulfill the requirements of a one-semester senior research project, a third-year chemistry student (JL) helped coordinate the work of the environmental chemistry class. JL and the professor (PGM) worked together to guide the class project; coordinate the writing, editing, and peer review; and prepare the final manuscript.

Approaches and Orientations to Resourcing Climate Empowerment

Students were asked to engage with several approaches and orientations relevant to identifying and piloting climate change resources for university chemistry educators. Summarized below, these included learning domains, systems thinking, and the Planetary Boundaries framework.

Tapping Cognitive, Affective, and Kinesthetic Domains of Learning

The class reflected on how to best help chemistry educators provide learning resources to their students that move beyond the acquisition of knowledge about chemistry and climate change to empowering climate action. Cognitive, affective, and kinesthetic domains of learning were briefly introduced, and students discussed the value of learning that not only engages their minds (cognitive domain) but taps into their attitudes, motivation, interests, self-concept, values, and morals (affective domain) and explores concepts through physical activity (kinesthetic domain).[10] In the examples and activities that follow, students identified several online KCVS resources freely available to educators wishing to incorporate cognitive, affective, and/or kinesthetic domains of learning in their classrooms.

Systems Thinking and Earth System Connections

Earth system science provides the compelling perspective that analysis of anthropogenic changes to the core climate Earth system process must show connections to other Earth system processes, as illustrated in the discussion of the Planetary Boundaries framework below.[11] One pedagogical framework to address the complexity that results from teaching chemistry in sustainability contexts develops integrated competencies for foundational chemistry courses through (a) systems thinking and cross-cutting reasoning; (b) core understandings related to central chemistry ideas, socio-environmental literacy and responsibility; and (c) fundamental science, disciplinary and collaborative problem-solving practices.[6]

Systems thinking approaches are gaining considerable attention among global chemistry educators for their ability to help learners see and understand the place of chemistry in dynamic and interconnected systems, especially those that provide the molecular/material basis for the sustainability of Earth and societal systems, including the climate change Earth system process.[12,13] Researchers have recently examined the benefits of implementing systems thinking in chemistry education and identified challenges faced by both students and educators when doing so.[14,15,16] A recently published educational framework for teaching chemistry using systems thinking approaches, developed by an IUPAC task force, offers support for this framework.[17]

System-Oriented Concept Maps

In developing their understanding of the climate change Earth system process and visualizing its connections to chemistry topics and socio-economic issues, each student group explored the boundaries of a system related to their investigation by creating a System-Oriented Concept Map Extension (SOCME) using the KCVS SOCME on-line construction kit (SOCKit).[18] Critical components, important relationships, system behavior, and granularity of topics were considered when drafting a map. One of these student generated SOCME maps is shown in Figure 3.

Planetary Boundaries Framework

Using systems thinking, connections between the climate change and other Earth system processes and chemistry curriculum topics can be readily explored through the Planetary Boundaries Sustainability Framework. Initially published by a team led by The Stockholm Resilience Centre, the Planetary Boundaries framework describes nine Earth system processes that provide a semiquantitative measure of the extent to which human activity poses risks of destabilizing the entire Earth system.[19,20] Each Earth system process is defined by control variables and numerical boundaries that describe the safe operating space for humanity.[19] Two Earth system processes (climate change and loss of biodiversity) are designated as core systems because they interact most substantially with other systems and because each has the potential on its own to destabilize the entire Earth system if sufficient mitigation action is not taken.[19] The remaining seven Earth system processes are novel entities, stratospheric ozone depletion, atmospheric aerosol loading, ocean acidification, biogeochemical flows of N and P, freshwater use, and land system change.[19]

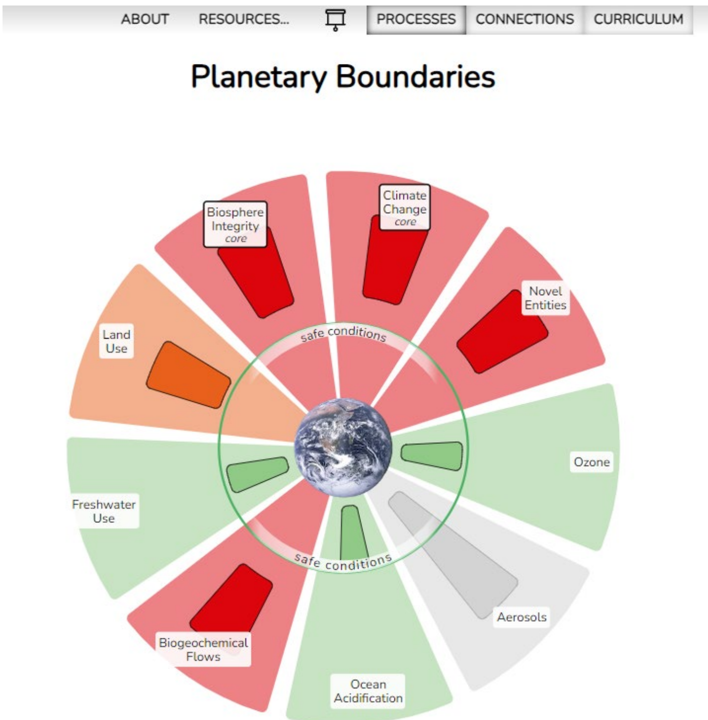


Figure 2: Screen capture from the KCVS interactive Planetary Boundaries learning tool.[11]

In collaboration with Sarah Cornell from the Stockholm Resilience Centre, KCVS created the dynamic Planetary Boundaries visualization learning tool (Figure 2) to help explore the framework and see system connections.[8] The learning tool incorporates key elements of systems thinking such as identifying parts of a system and their connections, understanding the system as more than a sum of its parts, exploring flows and cycles, and recognizing change over time.[11] Detailed information about each Earth system process and the Earth system as a whole is available in the main process view, where graphs of the level of risk over time are displayed.

