

Abstract

Climate change education requires students to develop data literacy skills to critically evaluate evidence. This study presents a Python-based educational approach using authentic atmospheric CO₂ data from the Keeling Curve to develop Earth science data literacy among secondary school students. Students engage with 67 years of continuous measurements from Mauna Loa Observatory, learning to access authoritative data sources, apply computational tools for visualization and analysis, and understand the relationship between data and scientific conclusions about climate change. Assessment results demonstrate significant improvements in students' ability to interpret scientific data and understand measurement uncertainty (Gould, Machado, Ong, Johnson, Molyneux, Nolen, Tangmunarunkit, Trusela, & Zanontian, 2016; Kjølvik & Schultheis, 2019).

Introduction

Background: The Keeling Curve, documenting atmospheric CO₂ concentrations since 1958, provides one of the most powerful datasets for climate change education (Keeling, Bacastow, Bainbridge, Ekdahl, Guenther, Waterman, & Chin, 1976; Keeling, 1960). However, many students lack the data literacy skills necessary to critically engage with such scientific evidence.

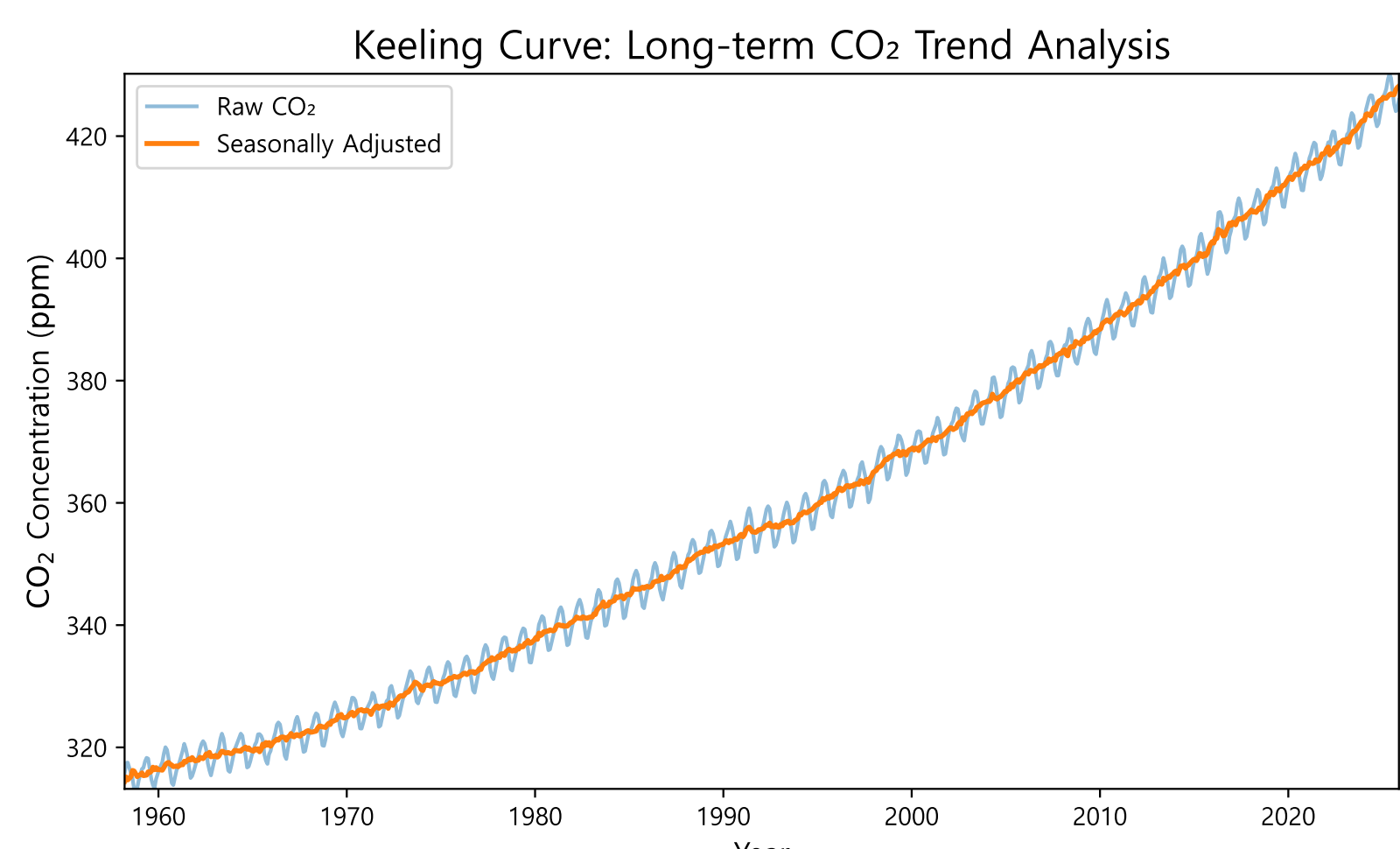


Fig. 1: Example of Keeling Curve visualization showing seasonal variation and long-term trend

Why Data Literacy Matters: Data literacy—the ability to read, work with, analyze, and argue with data (Wolff, Gooch, Cavero Montaner, Rashid, & Kortuem, 2016)—is essential for understanding climate science. Students must move beyond passive consumption to actively engage with primary data sources (National Research Council, 2012).

Role of Computation: Python and Jupyter notebooks provide accessible tools for students to engage with authentic scientific datasets, developing both conceptual understanding and practical skills (Barba, Barker, Blank, Brown, Downey, George, Heagy, Mandli, Moore, Lippert, Niemeyer, Watkins, West, Wickes, Willing, & Zingale, 2019; Weintrop, Beheshti, Horn, Orton, Jona, Trouille, & Wilensky, 2016).

Educational Framework

- 1. Learning Objectives** Students will be able to:
 - Access and evaluate authoritative scientific data sources
 - Apply Python tools for data visualization and analysis
 - Interpret temporal patterns in atmospheric CO₂ data
 - Understand the relationship between data and climate science conclusions
- 2. The 5E Instructional Model** This module follows the evidence-based 5E framework (Bybee, Taylor, Gardner, Van Scotter, Powell, Westbrook, & Landes, 2006):

