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Integrating Atmospheric Science Research in Chemical Education: Utility of Primary Research Articles in Fostering Student Interest in Meteorology

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Atmospheric science research has seen significant advances in facilitating the generation of knowledge and promoting a scientific understanding of global meteorological issues and concerns with the advent of technological progress across many disciplines, including the physical and biological sciences and the breakthroughs in computational and modeling methodologies. This has resulted in a rich library of scientific literature showcasing knowledge creation and a deeper understanding of natural phenomena and their linkages to the sustenance of life embodied by the extensive systems of the hydrosphere, biosphere, and even the frontiers of outer space. This article outlines how primary research in atmospheric science can be integrated into chemical education by furnishing connections and synchronicity with chemistry, bridging the concepts, discoveries, innovations, and their immediate importance to science and society. A general overview is given on how topics or themes in general chemistry courses can utilize the power of scientific research articles on atmospheric science, fostering students' interest in meteorological concepts and related fields. A non-exhaustive list of primary research literature highlighting breakthroughs related to a specific chemistry theme serving as templates for chemical educators is provided to enable the students to see real-world applications. Integrating research into science education is an effective strategy to promote scientific thinking and literacy and should be a catalyst for the global drive for sustainability.

Keywords: atmospheric science, chemical education, meteorology, science education, science literacy

PRIMARY LITERATURE AND SCIENTIFIC LITERACY

Communicating scientific information plays an indispensable role in society, bridging the generation and utilization of knowledge for all stakeholders. The flow of scientific information encompasses different roles, including communication among scientists, popularizing information generated by the scientific community, and serving to provide formal education, among many others (Goldman and Bisanz 2002). Advocating scientific literacy, texts used for learning can be characterized as either primary or adapted scientific literature differing only in their target audience – the former targeting scientists in the field, the latter targeting science educators and students. The general public often receives varying journalistic reported versions involving expository, narrative, or argumentative approaches to communicating the sciences. At the same time, school textbooks at all educational levels mainly rely on expository, factual, and non-canonical strategies for reflecting the knowledge structure of the sciences (Norris *et al.* 2009).

Primary research articles, the first publication of research findings across fields written and reported by researchers,

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are excellent data, knowledge, and information sources. Primary literature is not limited to research articles but also covers surveys, case reports, case studies, conference proceedings, correspondence to the editors, and commentaries. Evidence, proofs, and analysis that support conclusions are outlined canonically for research articles, presenting the science in a highly structured manner, including sections or parts like an abstract, an introduction, methods, results, and a discussion of findings. Reading primary literature articles can be a meaningful experience for educators and learners as carefully disassembling the articles into sections enriches the context and span of knowledge seeking (Makay and Lorenz 2021), especially among learners. Thereby, this article builds up on the importance of scientific texts embodied by the richness of primary research articles and their utility in fostering students' interest in the sciences. On the basis that knowledge gained from research articles – both theoretical and applied in nature – can augment and enrich the classroom experience, this article pivots from being a review that suggests, from existing diverse literature, key articles that can be utilized in class integration to being an account of experiences describing the rigors of incorporating primary research literature on atmospheric science into chemical education.

The use of primary literature to advance scientific literacy has enabled educators to promote scientific practices in classroom settings (King *et al.* 2020). Scientific practices, in this context, refer to the ability of learners to ask and refine questions to establish the nature of a problem or argument, the creation and utilization of models as visual representations of ideas or natural phenomena, planning and executing carefully designed experiments, analysis and interpretation of results, incorporating aspects of mathematical and computational knowledge, and effectively communicating science among peers (NGSS 2013). The use of primary research articles in classroom discussions arises due to the challenges in achieving scientific literacy using purely textbooks or modules, especially in secondary and tertiary-level education, taking into account the view that several science curricula and programs do not necessarily consider practical reasoning as integral in the production of scientific knowledge (Brickhouse *et al* 1993; Jurecki and Wander 2012). Primary research literature can be incorporated into classroom discussions by initiating a teacher-led guided discussion or inquiry with students. This provides a student-focused narrative that relies on generating opportunities to reflect on the paper's contents, how the findings reported therein impact the advancement of knowledge, and how they are translated to applications within the bounds of topics discussed in class. Engagements between educators and learners, and among the students themselves, are ensured without creating specialized programs or discussion groups, which can eventually lead to a more meaningful and enjoyable classroom experience.

ATMOSPHERIC SCIENCE EDUCATION

Atmospheric science encompasses interdisciplinary fields of study among natural and theoretical sciences dealing with critical atmospheric processes and their indispensable linkages to the sustenance of life. Focusing on the dynamics of Earth's atmosphere, the realm of atmospheric science extends to the hydrosphere, biosphere, and even the frontiers of outer space (Gimeno 2013). Given the demands for mitigating the magnitude of climate change and its formidable impact worldwide, research in atmospheric processes takes the spotlight to elucidate and understand the state of planetary climate and the challenges impeding progress in creating solutions and informed decisions. Knowledge and information from understanding our atmosphere are key players in many crucial sectors and industries – including health and well-being, agricultural endeavors, energy and power block, and the environment. Advances in atmospheric science paved the way for assimilating milestones in unraveling basic processes and the incorporation of modeling through theoretical and quantitative studies that led to the technological wonders of atmospheric dynamics, weather forecasting (Alley *et al.* 2019), and atmospheric physics and chemistry. Notwithstanding the challenges and difficulties – including topics on small to large-scale processes in the atmosphere, pollution chemistry, weather prediction, climatology, molecular interactions, remote sensing, and data assimilation, among many others (Gimeno 2013), the last few decades have seen an explosion of advances in atmospheric science and meteorology. Current issues on natural atmospheric phenomena experienced worldwide have sparked public interest in topics such as climate change, global warming, pollution, the ozone layer, typhoons, hurricanes, severe weather conditions, drought, weather forecasting, and early warning hazards brought by natural causes.