The connections tab on this learning tool uses a force-directed graph to connect the Earth system processes together and highlight the importance of systems thinking within the Planetary Boundaries framework. Users can explore how each Earth system process is connected to the web of other processes, especially the core processes, climate change and biosphere integrity.

The curriculum tab, developed in collaboration with the IUPAC STCS-2030+ project, maps a set of eight core chemistry curriculum topics onto Earth system processes, helping educators identify points in which sustainability and climate change concepts can be integrated with topics already in the curriculum.[11,21] A kinesthetic activity based on the planetary boundary interconnections is found in Activity S.2.

Two control variables define the state of the climate change Earth system process: (a) atmospheric carbon dioxide concentration and (b) energy imbalance at the top of the atmosphere relative to preindustrial levels.[19] Transgressing these control variables results in temperature rise that impacts multiple interconnected environmental systems. One example is habitat disruption due to temperature changes, which impacts the biosphere integrity Earth system process.

Changes in other Earth system processes amplify climate change. The production of ammonia and reactive nitrogen fertilizers in the Haber-Bosch process requires 1.8% of all fossil fuel energy used on our planet, releasing large amounts of CO_2 into the atmosphere.[22] This contributes to pushing the CO_2 climate change control variable further into a zone of very high risk. In addition, the over-application of nitrogen fertilizer derived from the Haber-Bosch process (biogeochemical flow of N Earth system process) increases the atmospheric concentration of nitrous oxide, which is both a potent greenhouse gas and stratospheric ozone depletor. Representative connecting concepts are illustrated in the SOCME system map in Figure 3.

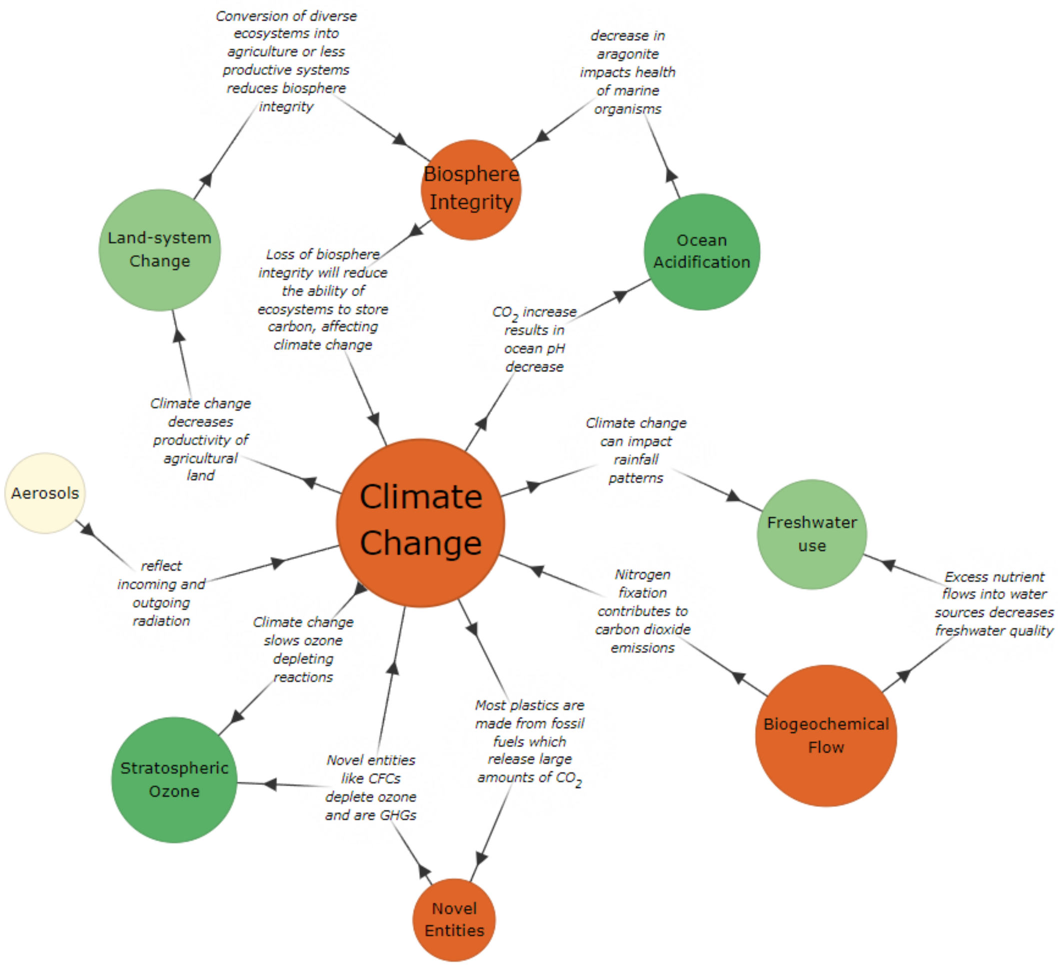


Figure 3: SOCME Diagram highlighting climate change and its Earth system connections.

175 Students also explored ways to enhance teaching of acid/base concepts and precipitation/solubility/equilibrium topics by mapping connections between climate change and ocean acidification, as demonstrated in Activity S.1.

The selected list of climate topics and key chemistry curriculum connections are shown in Table 1.

Table 1. Select climate topics and chemistry curriculum connections.

