© IJARW | ISSN (O) - 2582-1008
June 2026 | Vol. 7 Issue. 12
www.ijarw.com

STUDENTS' CONCEPTUAL UNDERSTANDING AND PERCEPTIONS OF ARCTIC ALBEDO FEEDBACK THROUGH A 5E GOOGLE EARTH ENGINE INTERVENTION: A CASE STUDY

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ABSTRACT

This case study explored the application of a 5E Google Earth Engine intervention to improve graduate science students' understanding and perceptions of Arctic albedo feedback. It was conducted on eleven (11) masteral students at the Cotabato Foundation College of Science and Technology. A mixed methods research design employed a pretest, posttest, perception survey, observation logs, and feedback loops to analyze students' understanding and perceptions related to five main concepts: (a) prior conceptions of albedo and energy budget, (b) post-intervention knowledge and understanding of concepts, (c) perceptions of temporal scaling, digital twin, active learning, and geospatial literacy, (d) knowledge and understanding development on the ice albedo feedback, and (e) integration of findings to explain the systems thinking and climate literacy. Low understanding was evidenced in initial and prior knowledge assessment, with 52.27% of increase after the intervention with 10.45/20 mean gain and high effect size for pretest/posttest assessment while high agreement with perception question domains with a grand mean of 4.18/5 for perception survey and a change in their understanding of albedo from surface color to feedback system, positive reinforcement and tipping points. Convergent results suggest that the 5E GEE intervention enhances systems thinking and climate literacy among graduate science students in climate-vulnerable areas, and it is encouraged to use geospatial tools to strengthen the climate education of masteral science students.

Keyword: Arctic albedo feedback , 5E instructional model , Google Earth Engine , systems thinking ,climate literacy

1. INTRODUCTION

Climate literacy is urgently needed because accelerating Arctic sea ice melt has become a key visual demonstration of global climate change. Central to this melt is the Arctic albedo feedback, which involves the replacement of bright, highly reflective sea ice by dark, sun-absorbing ocean water, increasing regional temperatures and driving more melting (NOAA/SHEBA, 2019). While extensively documented in science, it is underrepresented in education as feedback, and most students across different levels tend to conceive of it as a linear process instead of a circular system, which in turn limits their capacity to reason about climate change.

This gap in understanding has been documented in several studies. Shepardson, Niyogi, Choi and Charusombat (2011) reported fragmented mental models about the greenhouse effect among secondary students, where students omitted feedbacks, incorrectly understood surface energy exchange and lack of an encompassing system view. Similar results have been seen in research by Kurup, Li, Powell and Brown (2021), which found that although students are aware that climate change is occurring and is an international issue, they lack an adequate level of understanding when explaining underlying mechanisms such as albedo feedback based dynamics. Both studies suggest that the deficit stems not from student inability but from structural problems in instruction. Instruction based on static diagrams and purely declarative knowledge fails to provide students with a systems perspective, leading to an inadequate understanding of positive feedback.

Such depth in climate literacy is crucial; Boyd, Gold, Chandler and Crim (2025) argue that effective climate science instruction, and ultimately successful teaching about climate change, require a deep understanding of complex dynamics, feedbacks, and uncertainty. During conceptualization, teachers act as intermediaries between complex knowledge. Pedagogical content knowledge shapes classroom instructional practices. Hence, Master of Science in Education students are a target population of great importance. As future educators at the secondary and tertiary levels in the Philippines, students' conceptualization and comfort with utilizing robust, data-intensive pedagogies are instrumental to future climate science education delivery at these levels.

With passive learning modalities proven ineffective in addressing the problem, an active, data-driven pedagogy can address the need for in-depth climate science understanding. A systematic review by Monroe, Plate, Oxarart, Bowers, and Chaves (2019) determined that engaging in hands-on experience with real-world climate data, inquiry-based activities, and relevant contexts had the strongest correlation with gains in climate change-related concepts. Learners who actively engage with data demonstrate improved retention and more accurate mental models than those in passive learning environments. This type of learning closely aligns with the BSCS 5E model (Bybee, Taylor, Gardner, van Joolingen, & Alexander, 2006), in which engagement, exploration, explanation, elaboration, and evaluation make up the learning cycle. A meta analysis by Polanin, Austin, Taylor, Steingut, Rodgers and Williams (2024) confirmed that teaching methods based on the 5E model positively impact concept understanding, higher order thinking, and student motivation, particularly if learners act as investigators.

Cloud-based geospatial platforms further enhance this instructional potential. Google Earth Engine offers users decades of multispectral satellite images as well as powerful analytic tools typically used in professional practice (Google Earth Engine, 2024). Its time-series visualization capability enables learners to condense decades of melt into an hour-long session, making temporal scaling and feedback accessible in real-time. An experimental intervention on wildfire burn severity using Google Earth Engine showed gains in student environmental literacy and geo-spatial skills relative to those utilizing static map interfaces (Dema & Sivitskis, 2025), which could offer similar affordances in teaching Arctic albedo feedback dynamics.