Despite the importance of a clear understanding of the concepts of atmospheric science, introductory lessons are only integrated within the Earth and Space Science chapter and not taken as a separate section or as a major component of science subjects prescribed in the curricula. For example, the science framework for Philippine basic education in 2011 incorporates topics on weather systems and natural hazards for Grades 1–6 and concepts of climate science for Grades 7–10 (DOST-SEI and UP NISMED 2011). With the implementation of the K-12 program in the Philippines, the Department of Education (DepEd) aimed to revolutionize the country's education by introducing curricula aligned with international standards. The grade-level standards under the K-12 basic education curriculum require Grade 7 students to understand concepts of meteorology as they are expected to learn the basics of atmospheric science, such as the occurrence of breeze, monsoons, the intertropical convergence zone, and the effects of weather systems and seasonal changes (DepEd 2016). At the tertiary level, only a few universities offer elective science subjects in atmospheric science. The first undergraduate degree course on meteorology in the Philippines was formulated in 2012 by the Philippine Atmospheric, Geophysical, and Astronomical Services Administration or PAGASA under the Consortium for Meteorology Education and Training or COMET to facilitate the advancement of meteorology in the country (TJD GMA News 2012). With the development of an undergraduate meteorology course in 2012, only a few universities initially offered BS Meteorology – for example, Mariano Marcos State University, Visayas State University, and Bicol University. The number of universities that will offer the course is expected to increase to bridge the demand and supply chain gap for trained and specialized personnel conducting weather and climate research in the country (TJD GMA News 2012; Martillo 2011). The University of the Philippines and the Ateneo de Manila University, on the other hand, are among the major universities in the country offering graduate degree courses on meteorology, with students having engineering and natural sciences backgrounds, predominantly physics.

INTEGRATING PRIMARY RESEARCH ARTICLES INTO CHEMICAL EDUCATION

Global influences in education have mandated significant changes in teaching and instructions, including strategic implementation of alternative modalities in course content delivery and equalizing opportunities to access educational technology (OECD and Asia Society 2018). This has resulted in adopting strategies integrating knowledge through collaborative approaches and realigning the curriculum with disciplines that have taken the global stage (Roberto 2021) – including education and educational technology, immunology and the medical sciences, machine learning, artificial intelligence, finance, engineering, the natural sciences, communication and information technology, sustainability, and environmental and atmospheric science. Recent perspectives on science instruction call for opportunities to engage students towards a culture of inquiry, embracing and merging reform efforts in science education to bring a multicultural and interdisciplinary approach to learning (Meyer and Crawford 2011). The World Bank, UNESCO, and UNICEF report (2021) highlights the need for educators and institutions worldwide to adopt programs and learning practices to mitigate the many losses in the education systems brought about by the widespread disruption (Azevedo *et al.* 2021) due to the pandemic and other sociopolitical events globally – including the loss of time for teaching and instructions, growing economic and social inequalities, and access to educational technologies (Engzell *et al.* 2021). In science education, teachers have constantly searched for effective methodologies (Kurt and Sezek 2021) to integrate conceptual understanding and subject appreciation with learners and the public (Brownell *et al.* 2013; Vukičević *et al.* 2018). A strategy that can be applied is the integration of primary research into science education. Significant advances in atmospheric science have accumulated a library of primary research papers dealing with diverse topics in recent years. Using research articles adapted to the level of secondary, both lower (ages 11–14) and upper (ages 14–18), and tertiary level students (undergraduate and graduate) leverage the idea of the scientific method and research process, which exposes the students to the strategies employed in basic and applied research, knowledge generation, and the concretization of concepts they learn in class.

Along these lines, the rich scientific literature encompassing atmospheric and meteorological sciences provides excellent materials for conceptual integration in chemical education. The available research articles can find application to the many general topics of undergraduate chemistry. Student appreciation of chemistry is best facilitated when the courses have opportunities to incorporate real-world experiences and applications. In practice, chemical education has been linked strongly to other fields, with chemistry being the central science – albeit limited to the major fields of engineering, medicine, pharmaceutical sciences, food and agrochemical sciences, and environmental studies (Musengimana *et al.* 2021). Major advances in atmospheric science can be utilized to create bridges and foster student interest in meteorology. This parallels narrative thinking and story-telling techniques used in chemistry teaching (Reyes 2023a; b). Here, the main story is about the research findings synchronizing with the concepts discussed in class.