Climate Topic	**Chemistry curriculum connections**
System thinking and Earth system connections	Chemical equilibrium, acids and bases, speciation, speciation curves

Nature and evidence for climate change	Isotopes, mass spectrometry
Earth's radiation balance: • Greenhouse gases • Climate engineering	Infrared radiation, structure and bonding, thermochemistry, properties of gases
Models to forecast the future	Nature of scientific evidence and models
Chemistry's role in solutions	Quantum theory, photochemistry, electrochemistry, thermochemistry

Suggested Topics for Chemistry Educators

1. Nature and Evidence for Climate Change

The largest contributors to changes in Earth's radiation balance over the past two centuries are from the increasing concentration of anthropogenic greenhouse gases (GHGs), especially CO_2 from the combustion of fossil fuels.[23,24,25] GHG emissions trap IR energy emitted by Earth in the atmosphere, rapidly increasing Earth's temperature since the Industrial Revolution, when emissions began escalating. Using the average global temperature in 1750 as a reference point, the Paris Agreement set goals to keep average global surface temperature increases to +1.5˚C.[26]

Given the observation of greater than expected impacts of climate change with increasing temperature, and given divergent public understandings of the reality and severity of climate change, instructors may find it helpful to provide resources for students to explore scientific evidence of climate change by analyzing atmospheric CO_2 concentrations and by correlating global temperatures and GHG concentrations over recent and deep time.[1,27]

Evidence of Historical CO_2 and Temperature Increases

Various direct and proxy methods have been employed to provide evidence of historical GHG concentrations and temperature changes over time. Precipitation has accumulated for millions of years in Antarctic and Greenland ice sheets, trapping atmospheric gases in the ice. As a result, direct measurements of CO_2, CH_4, and N_2O concentrations in ice cores can be obtained. Along with direct analysis of concentrations of gases, measurements of isotope ratios of heavy and light water in ice cores from ice sheets and glaciers can be readily connected to the curricular coverage of stable isotopes in chemistry courses.[28] Depending on the analytes, isotope ratio mass spectrometry, gas chromatography, and laser absorption spectrometry are used to analyze the samples.[29]

The process of deposition of ice and trapped gases provides information on climate events such as timing of glaciation. The ratio of stable O isotopes in water provides a proxy measurement of atmospheric temperature at the time of deposition to glaciers.[30] Heavy and lighter isotopologues of water respond differently to temperature variations during evaporation and condensation. As temperature increases, heavier isotopologues containing ^{18}O atoms are more prevalent in water vapor and therefore in ice core data.[28] Students can engage with the KCVS Ice Core Extraction and Analysis learning tool to understand ice core extraction methods, analysis, and importance – and to correlate CO_2 and other GHG concentrations with global temperature fluctuations.

Carbon isotope ratios in CO_2 samples also reveal human influence on Earth systems. Anthropogenic CO_2 samples are characterized by lower $^{13}C/^{12}C$ ratios relative to natural carbon sources.[31] Therefore, the isotopic composition of historic atmospheric CO_2 samples provides evidence of the extent of human activity. This data, together with O isotope data, provides a proxy measure of temperature, enabling strong correlations between CO_2 concentrations and temperature over time.

While undergraduate students may be familiar with radioisotopes, stable isotopes receive relatively little attention in introductory chemistry courses. Rich connections to their importance can be seen in the use of carbon isotope ratios to determine the source of carbon-containing atmospheric substances such as CO_2 and CH_4. Through the KCVS Isotopes Matter set of resources, students can access the interactive IUPAC Periodic Table of the Elements and Isotopes, which includes a complete list of isotopes for each element as well as applications to climate science and other areas.[8]

Leaving the Holocene Epoch

The Holocene epoch in the Quaternary Period of the geologic time scale began after the last ice age. Characterized by stable conditions, the Holocene supported the thriving of human and other forms of life, with temperatures fluctuating by only ±1˚C for 11,700 years.[2] Because of this stability, the Holocene is used as a reference point for the much greater temperature fluctuations seen today. The changes to Earth's features caused by human activity have been so pronounced recently that a new epoch has been proposed: the Anthropocene Epoch.[2]

While the jury is still out on whether professional geologists will eventually agree to the recommended formal declaration of a change from the Holocene to the Anthropocene Epoch, it is clear that we live (and study chemistry) during a period in our planet's history when human activity overwhelms all other influences on planetary change. Activity S.3 demonstrates this reality by showing the slope of temperature changes in the atmosphere using the interactive KCVS learning tool Historical Climate Trends.[8] Using this tool, students can explore and compare temperatures and GHG concentrations from ice-core data sets and measure the slopes of these curves over different times in the data set. Doing so makes clear that the biggest difference in the temperature record over the past century compared to the previous million years is the striking increase in rate of change.

Evidence of Human Impact

The Mauna Loa Keeling Curve (Figure 4) illustrates anthropogenic factors influencing CO_2 trends over the past 65 years. The northern hemisphere sees annual oscillations of up to 10 ppm changes in CO_2 concentrations due to seasonal photosynthesis changes in forests,[32] but the overall steady increase in the trendline for the curve in data sets from both the Mauna Loa Observatory and the South Pole reflects increasing anthropogenic CO_2 concentrations.

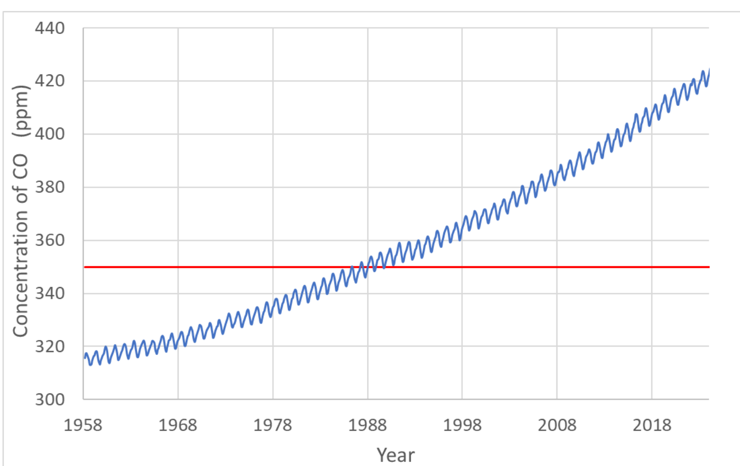


Figure 4. Keeling Curve from Scripps CO_2 program data, with planetary boundary shown in red.