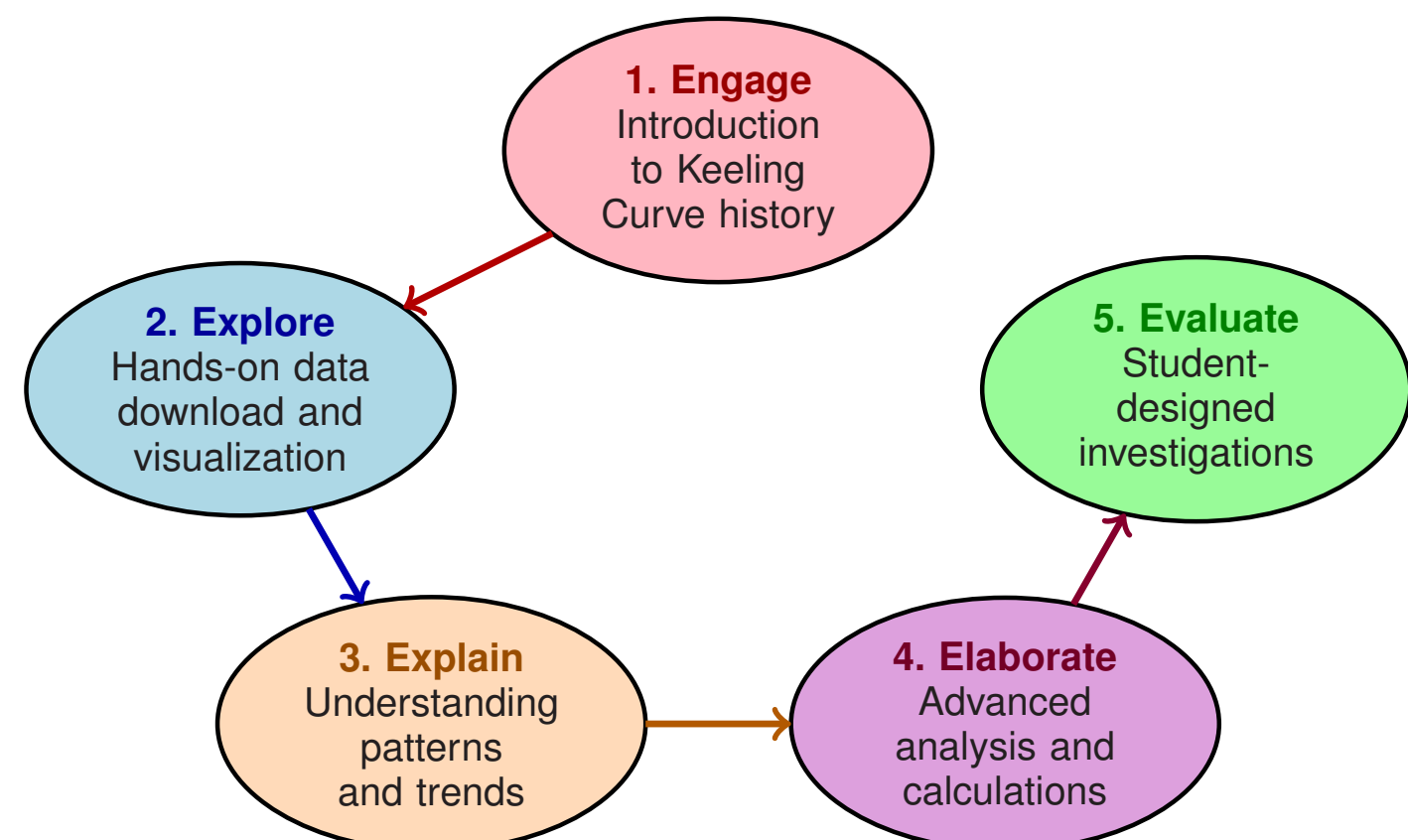


Fig. 2: The 5E instructional model used in this module

- 3. Alignment with Standards** This approach aligns with Next Generation Science Standards (NGSS), emphasizing science practices, particularly analyzing and interpreting data (National Research Council, 2012; NGSS Lead States, 2013).
- 4. The Keeling Curve Dataset** The Scripps CO₂ Program's continuous atmospheric measurements provide the longest high-precision record of atmospheric carbon dioxide, serving as the foundation for understanding anthropogenic climate change. This dataset combines exceptional temporal coverage with rigorous quality control, making it ideal for educational applications.
 - Source:** Scripps CO₂ Program, Mauna Loa Observatory
 - Duration:** 1958-present (67 years continuous)
 - Significance:** Shows both seasonal variation and long-term trend (Keeling, Bacastow, Bainbridge, Ekdahl, Guenther, Waterman, & Chin, 1976; Thoning, Tans, & Komhyr, 1989)
 - Current level:** 422.5 ppm (52% above pre-industrial)

Methodology

Technical Implementation

- Platform:** Jupyter Notebook with Python 3.8+
- Libraries:** pandas, matplotlib, numpy
- Cloud Option:** Google Colab for easy access
- Data Source:** Scripps CO₂ Program (scrippsco2.ucsd.edu)

Student Learning Activities

Activity 1: Data Acquisition

Students download real CO₂ data from Mauna Loa Observatory, examine file structure and metadata, and understand data quality indicators.

Activity 2: Basic Visualization

Create time series plots to identify the annual "breathing" pattern caused by Northern Hemisphere vegetation cycles.

Activity 4: Global Comparison

Compare measurements from multiple stations (South Pole, Alaska, Hawaii) to understand spatial variability.