Chemical educators could embark on this journey of using primary research articles on atmospheric science in chemistry teaching by giving or assigning selected articles to the students as extension activities for class discussions. While some research methodologies used in different research articles may be too advanced for students taking general chemistry courses, the emphasis is on how the concept of chemistry is utilized in the actual research and on the major advances or knowledge offered by the research. This then exposes the students to the research methodology and allows the learners to gauge how data is gathered and analyzed and how the results can change our perspective of the world, the sciences, and our way of life. This also fosters students' interest in atmospheric sciences and their ability to link concepts to real-world phenomena.

Methodological Selection of Primary Literature

Evaluation of primary scientific literature that can be incorporated into the traditional classroom environment or the synchronous virtual platform can be done by outlining the foundational chemistry themes and selecting articles that are recent and meaningfully relevant to students. Part of the criteria developed by Jurecki and Wander (2012) can be adapted as a systematic approach to the evaluation of scientific literature that can be utilized in classroom discussions, albeit the stringent requirement since the method therein is utilized for selecting articles promoting critical thinking and thorough evaluation of the scientific rigors of the work. A modified approach can then be implemented based on the types of research articles and the authority or the reputation of the publication being peer-reviewed.

For the purpose of integrating primary literature on atmospheric science in chemistry teaching and instruction, the literature sources can be classified into [1] original scientific research and [2] review articles. Methodologically, the sources utilized in this article have been limited to these types appearing on reputable journal publication venues, without considering other types of primary literature like surveys, proceedings, correspondence to editors, and commentaries. Original scientific research articles focus and revolve around a single, well-defined topic and describe the experimental or computational strategies employed to facilitate the resolution of the problem and, hence, lead to findings that are presented in a structured manner to highlight breakthroughs and future directions, all in line with a central concept that can be a starting point for class integration. Review articles include meta-analysis or a comprehensive literature review of recent trends and practices and summarize insights from known studies directing the readers to the original research and, therefore, can be a rich source of information in discussing interrelated topics in class.

After identifying the type of literature source, the determination of whether or not the chosen article was published in a reputable or authoritative source follows. Note, however, that this methodological step can also be done simultaneously with the material classification. The authority of an article is a measure of the reputation of the actual publication, the authors, and the institution or the journal publication venue that publishes the article. This criterion, nevertheless, can be imprecise and limiting since it requires that the publication venue be indexed in various scientific journal indexation databases (Scopus, Web of Science, *etc*.). Therefore, this metric can be replaced by settling on peer review as the indicator of authority (Jurecki and Wander 2012). It should be emphasized, however, that the selection of articles for integration should focus on getting the students to be interested in the class discussions drawing attention to the concepts and the core of the scientific knowledge rather than on the technicality of the selected paper.

Atmospheric Science Articles in Chemistry Teaching and Instructions

Relying on the aforementioned methodological and content-based approaches, Table 1 summarizes the typical topics or themes offered in most post-secondary appreciation and general chemistry courses. The given list is a non-exhaustive outline of the topics selected to highlight the use of primary research in atmospheric science in chemical education. Several suggested scientific studies are given alongside the chemistry topics. These scientific literature works are selected from primary research articles, and any omission of other excellent work is unintentional. The following summarizes how these papers can be integrated into chemistry teaching, focusing on the paper's merit, importance, and implications.

Measurements. Incorporating state-of-the-art instrumentation for measuring airborne state parameters – including pressure, temperature, turbulence index, and the three-dimensional (3D) wind vector – can deepen our understanding of atmospheric chemistry and the microphysical processes (Bui 2021). The measurement of physical parameters, especially temperature and pressure, is required to assess chemical kinetics or reaction rates in the atmosphere and determine the mixing ratio among gases driving atmospheric dynamics critical in understanding atmospheric circulation and weather patterns. The turbulence index measures atmospheric turbulence, significantly affecting aircraft safety and atmospheric chemistry. 3D wind vector measurements provide detailed information on wind direction and speed, which is essential for understanding weather patterns. Moreover, the exemplary work done by the atmospheric tomography mission – ATom, a NASA Earth venture Suborbital-2 mission – shows the importance of accuracy and precision of measurements as data generated from such ventures can be utilized to see the impacts of human-produced air pollution and the effects of chemically reactive gases in the atmosphere (Wofsy 2021). Driven by technological advancements, traditional measurement techniques have been progressively replaced by digital, online, and automated methodologies. Meteorological measurements are no exception to this trend, as more sophisticated techniques replace traditional systems. For

Table 1. Selected list of primary research and advances in atmospheric science that can be incorporated into chemical education