While pre-industrial concentration of CO_2 is 280 ppm, this value has fluctuated over deep time and correlates with changes to Earth's temperature. Atmospheric CO_2 levels typically have ranged from

180-190 ppm in colder periods to 270-290 ppm in warmer periods.[33] The current atmospheric concentration of CO_2 is 425 ppm, a level not seen since before humans populated the planet.[2] Although natural forces do cause changes to Earth's overall temperature, they alone cannot explain the steady temperature increase in the last 100 years. This concept is demonstrated by the KCVS Climate Contributions learning tool in which students can visualize the contributions from both natural and anthropogenic sources to our changing climate.[33]

Quantitative metrics of CO_2 and other GHG concentrations and temperature provide important evidence of climate change, but climate change is much more than increases in surface temperature. A good example is the weakening of ocean currents such as the Atlantic Meridional Overturning Circulation (AMOC) due to freshwater inputs to the ocean from melting glacier runoff near the poles, which may significantly impact planetary life.[34,35,36] These currents have allowed milder winters in parts of Europe compared to other countries of similar latitudes. Glacier melt due to enhanced warming trends at higher latitudes is itself an early warning signal for other effects.[33] Shrinking permanent ice cover, which decreases Earth's albedo and increases temperature, is another metric for climate change.[2]

2. Earth's Radiation Balance

Earth's surface temperature is determined by the balance of reflected, absorbed, and emitted electromagnetic radiation. Radiative forcers (RF) either increase or decrease Earth's temperature and change its radiation balance. Negative RFs enhance Earth's albedo, reflecting incoming visible light from the sun and decreasing surface temperature. Positive RFs such as greenhouse gases (GHG) contribute to atmospheric warming, trapping excess energy in the atmosphere and increasing temperature. In Activity S.4, the KCVS learning tool Build a Planet (Figure 5) demonstrates how the surface temperature and energy balance for a planet (such as Earth!) depend on distance from the sun, albedo, and the GHG effect.[8]

Figure 5. Screen capture from KCVS Build a Planet interactive learning tool.

Greenhouse Gases

Figure 6 shows the change in positive radiative forcing attributed to the major GHGs from 1750 to 2019. As discussed below, some of the warming from GHGs is balanced by processes that increase Earth's albedo, causing cooling.

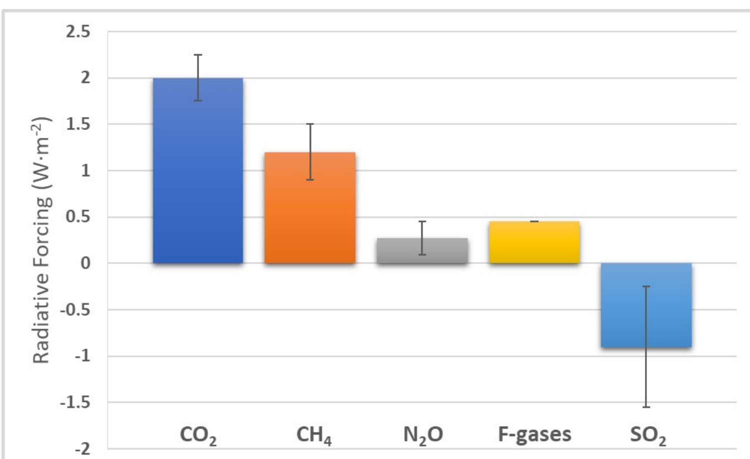


Figure 6: Change in radiative forcing of GHGs since 1750[1]

The amount of change a GHG makes on the radiation balance of our planet depends on (a) its concentration, (b) its IR absorption spectrum, and (c) its atmospheric lifetime. Activity S.5 illustrates this concept with methane gas.

a) Greenhouse Gas Concentration

The atmospheric concentration of a GHG plays an important role in its contribution to changing the radiation balance of our planet. The concentrations of many key GHGs have increased dramatically over the past 70 years, leading to increased IR absorption, which intensifies GHG warming. Unlike substances that catalytically destroy ozone in the stratosphere, the absorption of IR by a GHG is a non-destructive process.

b) IR Absorption Spectra of GHGs

Each GHG exhibits distinct structural characteristics that affect its ability to absorb IR and contribute to tropospheric warming. For a GHG to absorb IR there must be a change in charge distribution during a vibration. Ninety-nine percent of Earth's atmosphere is composed of nitrogen and oxygen gas, both of which are homonuclear diatomic gases and infrared inactive. Heteronuclear diatomic molecules and other gases with three or more atoms can undergo vibrational excitation when absorbing IR emitted by Earth. Heating results from processes such as collisional de-excitation, where vibrationally excited GHGs such as CO_2 and CH_4 transfer energy through collisions with N_2 (g) and O_2 (g) molecules. This interaction results in increased translational energy of air molecules and increased atmospheric temperature. The KCVS resource Collisional Heating Learning tool (Figure 7) demonstrates the interaction of various vibrationally excited GHGs with O_2 or N_2 following absorption of the appropriate wavelength of IR.[8]