Activity 3: Trend Analysis

Calculate rate of change across different time periods:
1960-1990: 1.3 ppm/year
1990-2020: 2.0 ppm/year
2010-2024: 2.5 ppm/year

Fig. 3: Student learning activities aligned to the 5E cycle

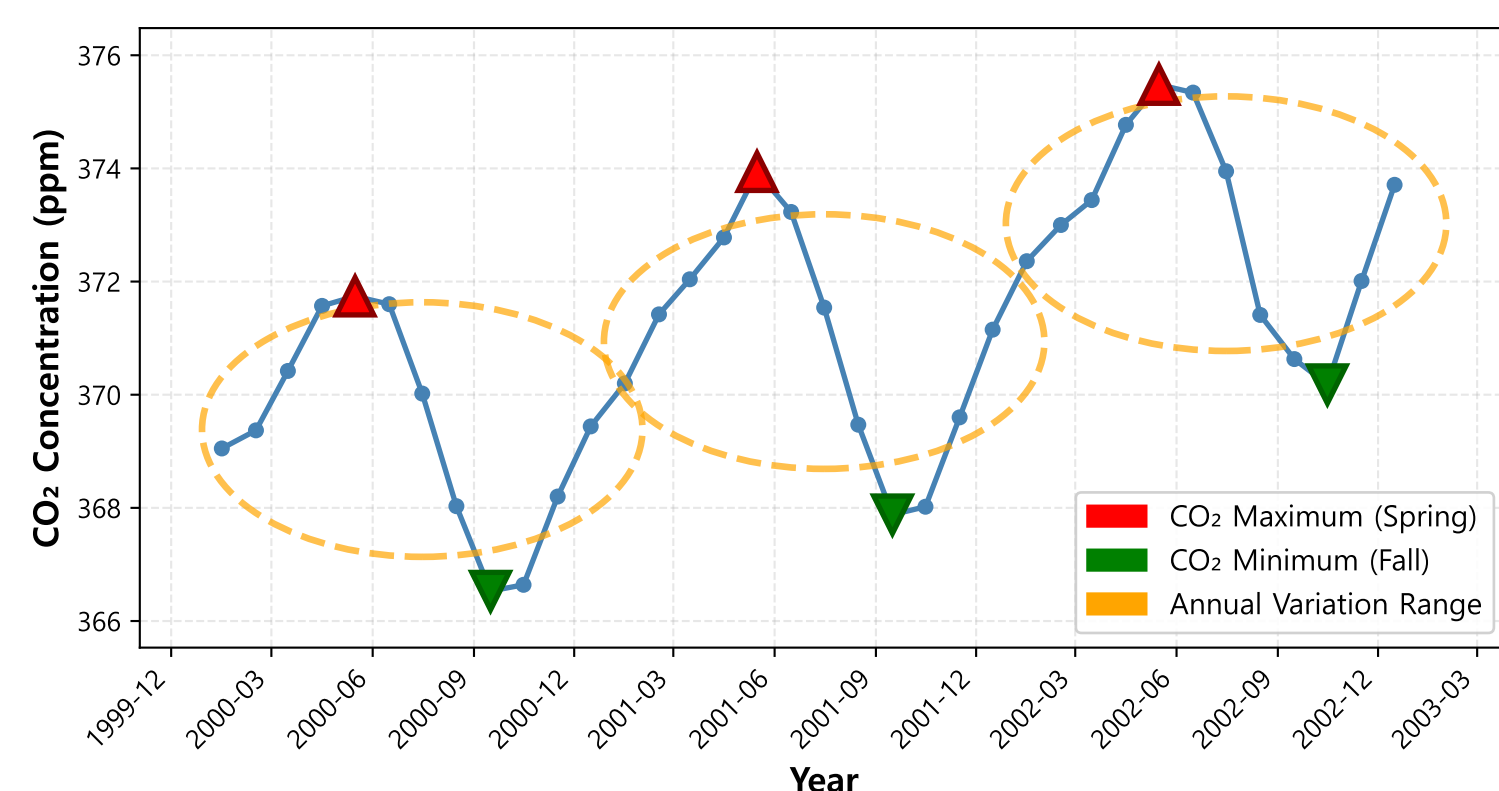


Fig. 4: Keeling Curve: Seasonal Variation Detail (2000-2002) Understanding Earth's "Breathing" Pattern