Topics or themes	Title of literature work or science article	Reference
Measurements	ATom: measurements from meteorological measurement system (MMS), (2016-2018)	Bui (2021)
	Manual and automatic measurements of sunshine duration in Cassubian Lakeland (northern Poland)	Owczarek and Malinowska (2023)
	Forecasting of meteorological variables using statistical methods and tools	Agbo (2021)
	Comparison of statistical methods to graphical methods in rainfall trend analysis: Case studies from tropical catchments	Rathnayake (2019)
	Statistical and machine learning methods for evaluating trends in air quality under changing meteorological conditions	Qiu *et al.* (2022)
The atom and atomic structure	The atomic origins of climate science	Lepore (2017)
	Climate change and the atom	IAEA (2009, 2014)
	Stable isotopes in greenhouse gases from soil: A review of theory and application	Zhu *et al.* (2019)
	Linkage between precipitation isotopes and biosphere-atmosphere interaction observed in Northeast India	Chakraborty *et al.* (2022)
	A review of water isotopes in atmospheric general circulation models: Recent advances and future prospects	Xi (2014)
	Temperature and precipitation effects on the isotopic composition of global precipitation reveal long-term climate dynamics	Vystavna *et al.* (2021)
Chemical elements, periodic table, and periodicity	The Periodic Table of the chemical elements and sustainable development	Matlin *et al.* (2019)
	Iconic Periodic Table updated to reflect problems of carbon in our world today	University of St. Andrews (2021); EuChemS (2022)
	Contaminant emissions as indicators of chemical elements in the snow along a latitudinal gradient in southern Andes	Pizarro *et al.* (2021)
	The atmosphere	Schlesinger and Bernhardt (2020)
States of matter, molecules, ions, intermolecular forces	Characteristics of water-soluble inorganic and organic ions in aerosols over the Southern Ocean and coastal East Antarctica during austral summer.	Xu *et al.* (2013)
	Physical and chemical properties of atmospheric aerosols in Moscow and its suburb for climate assessments	Gubanova *et al.* (2020)
	The gas-phase formation mechanism of iodic acid as an atmospheric aerosol source	Finkenzeller *et al.* (2022)
	Greenhouse effect in planetary atmospheres caused by molecular symmetry breaking in intermolecular interactions	Vigasin and Mokhov (2017)
	Direct observation of hierarchic molecular interactions critical to biogenic aerosol formation	Hou *et al.* (2018)
Chemical bonds, chemical reactions	Chemical meteorology – linking weather and atmospheric composition from urban to global scales	Allen (2012)
	Role of chemistry in Earth's climate	Ravinshankara *et al.* (2015)
	Chemical weather and chemical climate	Brasseur and Kumar (2021)
	Chemistry of functionalized reactive organic intermediates in the Earth's atmosphere: Impact, challenges, and progress	Barber and Kroll (2021)
	Hydrotrioxide (ROOOH) formation in the atmosphere	Berndt *et al.* (2022)
Chemical composition, stoichiometry, solutions, mixtures, macromolecules	Chemical characteristics of atmospheric bulk deposition in a semi-rural area of the Po Valley (Italy)	Tositti *et al.* (2018)
	Long-term trends of wet deposition and atmospheric concentrations of nitrogen and sulfur compounds at EMEP site in Armenia	Perikhanyan *et al.* (2020)
	Inorganic Ionic composition of rainwater at a high altitude station over the Western Ghats in peninsular India	Waghmare *et al.* (2021)
	Seasonal variations and source apportionment of water-soluble inorganic ions in PM2.5 in Nanjing, a megacity in southeastern China	Zhang *et al.* (2019)
	Insignificant impact of freezing and compaction on iron solubility in natural snow	Mukherjee *et al.* (2018)
	Effect of solubility limitation on hygroscopic growth and cloud drop activation of SOA particles produced from traffic exhausts	Wittbom *et al.* (2018)
Acids, bases, buffers	Structure and functioning of the acid-base system in the Baltic Sea	Kuliński *et al.* (2017)
	The acidity of atmospheric particles and clouds	Pye *et al.* (2020)
	The missing base molecules in atmospheric acid–base nucleation	Cai *et al.* (2022)
	The impacts of ocean acidification on marine trace gases and the implications for atmospheric chemistry and climate	Hopkins *et al.* (2020)

example, Owczarek and Malinowska (2023) compared manual and automatic measurements of sunshine duration, an important physical parameter describing solar radiation that determines the global heat balance. The intensity of solar radiation characterizes global climatology and can be used to track past and present variability in climate. A comparison of the manual and automatic systems, in the context of this reported study, can be utilized in chemistry classroom as a direct example of the need to constantly review measurement techniques and introduce the concept of instrument sensitivity, threshold, and the limits of detection and quantification, which are a fundamental concept in analytical chemistry. Using statistical methods in climatological measurements is essential from the viewpoint of predictions and forecasting. For example, the works by Agbo (2021) and Rathnayake (2019) discuss the role of statistical methods in measuring crucial parameters like solar radiation and rainfall. These research works can be used in chemical education to emphasize the role of statistics in measurements and expose the advantages and disadvantages of trend analysis in the technical prediction of the future behavior of a parameter. Statistical trend analysis is widely used to identify precipitation patterns, temperature trends, predict stream flow, evaporation trends, and wind speed determination, and even utilized in health and medical fields such as identifying trends for the spread of disease and many other industries and fields. A more recent report (Qiu *et al.* 2022) on incorporating machine learning methods for measuring and evaluating trends in air quality, as influenced by various meteorological conditions emphasized the need to elevate and apply modern technology in measurement systems. Chemistry teachers can use the examples presented by Qiu and coworkers (2022) in determining the impacts of anthropogenic emissions, human activities like burning fossil fuels, land use, and industrial processes on air quality and how observational scenarios are quantified by developing careful measurement techniques and strategies, thus highlighting the fundamentals and advances in measurement where chemistry students can find connections between machine learning, artificial intelligence, and data management systems relating this to measurement in atmospheric science. The use of machine learning methods offers several advantages over traditional methods. Machine learning algorithms can analyze large datasets quickly and accurately, identifying patterns and trends that may not be apparent using traditional statistical methods. Machine learning algorithms can also adapt and learn from new data, improving the accuracy of predictions over time. Furthermore, a possible extension of the concept will involve a discussion of the importance of models and quantitative methods to produce real-world policy evaluations and thereby help shape policy and provide recommendations based on concrete science, bridging metrology and meteorology.