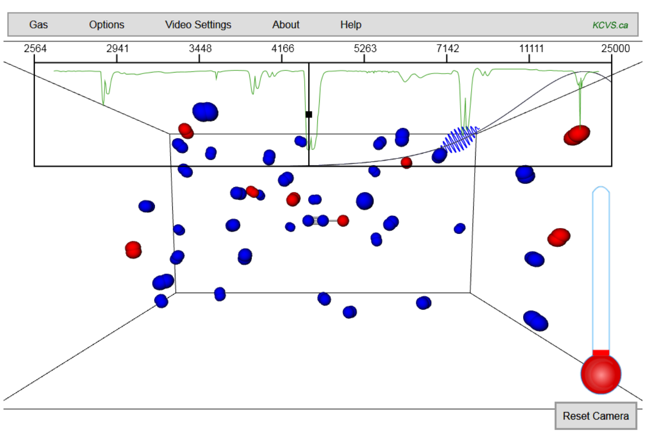


Figure 7. Screen capture from KCVS Collisional Heating interactive learning tool.

Earth's blackbody curve represents the various wavelengths of IR emitted by Earth. Naturally occurring GHGs such as CO_2 and water vapor have played an important role through our planet's history in absorbing IR at specific wavelengths and making Earth warm enough to be habitable. Regions in the emission spectrum corresponding to Earth's blackbody curve where CO_2 and water vapour do not absorb IR are called spectral windows. In the spectral windows regions, IR radiation from Earth can escape through the atmosphere to space, cooling our planet. CH_4 and other GHGs, including N_2O, F-gases, and tropospheric O_3, absorb in these spectral windows. As the concentration of these GHGs increases and their absorption in IR spectral windows increases, significant impact on the radiation balance of Earth occurs. The KCVS IR Windows Learning tool (Figure 8) visualizes the blackbody curve and absorption of IR by CO_2, water vapor, and other key GHGs.[8]

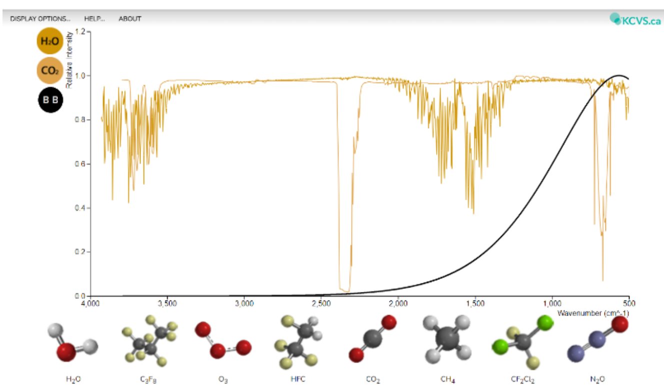


Figure 8. Screen capture from KCVS IR window for greenhouse gases interactive learning tool

Complementing the KCVS IR window learning tool is the KCVS Bad Vibrations, created by a King's University chemistry graduate who is also a musician. The tool taps the affective domain of listeners by sonificating the IR spectra of GHGs, ending with a provocative question as to what sounds of nature we are willing to drown out.[37]

c) Atmospheric Lifetime

Atmospheric lifetime refers to the length of time a substance exists in the atmosphere before being removed. Atmospheric lifetime can often be correlated with structural features of GHG such as the presence of C-H or C=C bonds and water solubility. For example, CH_4 experiences a shorter atmospheric lifetime than many other GHGs, due to abstraction of H from C-H bonds in CH_4 by tropospheric hydroxyl radicals, which initiates the oxidation of CH_4 to CO_2.

Global Warming Potential

An important tool to assess whether a GHG has the potential to warm climate if found in sufficiently high concentration is its global warming potential (GWP). GWP measures the capacity of a GHG to cause warming over a defined time compared to the same mass of CO_2. Table 2 gives the GWP of CO_2, which is arbitrarily assigned a value of 1, and its "lesser-known cousins," CH_4, CFC-12, and N_2O.

Table 2. GWP of CO_2 and other important GHG over periods of 10, 50 and 100 years[38]

Gas	Atmospheric Lifetime (years)	Global Warming Potential		
		10 years	50 years	100 years
CO_2	variable	1	1	1
CH_4	12	72	25	7.6
N_2O	114	289	298	153
CFC-12	100	11 000	10 900	5200

Methane has a GWP of 72 over 10 years, meaning if CO_2 and CH_4 were of equal atmospheric concentration, CH_4 would contribute 72 times as much to radiative forcing than CO_2. The GWP of a GHG depends on where in the IR spectrum and how strongly the gas absorbs IR and its atmospheric lifetime, but not its concentration, as by definition GWP is measured against an equal amount of CO_2. N_2O and CFC-12 have high GWPs because they have long atmospheric lifetimes (low water solubility and little reactivity with the hydroxyl radical) and strong IR spectral window absorptions.

Feedback Loops

Positive feedback loops, such as those involving water vapor ($H_2O_{(g)}$), amplify RF effects through a chain of events. As Earth's surface temperature increases, more water evaporates, increasing its atmospheric concentration. $H_2O_{(g)}$ is a GHG that further increases temperature. Another positive feedback loop involves methane clathrate hydrates, which are found in Arctic permafrost and in sediments off continental shelves. These clathrates are formed of CH_4 molecules held by weak intermolecular forces in cages of water molecules. Earth's increasing temperature, which is pronounced at the poles, causes the melting of ice and release of CH_4 into the atmosphere. Since CH_4 is a GHG with a large GWP, it absorbs infrared radiation (IR), accelerating climate change and further contributing to CH_4 release through Arctic ice melting. The KCVS resource ExplainingClimateChange.ca: Lesson 6, Key Idea 3 provides an interactive overview of methane clathrates and positive feedback loops.[8]

Negative Radiative Forcing

White and bright surfaces on Earth contribute to Earth's albedo and reflect visible light from the sun back into space before it can be absorbed by Earth. Polar icecaps, snowfields, cloud cover, and changes in land use that increase reflectivity all contribute to Earth's albedo. Human activity not only increases positive radiative forcing through GHG production but can also increase or decrease negative radiative forcing. The sum of the positive and negative RF contributions determines the overall change in Earth's radiation balance since 1750. The sum of these two changes to Earth's radiation balance is used by the IPCC and is the second control variable for the climate change Earth system process in the Planetary Boundaries framework. This control variable is particularly useful for chemistry students, as it is regulated by many other chemical players in the troposphere besides CO_2.