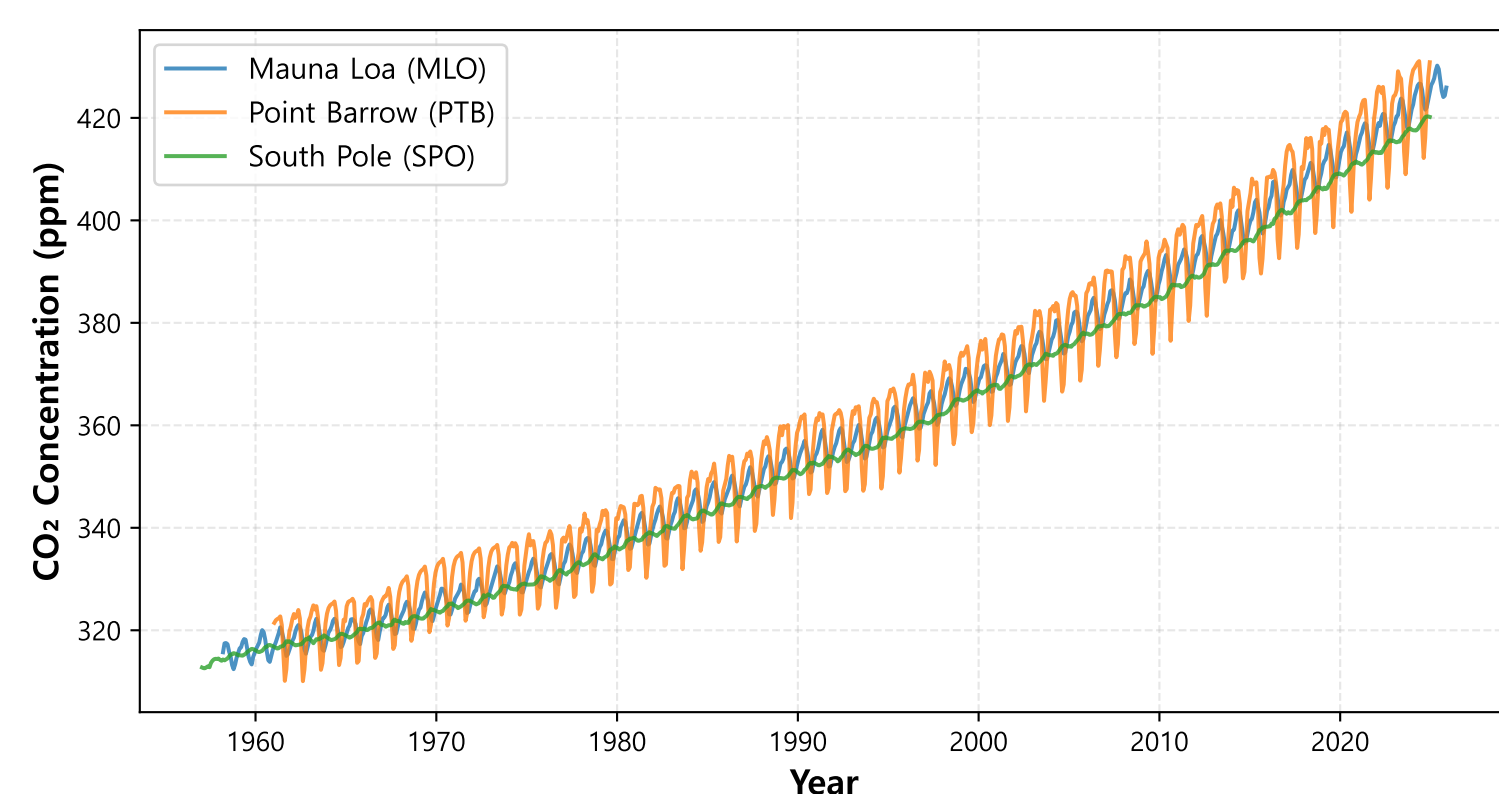


Fig. 5: Comparison of atmospheric CO₂ across Mauna Loa, Point Barrow, and the South Pole