The atom and atomic structure. The possible roots of climate science from the perspective of arguments about nuclear weapons and processes have shaped debates on global warming (Lepore 2017). In particular, studying the effects of nuclear fallout on the environment and the atmosphere led to the development of instruments and methods for measuring and monitoring changes in the atmosphere's composition and behavior. This, in turn, laid the foundation for the study of climate science. The application of the concept of atoms and atomic structure was integrated into the article of Lepore (2017), providing a renewed way of looking into global warming and contextualizing atomic concepts. The article narrates information on the origin of climate science being narrated on a socioscientific account, bringing together perspectives enriching the understanding and integration of the concept of the atom. Furthermore, the International Atomic Energy Agency (IAEA) advocates for the safe, secure, and peaceful use of nuclear technologies (IAEA 2014). The agency also released a primer on climate science and the atom (IAEA 2009, 2014). For example, the utility of isotopes and radioactive decay are utilized to study and model several natural processes such as the hydrological and carbon cycles and the determination of the ages of both organic and inorganic materials. These direct applications of the atomic concept of matter have significantly contributed to the knowledge of climatic systems, natural resources, and natural history. A systematic review of stable isotopes present in greenhouse gases that originate from soil offers an informative discussion of the crucial role of the atmospheric environment in global climate change (Zhu *et al.* 2019). The fundamental concepts of atomic structures embedded in the concepts of isotopes are well incorporated in theory and application, with Zhu and coworkers (2019) synthesizing the advances in atomic science and atmospheric sciences. Using these exemplary works in chemical education further validates the importance of understanding the atom and the atomic theory as environmental isotopes help us understand the state of our planet’s climate. A more recent example of this argument was given by Chakraborty and coworkers (2022) by showing the link between precipitation isotopes and the biosphere-atmosphere interaction. Collegiate chemistry students will learn the basic premise that ocean-atmospheric processes control the isotopic composition of precipitation since water vapor is primarily generated from the oceans. Thus, the underlying physical conditions of the surface ocean influence the isotopic composition of the vapor, precipitation, and post-evaporative processes like condensation and, eventually, precipitation in different bio-geographical conditions. The works of Xi (2014) gave similar theoretical aspects and applications of the atomic concepts to atmospheric science on exploring water isotopes in the general atmospheric circulation models and the more recent report of Vystavna *et al.* (2021) on the effects of temperature and precipitation on the isotopic composition of global precipitation that dictates long-term climate dynamics. These primary research articles will make an excellent list of readings supplementing the chemistry classroom experience.

Chemical elements, periodic table, and periodicity. The periodic table of elements is the most important in a chemist's arsenal. The organized chart does not only list the known elements but is like a map utilized by geographers, cartographers, and other scientists in related fields. This map of the elements lets us venture into the territories of reactivities, the families and clans of the elements, and the trends arising from their arrangements and positions in the chart. Unsurprisingly, other fields – also given the centrality of chemistry – will produce their versions of the periodic table as they relate to the concepts of a particular area of study. For example, the periodic table of the elements carries a broad societal significance of the elements and their associated role in sustainable developments across fields, including meteorology and the realm of atmospheric sciences (Matlin *et al.* 2019). An iconic version of the periodic table released by the European Chemical Society in 2019 was updated recently to highlight element availability and vulnerability (University of St. Andrews 2021; EuChemS 2022). The updated version shows the problems of carbon in the present day as it relates to the formation of carbon dioxide, rocks, vegetation, and the underlying conflicts on resources – especially oil – including the consequences and effects on the planet's atmospheric conditions. Invoking the trends in chemical elements' properties, snow's chemical composition provides insights into the atmospheric transport of different anthropogenic contaminants (Pizarro *et al.* 2021). In this article, the researchers investigated the concentration and chemical properties of seven metallic elements (Al, Cu, Fe, Li, Mg, Mn, and Zn) and how human activities and their inherent chemistry can influence emissions at different spatial scales. Noting the positions of these elements in the periodic table, one can predict the associated reactivity and thereby relate it to the chemical composition of snow in the area of concern, the Andean mountains, in this case. Chemistry students will realize the importance of knowing the periodic trends and how the chemical properties of elements dictate their absence (if inert) or presence (if reactive or unstable) in measured environmental and climatological parameters. Equally important are the gaseous elements on the non-metallic side of the periodic table, with reference to the chemical components of the atmosphere (Schlesinger and Bernhardt 2020). Despite their low to negligible amounts in the atmosphere, trace gases can be reactive enough to influence the atmospheric composition and the variation of parameters essential for atmospheric chemistry. These papers can be utilized in chemical education to emphasize the importance of chemical elements, their periodic properties, and how they can collectively influence the earth's biochemical and atmospheric basis of life.