Climate Engineering

Strategies beyond GHG mitigation are being researched and tested to combat rapidly rising global temperatures. One approach would engineer negative radiative forcing by injecting ocean water into the marine boundary layer, creating sea salt-based aerosols. This "marine cloud brightening" increases clouds' albedo effect and lifetime by dispersing large water droplets in low-lying clouds. Studies demonstrate that marine cloud brightening can restore precipitation and sea ice levels due to the introduction of water into the atmosphere. However, this strategy also has the potential to affect cloud structure and salt concentrations in rainwater, exposing biodiversity and ecosystems to increased salt.[39]

Other approaches to engineering negative radiative forcing involve infrastructure design and crop mediation to increase the albedo effect. For example, high albedo sugar cane crops can be grown and then used as sources of biofuel. Introducing high albedo paints, roofing, and pavement into cities has been considered in some regions.[40]

A particularly controversial strategy is stratospheric aerosol injection,[41] often using sulfate aerosols. SO_2 is a byproduct of fossil fuel combustion that can be readily converted into sulfate aerosols by oxidation via hydroxyl radicals and other oxidants in the atmosphere.[39] Sulfate aerosols are significant negative RFs. What's more, they have much longer lifetimes in the stratosphere than in the troposphere, increasing the duration of albedo changes.

The benefits, disadvantages, and unintended consequences of engineering changes to RF can ignite engaging conversations in undergraduate chemistry courses. Students can consider the socio-political consequences of climate engineering by asking questions such as these:

- "Can a polluting country or an entrepreneur simply cancel out their GHG impact by sending aerosols into the stratosphere?"
- "Should governments or intergovernmental organizations regulate climate engineering through solar radiation management?"
- "Will reliance on short-term cancellation of positive RF from GHG through climate engineering stall efforts to mitigate GHG?"
- "What effect would that have on global phenomena such as the CO_2 levels that cause ocean acidification?"
- "What risks does stratospheric engineering in one region pose to droughts, crops, and changes to weather patterns in other parts of the world?"
- "Should regional air quality or global surface temperatures be prioritized in climate discussions?"
- "We are already engineering our climate through massive positive radiative forcing. Shouldn't we consider countering that with solar radiation management?"
- "How does a holistic systems thinking approach to Earth's energy balance change the conversation?"

Case studies are useful methods to engage students in climate chemistry topics.[42] The case of the International Maritime Organization (IMO) and the regulation of shipping bunker fuel demonstrates the need for using systems thinking in addressing complex environmental issues. Bunker fuel used by ships has historically been low-grade, inexpensive, and sulfur-rich.[43] SO_x emissions from shipping are associated with ~400,000 annual premature deaths from lung cancer and cardiovascular disease and ~ 14 million childhood asthma cases, along with cancer, asthma, heart attacks, and other health conditions.[43,44] However, implementing IMO regulations to decrease the S content of fuels led to a decrease in sulfate aerosols from oxidized SO_2, which may have measurably lowered Earth's albedo and contributed to an unintended increase in Earth's temperature.[41,45] Activity S.4 provides further details.

3. Models to Forecast the Future

Predicting the consequences of anthropogenic changes to radiative forcing is one of the most challenging and high-stakes activities taking place on a global stage through UN-level conferences on climate change and the work of the Intergovernmental Panel on Climate Change (IPCC). Getting it right has enormous consequences for driving timely and appropriate mitigation and adaptation interventions, with huge socio-economic implications. Climate empowerment requires a good understanding of both the power and the limitations of models, coupled with concerted efforts to communicate both to the public. Models use data algorithms that represent the current trajectory of climate activity, predicting the future of climate. By enabling the public to visualize climate impacts, models hold promise to encourage climate action. Students may find two climate simulators helpful for understanding the relative and combined impact of various mitigation strategies, to prioritize actions, and to bring hope that feasible solutions can be found.

The KCVS Design our Climate Simulator (DOCs) divides the overwhelming challenge of reducing greenhouse gas emissions into smaller, accessible solutions, using currently available technology and mindful improvements in lifestyles (Figure 9).[8] After completing a simulation, users are invited to map their results onto Project Drawdown's list of solutions and develop an action plan that considers a user's various spheres of influence.[46]

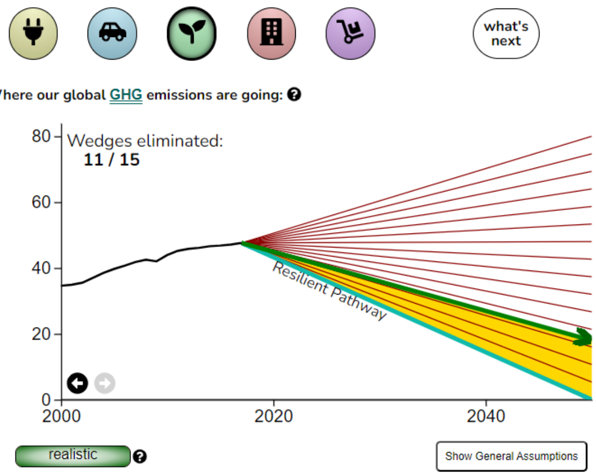


Figure 9. Screen capture from KCVS Design our Climate Simulator interactive learning tool.