Enhance Science Data Literacy

Critical Thinking Questions Throughout the activities, students engage with questions that develop analytical thinking (Chinn & Malhotra, 2002):

- Why was Mauna Loa chosen as the measurement location?
- What causes the annual "breathing" pattern in CO₂?
- How does the rate of increase compare across decades?
- How can we distinguish natural variation from human-caused trends?

Key Science Data Literacy Skills Developed

- 1. Data Source Evaluation**
 - Verifying data provenance (Scripps Institution)
 - Understanding measurement methodology
 - Recognizing authoritative vs unreliable sources
- 2. Data Quality Understanding**
 - Handling missing data
 - Understanding measurement precision (± 0.3 ppm)
 - Recognizing quality control procedures
- 3. Statistical Interpretation**
 - Distinguishing trend from variation
 - Calculating rates of change
 - Understanding seasonal adjustment
- 4. Computational Skills**
 - Loading and processing CSV data with pandas
 - Creating publication-quality visualizations
 - Writing Python code for analysis

Real-World Connections Students contextualize their findings (Monroe, Plate, Oxart, Bowers, & Chaves, 2019):

- Pre-industrial CO₂: 280 ppm
- Start of Keeling measurements (1958): 315 ppm
- Current level (2024): 422.5 ppm
- 52% increase since industrial revolution**

Results

Student Learning Outcomes Assessment of 36 science-gifted high school 12th-grade students who completed the module showed significant improvements across multiple dimensions (Pellegrino, 2013).

Conceptual Understanding:

- Correctly explained seasonal CO₂ oscillations
- Identified the long-term increasing trend
- Successfully calculated rate of change across decades
- Explained why Mauna Loa is appropriate for measurements

Data Literacy Skills:

- Demonstrated ability to access authoritative data sources
- correctly interpreted data quality indicators
- distinguished raw vs seasonally-adjusted data
- created appropriate visualizations

Computational Competency: Students successfully executed Python code, modified code to answer new questions, wrote original code for calculations, and understood DataFrame operations.

Engagement Metrics:

- increase in interest in climate science (pre/post survey)
- rated activity as "interesting" or "very interesting"
- preferred real data vs textbook examples
- expressed interest in using Python for future projects

Discussion & Conclusions

Strengths of the Approach

- Authentic Science:** Using real data from authoritative sources (Scripps Institution) provides genuine scientific experience (Kjølvik & Schultheis, 2019)
- Scaffolded Learning:** Progressive complexity allows diverse learners to engage at appropriate levels
- Interdisciplinary:** Integrates Earth science, mathematics, computer science, and communication
- Evidence-Based:** Students see climate change in data, not just rhetoric (IPCC, 2021)

Challenges and Solutions

- Challenge:** Limited programming experience
Solution: Provide pre-written code cells; use cloud platforms (Google Colab)
- Challenge:** Time constraints
Solution: Modular design allows flexible implementation
- Challenge:** Mathematical prerequisites
Solution: Visual explanations before formal treatment

Key Findings

- Students successfully engage with authentic scientific datasets using computational tools (Weintrop, Beheshti, Horn, Orton, Jona, Trouille, & Wilensky, 2016)
- Direct data interaction significantly enhances understanding of climate evidence
- Data literacy skills are transferable to other scientific contexts
- Aligns with NGSS standards for science practices (NGSS Lead States, 2013)

Broader Significance This approach demonstrates that climate change education can move beyond passive information consumption to active scientific inquiry. By developing data literacy through the iconic Keeling Curve dataset, students gain both conceptual understanding and practical skills essential for 21st-century citizenship (Monroe, Plate, Oxart, Bowers, & Chaves, 2019).