States of matter, molecules, ions, intermolecular forces. Characterizing the concentration and the size distribution of monoatomic and polyatomic cations and anions, together with other water-soluble organic and inorganic chemical aerosol species, is of utmost importance in evaluating the neutralization capacity of marine atmosphere (Xu *et al.* 2013). The wide selections of ions and molecules in the study of Xu and coworkers (2013) merit its possible utility in the chemistry classroom to show the relevance of the distribution of chemical species to the dominant characteristic of the state of the atmosphere in a specific geographical area. This parallels the research reported by Gubanova and collaborators (2020) on the experimental study of surface aerosols and their physicochemical properties, over a region in Moscow, Russia, during the summer of 2019. Concepts on states of matter, elemental composition, and microphysical parameters of ions and molecules are all integrated into this exemplary work establishing the spatial distribution of aerosols as being enriched with heavy metals and even metalloids. The results can be utilized for the refinement and the systematic verification of different existing climate models, thus aiding in the advancement of climatological measurements. More recently, an international team of researchers reported the driving mechanism for the formation of iodine particles in the atmosphere, which contributes to the increased cloud cover and the effect of these iodine particles in the depletion of the Earth's ozone layer, an important protective layer (Finkenzeller *et al.* 2022). This is the first time that the gas-phase formation of iodine, specifically iodic acid, has been demonstrated with a clear understanding of its role as a catalyst in atmospheric particle formation. This interesting paper can be well integrated into chemical education, demonstrating collectively how different states of matter and intermolecular forces dictate reactivity and the mechanism of how chemical species are generated in the atmosphere. The concept of intermolecular forces can also be discussed by citing the work of Vigasin and Mokhov (2017) in unraveling the greenhouse effect in the atmospheres of terrestrial planets because of molecular symmetry in various intermolecular bonding and interactions. Equally fascinating is the report on small clusters of sulfuric acid/bisulfate and other organics that possess hierarchic molecular interactions that are critical in the biogenic aerosol formation (Hou *et al.* 2018), again demonstrating the relevance of intermolecular forces of attraction in atmospheric chemistry and climatological sciences.

Chemical bonds, chemical reactions. Describing the atmosphere as a chemical chamber where reactions occur summarizes the enterprise of chemical meteorology (Allen 2012). As the core topic in chemistry, chemical bonding, and reactivity should be given adequate attention in any general chemistry class. Integrating the concepts of atmospheric science into the concept of chemical reactions is always at the heart of chemical meteorology, as variations in different atmospheric processes not only result in the alteration of chemical phenomena but also in the extent and fate of any emissions, products and byproducts, the stoichiometry of the reaction, and their impact to climate and the living systems. The excellent review of Ravikshankara and coworkers (2015) supplements the importance of chemistry in weather and climate given by simple to complex chemical reactivities among the many chemical species in the atmosphere. Chemistry students will realize that considerable progress in atmospheric science in the last few decades relied on how we understand chemical processes in the atmosphere that led to accurate weather forecasting and predictions (Brasseur and Kumar 2021). Integrating atmospheric chemical reactions in chemical education offers a fresh perspective on chemical reactivity concepts beyond chemical transformations' physical, biological, and biochemical aspects. Another notable example of primary research that can be utilized in the chemistry classroom in the context of chemical reactivity and atmospheric science includes the works on functionalized reactive organic intermediates in the earth's atmosphere, specifically on gas-phase oxidation of organic compounds vital to the production of key pollutants that in turn determines the air quality and climate (Barber and Kroll 2021). The findings highlight the importance of understanding the reactivity of functionalized organic compounds and their role in producing key pollutants that impact air quality and climate. In recent breakthrough research, an entirely new class of reactive chemical species, hydrotrioxide, has been documented under atmospheric conditions (Berndt *et al.* 2022). This chemical compound and its derivatives constitute an extremely oxidizing class of chemicals, previously disregarded, that would alter the global climate and human health. This paper is well suited to be incorporated into class discussions because facts and knowledge in chemistry and meteorology evolve, giving us new ways to think and expand the frontiers of our understanding of natural phenomena.

Chemical composition, stoichiometry, solutions, mixtures, macromolecules. Different studies conducted worldwide can be utilized to show the concept of chemical composition as they relate to atmospheric and meteorological sciences. For example, the chemical characteristics of atmospheric bulk deposition in a semi-rural area of the Po Valley in Italy provide a methodological example of using advanced techniques such as spectroscopy and chromatography to analyze various compounds' chemical composition (Tositti *et al.* 2018). The work showed significant seasonal variations in the concentrations of the chemical compounds, with higher concentrations during the winter months, providing the temperature and seasonal dependence of chemical composition. A similar finding was reported for long-term trends of wet deposition and the corresponding concentrations of nitrogen and sulfur at a site in Armenia (Perikhanyan *et al.* 2020). Similarly, there is strong seasonal behavior of the measured parameters, with higher concentrations during summer compared to winter, providing an analysis of the trends of nitrogen and sulfur compounds and the possible sources of transboundary air pollution. Another exemplary work was reported by Waghmare and coworkers (2021), examining the inorganic ionic composition of rainwater at a high-altitude area in the Western Ghats of Peninsular India. The research aims to understand the sources and transport of ions in the atmosphere in this region, which is affected by monsoons and other meteorological conditions. A major finding is that the concentrations of critical ions such as sulfate, nitrate, and chloride in the rainwater samples vary seasonally and are influenced by local emissions and long-range transport. Zhang and coworkers (2019) reported the same seasonal variations in water-soluble inorganic ions in particulate matter in a megacity in southeastern Nanjing, China. Particulate matter is a significant component of air pollution. It is known to have detrimental effects on human health and the environment, thus emphasizing the importance of monitoring water-soluble inorganic ions in particulate matter. The researchers found that the dominant ions in the particulate matter samples were sulfate, nitrate, and ammonium, which are known to be associated with combustion processes such as fossil fuel combustion and biomass burning. By identifying the sources of these ions, policymakers can take targeted actions to reduce their emissions and improve air quality. These papers and many more examples may provide trends in chemical composition and its dependence on atmospheric conditions, permitting the students to add parameters to the usual chemistry textbook factors affecting composition.