The second simulator, En-ROADS, is a powerful system dynamics model with a steeper learning curve. En-ROADS allows users to explore the impacts of dozens of policies and technologies on surface temperature, energy prices, and seal level rise. Inputs include electrification of infrastructure, carbon pricing, and agricultural practices.[47]

Hindcasting

Misinformation and uncertainty about taking necessary steps to mitigate climate change is reinforced by a lack of understanding of the validity of climate models for looking into the future. One important technique for assessing the accuracy of models intended to direct future action is to check how accurate early climate models were in predicting the climate we now are experiencing. The KCVS Climate Model Hindcasting learning tool (Figure 10) visually compares the predictions of eight historically important climate models against observed temperature increases, showing the climate sensitivity and key assumptions for each.[8] Starting in 1972 and working through the increasingly sophisticated models since then demonstrates how accurate even the early models were in predicting temperature increases and climate sensitivity, thus boosting confidence in the validity of models going forward. Activity S.6 demonstrates the importance of climate models for predicting climate future.

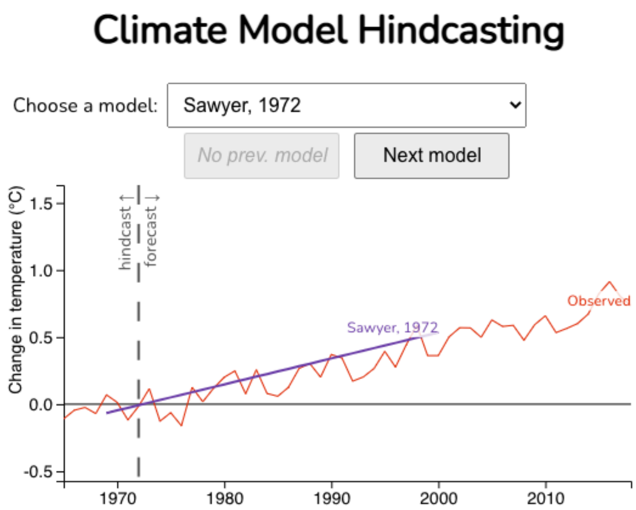


Figure 10. Screen capture from KCVS Climate Model Hindcasting interactive learning tool.

4. Chemistry's Role in Solutions

To satisfy unprecedented global energy demand while mitigating GHG emissions, fossil fuel energy sources (oil, coal, and natural gas) are being replaced with nuclear power and renewable sources.[48] These transitions can be expensive and require a variety of technologies, each with constraints. This section identifies several key areas where chemistry – and future chemists – have potential to contribute toward climate mitigation.

Renewable Energy Sources

Working through the KCVS DOCS simulation makes it clear that there is no "silver bullet" for transitions to meet global climate goals; rather, what's needed is an achievable potpourri of complementary solutions ("silver buckshot"). Key renewable alternatives under consideration are solar, thermal, wind, geothermal, hydro, and biomass energy. Each one draws heavily on chemistry. Battery technology advances are crucial to providing the increased energy storage required by intermittent sources of energy. Hydrogen and ammonia are receiving considerable attention as molecular energy carriers.

Solar energy is harnessed as thermal energy to produce heat and photovoltaic energy to produce electricity.[49] Solar photovoltaic energy accounted for three-quarters of net global renewable additions in 2023 and is expected to surpass nuclear and wind energy production.[50] Solar thermal energy is limited by its use of rare minerals whose feasibility is challenged by economic, political and environmental realities.[49] Solar energy technologies connect to numerous chemistry topics in the undergraduate curriculum, including the electromagnetic spectrum, thermochemistry, photochemistry, spectroscopy, and quantum theory.

Wind and water currents can both be harnessed to produce electricity. Tall wind turbines convert the turning motion of turbine blades caused by the kinetic energy of moving wind into electrical energy. Similarly, hydroelectric power is generated by harnessing the kinetic energy of flowing water. Both wind and hydro-energy sources relate to thermochemistry topics, including potential and kinetic energy and the conservation of energy.

Battery technology is a key priority area for chemistry and material engineering. The class engaged with a visiting speaker who provided an overview of emerging developments in lithium- and sodium-ion batteries, and of the opportunities and challenges in using batteries for storing energy produced with hydrogen.[51]

Other potential energy sources include geothermal energy, which utilizes stored heat reserves and thus facilitates economic independence in countries with suitable geothermal resources.[52] Bioenergy is produced by burning organic materials such as scrap lumber, agricultural crops, and food waste to generate steam that drives turbines to produce electricity.[52] The production of geothermal and bioenergy relates to chemistry topics such as thermal energy, endothermic and exothermic reactions, and Gibbs-free energy. The tradeoffs that must be weighed when using biomass for energy vs. food open important topics for engaging students in systems thinking with respect to energy transitions.

Hydrogen

As renewable energy demands grow, a deficit in battery storage capacity may limit ability to reach the global 2050 net-zero emissions goal. Hydrogen[53] has over three times the gravimetric energy density of petroleum, at 120MJ/Kg and 44MJ/Kg, respectively.[54] The combustion of hydrogen leads to a high energy output, with water as the only major product, giving a substantial climate advantage over the combustion of fossil fuels.

Colors of Hydrogen

But hydrogen isn't hydrogen when it comes to exploring the major role it may play as an energy carrier going forward. A systems thinking approach requires looking beyond the hydrogen combustion reaction (perhaps carried out in a fuel cell) to understand where hydrogen's atoms come from and recognize its climate implications over a complete life cycle. The colors of hydrogen framework categorizes hydrogen production pathways based on carbon emissions to inform choices for using hydrogen in transition to more sustainable forms of energy.[53] Table 3 illustrates production methods and carbon emissions for each major pathway for hydrogen production, along with connections to undergraduate chemistry concepts.