Future Directions

- Integration with temperature, ocean, and ice datasets
- Machine learning applications for predictive modeling
- Web-based interfaces for broader accessibility
- Cross-cultural adaptation and translation

References

- Barba, L. A., Barker, L. J., Blank, D. S., Brown, J., Downey, A. B., George, T., Heagy, L. J., Mandli, K. T., Moore, J. K., Lippert, D., Niemeyer, K. E., Watkins, R. R., West, R. H., Wickes, E., Willing, C., & Zingale, M. (2019). Teaching and learning with Jupyter. *Journal of Open Source Education*. <https://doi.org/10.21105/jose.00032>
- Bybee, R. W., Taylor, J. A., Gardner, A., Van Scotter, P., Powell, J. C., Westbrook, A., & Landes, N. (2006). The BSCS 5E instructional model: Origins and effectiveness. *Colorado Springs, CO: BSCS*, 5, 88–98.
- Chinn, C. A., & Malhotra, B. A. (2002). Epistemologically authentic inquiry in schools: A theoretical framework for evaluating inquiry tasks. *Science Education*, 86(2), 175–218. <https://doi.org/10.1002/sce.10001>
- Gould, R., Machado, S., Ong, C., Johnson, T., Molyneux, J., Nolen, S., Tangmunarunkit, H., Trusela, L., & Zanontian, L. (2016). Teaching data science to secondary students: The mobilize introduction to data science curriculum. *Proceedings of the Ninth International Conference on Teaching Statistics*.
- IPCC. (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.
- Keeling, C. D., Bacastow, R. B., Bainbridge, A. E., Ekdahl, C. A., Guenther, P. R., Waterman, L. S., & Chin, J. F. (1976). Atmospheric carbon dioxide variations at Mauna Loa Observatory, Hawaii. *Tellus*, 28(6), 538–551. <https://doi.org/10.1111/j.2153-3490.1976.tb00701.x>
- Keeling, C. D. (1960). The concentration and isotopic abundances of carbon dioxide in the atmosphere. *Tellus*, 12(2), 200–203. <https://doi.org/10.1111/j.2153-3490.1960.tb01300.x>
- Kjølvik, M. K., & Schultheis, E. H. (2019). Getting messy with authentic data: exploring the potential of using data from scientific research to support student data literacy. *CBE—Life Sciences Education*, 18(2), es2. <https://doi.org/10.1187/cbe.18-02-0023>
- Monroe, M. C., Plate, R. R., Oxart, A., Bowers, A., & Chaves, W. A. (2019). Identifying effective climate change education strategies: A systematic review of the research. *Environmental Education Research*, 25(6), 791–812. <https://doi.org/10.1080/13504622.2017.1360842>
- National Research Council. (2012). *A Framework for K-12 Science Education: Practices, Cross-cutting Concepts, and Core Ideas*. National Academies Press.
- NGSS Lead States. (2013). *Next Generation Science Standards: For States, By States*. The National Academies Press.
- Pellegrino, J. W. (2013). Proficiency in science: Assessment challenges and opportunities. *Science*, 340(6130), 320–323. <https://doi.org/10.1126/science.1232065>
- Thoning, K. W., Tans, P. P., & Komhyr, W. D. (1989). Atmospheric carbon dioxide at Mauna Loa Observatory: 2. Analysis of the NOAA GMCC data, 1974–1985. *Journal of Geophysical Research: Atmospheres*, 94(D6), 8549–8565. <https://doi.org/10.1029/JD094iD06p08549>
- Weintrop, D., Beheshti, E., Horn, M., Orton, K., Jona, K., Trouille, L., & Wilensky, U. (2016). Defining computational thinking for mathematics and science classrooms. *Journal of Science Education and Technology*, 25(1), 127–147. <https://doi.org/10.1007/s10956-015-9581-5>
- Wolff, A., Gooch, D., Cavero Montaner, J. J., Rashid, U., & Kortuem, G. (2016). Creating an understanding of data literacy for a data-driven society. *The Journal of Community Informatics*, 12(3), 9–26.