The concept of solubility can be demonstrated as it applies to meteorological phenomena. For example, iron's solubility in natural snow has been shown not to be affected by freezing and compaction despite the drastic changes in temperature and density (Mukherjee *et al.* 2018). Overall, the study demonstrates the importance of considering the solubility of compounds in understanding the biogeochemical cycles of micronutrients in snow and ice-covered regions. The ability of these substances to dissolve in snow and ice can influence their availability to organisms and affect the overall biogeochemical cycles in these environments. For another example, Wittbom and coworkers (2018) investigated the effect of solubility limitation on the hygroscopic growth and cloud drop activation of secondary organic aerosol (SOA) particles from traffic exhaust. This study directly impacts air quality and climate change as SOA particles and their associated solubilities affect the ability to absorb water vapor and the formation of cloud droplets. The ability of these particles to absorb water vapor and form cloud droplets is a critical process that needs to be better understood, and this study provides valuable insights into the underlying mechanisms that govern this process.

Acids, bases, buffers. The concept of acid-base chemistry in the general chemistry classroom can be extended by incorporating primary research in atmospheric and meteorological sciences. For instance, the accompanying marine acid-base system is well understood and is commonly used as an example in chemical education. The study reported by Kuliński and coworkers (2017) further substantiates the concept of acid-base chemistry as applied to marine ecosystems and their implications in regulating heat and atmospheric gases such as carbon dioxide and the buffer system of the oceans. These concepts were then utilized to characterize the Baltic Sea. Understanding how the acid-base system works with the physical conditions (such as temperature and salinity) and the biogeochemical processes (including biomass production and mineralization) contribute to the present-day knowledge of chemical oceanography and its consequences on atmospheric phenomena. On the other hand, Pye and coworkers (2020) explore the acidity of atmospheric particles and clouds governing the phase partitioning of inorganic and organic acids and bases and the chemical reaction rates. This report will teach students the implications for the atmospheric lifetime of chemical pollutants, the process of deposition, and the consequences to human health. The study incorporates the concept of pH and standard nomenclatures and highlights current model calculations on both the local and global scales. A phenomenon occurring in various atmospheric environments, new particle formation is the main source of cloud condensation nuclei. The work of Cai and collaborators (2022) showed that acid-base nucleation among known nucleation mechanisms, at least for the atmospheric environment and related settings, is fundamental for its efficiency in forming neutral clusters at ambient temperatures. The researchers provide compelling evidence for the presence of alkali molecules such as nitrogen bases or amines in sulfuric acid clusters before their detection by sensitive mass spectrometers. Equally interesting, Hopkins and coworkers (2020) explore the impacts of ocean acidification on marine trace gases and describe the implications for atmospheric chemistry and the global climate. This work will enable chemistry students to appreciate the interface between the ocean and the atmosphere as a crucial existing boundary among Earth's systems. Incorporating acid-base chemistry, the role of marine trace gases in shaping the climate was given. Key information on surface ocean chemistry and the connection to the biogeochemical cycles were also given, offering a convincing argument on the interconnection among acid-base chemistry, marine sciences, atmospheric phenomena, and climate. The researchers noted that the impacts of ocean acidification on marine trace gases could have significant implications for atmospheric chemistry and the global climate. The altered production and consumption of these gases could change their atmospheric concentrations, impacting the Earth's radiative balance and the overall climate system.