Table 3: Production pathways for colors of hydrogen and their carbon emissions and their undergraduate chemistry curriculum connections.[53]

Color	Production Method	Carbon Emissions Produced	Carbon Emissions Captured	Educational Concepts
Black	Gasification through black coal	Yes	No	Thermodynamics
Brown	Gasification through lignite	Yes	No	Thermodynamics
Grey	Steam Methane Reforming	Yes	No	Equilibrium
Blue	Steam Methane Reforming and Carbon Capture	Yes	Yes	Equilibrium, Solubility
Green	Electrolysis from renewable energy production	No		Electrochemistry
Yellow	Electrolysis through	No		Electrochemistry

	solar energy			
Pink	Electrolysis through nuclear energy	No		Electrochemistry
Turquoise	Methane pyrolysis	No		Kinetics
White	Natural hydrogen deposits	No		

Green hydrogen is becoming economically feasible and can be scaled for regions with solar insolation, wind potential, or hydro sources.[53] In regions where green energy sources are not readily available, pink and yellow hydrogen may be good alternatives, also relying on electrolysis to split water into hydrogen and oxygen. Turquoise hydrogen production is generated from methane pyrolysis, which uses thermal energy to break C-H bonds. Blue hydrogen couples steam methane reforming (SMR) with carbon capture and storage, a more sustainable solution for locations where green hydrogen is not viable. In methane-rich regions, blue hydrogen can repurpose gas extraction sites.[53] To explore the colors of hydrogen using systems thinking, students can use SOCKit to generate a SOCME of different colors of hydrogen that address decisions about system boundaries as well as possible unintended consequences of color choices.

Carbon Capture and Storage

The capture and long-term storage of concentrated streams of carbon dioxide from power plant emission stacks and industrial point sources plays an increasingly important role in plans by countries to meet Paris Agreement climate targets. Amine-based solvents dominate current carbon capture technologies, achieving approximately 80% efficiency but with large energy penalties. Ongoing research aims to optimize efficiency, reduce costs, eliminate troublesome impurities, and develop sustainable carbon capture solutions.[55] Major advances in chemistry are needed to utilize a significant portion of captured carbon dioxide, either for industrial processes such as enhanced oil recovery or as a feedstock for polymers.

It is much more difficult to capture carbon dioxide directly from ambient air or sea water, yet carbon capture research suggests several newer methods for capturing CO_2 from ambient air: physisorption, chemisorption, and moisture-swing sorption. Physisorption involves the use of metal-organic frameworks to form weak Van der Waals interactions. Chemisorption uses amine-based solutions to form chemical bonds with CO_2. Moisture-swing techniques utilize water's affinity for CO_2 to extract it from the atmosphere.[56]

Since the Industrial Revolution, oceans have captured about a third of anthropogenic CO_2 emissions. Current capture methods involve acidifying ocean water to shift the equilibrium between CO_2 and bicarbonate towards dissolved CO_2.[57] The water is then vaporized and passed through electrodialysis to separate gas phase CO_2 from steam.[58] The extraction of CO_2 from the ocean uses foundational principles in acid-base and equilibrium chemistry appropriate for undergraduate learning.

The long-term storage of 5,000-10,000 tons of CO_2 annually needed to meet climate targets, poses significant challenges.[1] Strategies for long-term storage include geological reservoirs, mineralization, and deep-sea ocean storage. Geological storage offers a reliable and safe site while repurposing oil and gas infrastructure.[59] Additionally, pressurized CO_2 density is greater than that of seawater, resulting in negative buoyancy, thus offering easily accessible storage sites.[60] Teaching about carbon storage connects chemistry principles in density, thermodynamics, and chemical reactions to global efforts in emission reduction. Activity S.7 draws on emission factors and hydrogen economy.

Conclusion and Limitations

As the world careens toward (and perhaps beyond) the 1.5 C Paris Climate Agreement target, chemistry educators and students have a responsibility to play a role in societal efforts to flip the switch to mitigate and adapt to climate change. This curated suite of resources and activities offers one step in that direction by providing tools to increase the climate literacy of undergraduate chemistry students and connect climate change with chemistry learning. The underlying frameworks, including systems thinking and the Planetary Boundaries framework, offer approaches that can be applied to an expanded range of sustainability topics. The processes of curating resources, articulating learning outcomes, developing activities for other students, and carrying out multiple rounds of peer review provided this group of undergraduate students with deep learning at the nexus of climate change and chemistry. Perhaps even more importantly, the semester-long activity contributed to a community of learning centered on empowering informed climate action.

The resources selected here were shaped by the learning goals for a course focused on environmental chemistry of the atmosphere, and as a result leave other important connecting points between chemistry and climate out of the picture. In particular, the role of the oceans in climate change might have received much more coverage if the course had a different focus.

A further limitation is that this paper focuses primarily on mitigation of climate. Urgent attention is also needed to strategies for adapting to climate change and to minimize suffering by people and the planet.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.XXXXXXX. [ACS will fill this in.] Learning outcomes and activities for students and educators, S.1-S.7 (word file)

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Author Contributions

PGM and JL conceived the project and designed the approach and developed a suggested list of topics and interactive learning resources. All authors contributed to drafting activities and topic descriptions and contributed to discussions and peer review, including the completed manuscript. AG created the graphical abstract. PGM and JL coordinated the group work and wrote, edited, and revised the manuscript. PGM and SG made final edits and revisions of the manuscript.

Notes

The authors declare no competing financial interests

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