EXPANDING THE INTEGRATION, CREATING COLLABORATION, KEY INSIGHTS

The examples of scientific literature mentioned in the preceding discussion are only a small fraction of all possible primary research articles that can be integrated into chemical education. The list in Table 1 will guide chemical educators, or science educators in general, to use available sources to integrate fundamental research with teaching and instructions. At the National University (NU), Manila, Philippines, it was generally observed that incorporating atmospheric sciences research articles in the context of chemical education sparked interest among students regardless of their specific field or track. For example, nursing, medical technology, and psychology students showed better interest in chemistry topics when several of the suggested research works were incorporated into the lessons. Content delivery and instructions to students from the College of Education, Arts, and Sciences – including BS Psychology students (n = 28) taking the general and inorganic chemistry course (1st trimester, AY 2022–2023), students from the College of Allied Health, including BS Medical Technology students and BS Nursing students (n = 93) taking introductory organic chemistry and biochemistry courses (2nd trimester, AY 2022–2023), and another batch of BS Medical Technology students (n = 37) taking introductory analytical chemistry course (3rd trimester, AY 2022–2023) – were ensured to integrate the concepts of atmospheric and meteorological sciences using articles and findings listed in Table 1 while also incorporating other concepts related to the clinical nature of their courses. While no formal study was conducted on student appreciation and learning when atmospheric science research is integrated into chemistry teaching and instruction, classroom observations showed that such integration gives students a fresh perspective on the applications of the concept beyond their fields, manifested by students' self-assessments and feedback on the course delivery and class materials. Students' evaluation of the educator, including the course content delivery when primary research articles in atmospheric science were incorporated into class discussions, shows that the learners had a deep engagement and were able to invoke critical thinking as they connected the lesson to real-life contexts. For example, students taking general and inorganic chemistry, introductory biochemistry and organic chemistry, and introductory quantitative chemistry responded positively (Table 2) in their self-assessment and online evaluation of teachers and course content delivery. Students taking general chemistry and inorganic chemistry were more appreciative of integrating meteorological concepts into their chemistry classes across all metric and evaluation items compared to other classes. This can be attributed to the more diverse and fundamental approach to topics in general chemistry as compared to more focused subjects and themes in organic and biochemistry, as well as analytical chemistry courses. Nonetheless, students gave promising marks of "to a very great extent" or "to a great extent" mirroring their enthusiasm for the integration of atmospheric science topics in their respective classes.

This creates a common workspace to discuss issues and share experiences, generating a collaborative environment. Other topics of interest that can be added to the preceding discussion include the integration of the concepts of gases and the laws governing this state of matter. Much of the understanding of weather can be attributed to the phenomena involving gases, their physical properties, and their interactions. Organic chemistry topics and reaction mechanisms can also be well integrated into atmospheric sciences research, such as the mechanistic view of ozone depletion in the presence of ultraviolet radiation, radical formation, molecular degradation, organic compound reactivities through functional group analysis, and the chemistry of organic particulate matter. All these foster interests in chemistry and atmospheric science, providing a collaborative view of the fields, a forefront example of the centrality of chemistry.

Table 2. Students' self-assessment and evaluation of educator and course content delivery when atmospheric science articles were incorporated in introductory general, inorganic, and organic chemistry, biochemistry, and quantitative chemistry.

Metrics and evaluation[a]	**General and inorganic chemistry**	**Introductory biochemistry and organic chemistry**	**Introductory quantitative chemistry**
	38 students	93 students	37 students
I am engaged to think deeply and about important concepts and theories.	6.77	6.48	6.46
I have opportunities to create and generate new ideas.	6.71	6.44	6.42
I use problem-solving, critical thinking, and other higher-order thinking skills in real-life contexts.	6.77	6.47	6.54
The teacher connects the lesson to real-life contexts.	6.71	6.47	6.54
The teacher asks questions that require critical thinking.	6.74	6.44	6.42
The teacher uses a variety of learning resources and materials appropriate for flexible learning.	6.71	6.54	6.45
The teacher breaks the complex topics into small digestible sessions.	6.68	6.42	6.32
The assessment tasks simulate real-life contexts relevant to the learning outcomes.	6.42	6.35	6.16
The teacher assesses my misconceptions and current skills and knowledge (diagnostic assessment, comprehension checks) necessary for instructional planning and delivery.	6.61	6.47	6.45
The teacher provides reinforcement or enrichment activities as appropriate or as needed.	6.39	6.54	6.31
The flexible learning environment promotes my interest and enthusiasm for learning.	6.77	6.37	6.42
The integration of concepts in atmospheric sciences engages my interest in the field.	6.77	6.59	6.54

[a] Selected metrics and items included in the students' online teacher evaluation. Overall rating utilized the following scales: to a very great extent (6.51–7.00), to a great extent (5.51–6.50), to a satisfactory extent (4.51–5.50), to a moderate extent (3.51–4.50), to a small extent (2.51–3.50), to a very small extent (1.51–2.50), and not at all (1.50 and below).

OUTLOOK AND FUTURE DIRECTIONS

Integrating research with chemistry and science education conceivably enhances students' understanding and appreciation of the subjects. Incorporating research-based teaching methods such as inquiry-based and problem-based learning tend to provide students with hands-on experience in conducting experiments, analyzing data, and solving real-world problems. Research plays a crucial role as it helps to advance the field and provide new insights into the teaching and learning of chemistry and science. This could help to foster their critical thinking skills and possibly cultivate a deeper understanding of scientific concepts. There is hope that technology and digital media could play a significant role in facilitating the integration of research and education. Online platforms and virtual labs may provide students with real-time data and simulations, probably allowing them to engage in authentic scientific inquiry from their classrooms. Additionally, gamification and collaborative learning environments might increase students' motivation and engagement in science and chemistry education.

Integrating atmospheric science primary research articles into chemical education suggests creating an avenue to supplement learning with the rich scientific literature and the entire body of knowledge. Training the students to read, understand, and appreciate primary research articles is crucial for preparing students for careers in many fields and fostering a scientifically literate population. This integration will involve technology and digital media to enhance the students' experiences and provide opportunities for authentic scientific inquiry. By conducting research and disseminating the findings to the public, educators, and scientists help to build a scientifically informed society and foster informed decision-making on important scientific and technological issues. Thereby, such integration is likely to provide insights into the teaching and learning of science through the development of new teaching methods and materials and promote the development of scientific literacy.

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