In the Philippine setting, these concerns are of paramount importance. The Department of Education has made climate change education a national imperative (Department of Education, 2022), but geo-spatial tools and explicit content about climate feedback have not been thoroughly incorporated into the curriculum for Master's level science educators. This represents a critical knowledge gap for a nation that is highly vulnerable to climate impacts, particularly at the graduate level, where science educators are educated to become effective science instructors in secondary and tertiary schools.

This study responds to three intersecting needs: a systems-level understanding of Arctic albedo feedback, the integration of the 5E model with real-world geospatial data, and an empirical study of Master of Science Education students' conceptualization and learning with such an intervention in the Philippines.

Therefore, this case study will explore this research gap by achieving a general objective: to examine the conceptualization and perceptions of Master of Arts in Teaching Science students of Arctic albedo feedback using a 5E-based Google Earth Engine intervention. More specifically, it seeks to describe baseline conceptualizations with pre-test data, identify changes in understanding post-intervention with post-test data, describe students' perceptions through post-test surveys, analyze conceptual reasoning with data from observation logs and feedback diagrams, and synthesize quantitative and qualitative data to discuss how the intervention fosters a systems approach and improves climate literacy for the Master of Arts in Teaching Science Students at Cotabato Foundation College of Science and Technology.

2 METHODS

2.1 Research Design

This study employed a mixed methods case study design to explore the conceptual understanding and perceptions of Master of Arts in Teaching Science students regarding Arctic albedo feedback following a 5E Google Earth Engine intervention.

This design was appropriate because the study used quantitative data about the change in concepts and qualitative data regarding student reasoning and perceptions to help explain the interpretation of the effect of intervention in a bounded educational system (Creswell & Plano Clark, 2018; Yin, 2018).

2.2 Research Locale

This study was conducted at the Cotabato Foundation College of Science and Technology, North Cotabato, Philippines. It was chosen as the research locale because it is a higher-education institution that provides graduate teacher education and is a suitable environment for studying climate literacy and geospatially supported science education.

2.3 Participants of the Study

Eleven Master of Arts in Teaching Science students at the Cotabato Foundation College of Science and Technology participated in the study.

2.4 Data Collection

The following instruments were used to gather data for this study: pretest, posttest, perception survey, Google Earth Engine observation log, and feedback loop diagram. The pretest assessed students' initial understanding of albedo, Earth's energy balance, and Arctic albedo feedback, while the post-test revealed their change in understanding. The survey questionnaire captured students' perceptions of temporal scaling, digital twin representation, active learning, and geospatially supported literacy, while the observation log and feedback loop diagram helped provide a clear view of student reasoning during and after the activity.

2.5 Data Analysis

Quantitative data were analyzed using the mean, percentage, standard deviation, weighted mean, and descriptive rating scale. The Wilcoxon signed-rank test was used to determine whether the mean difference in pre- and post-test scores was significant. The effect size was calculated to measure the magnitude of the change. Qualitative data from the observation log and feedback loop diagram were analyzed through thematic analysis for indications of reasoning, while the quantitative results explained the intervention for the students' improvement of systems thinking and climate literacy.

2.6 Ethical Considerations

Participation in the study was voluntary, and written informed consent was obtained from all respondents before data collection. All recorded data were coded to protect the respondents' identities. The respondents were assured of the confidentiality of the collected data and were informed that they could withdraw from the study at any time without consequence. The data collected were used only for this research study.

3. RESULT AND DISCUSSION

3.1 Baseline conceptualizations of Arctic albedo feedback using pretest results.

Participant	Pretest Score (/20)	Percentage (%)	Level of Understanding
R1	3	15.00	Low
R2	7	35.00	Low
R3	5	25.00	Low
R4	8	40.00	Low
R5	8	40.00	Low
R6	9	45.00	Low
R7	12	60.00	Moderate
R8	2	10.00	Low
R9	10	50.00	Moderate
R10	6	30.00	Low
R11	8	40.00	Low
Mean	7.09	35.45%	Low
SD	2.95		

(Classification: 75–100% = High; 50–74% = Moderate; below 50% = Low.)

Table 1. Baseline Conceptions: Pretest Results

Table 1 presents the pre-intervention conceptions of Master of Arts in Teaching Science students regarding albedo, the Earth's energy budget, and Arctic albedo feedback, preceding the 5E Google Earth Engine intervention. Pretest scores ranged from 2 to 12 out of 20, and most of the students scored below the 50% threshold, and therefore were designated as having a low level of understanding. Only two respondents (R7 and R9) achieved a moderate level of understanding, with scores of 60.00% and 50.00%, respectively. The average group score was 7.09 out of 20, or 35.45%, also reflecting a low group level of conceptual understanding, with limited variability of 2.95, indicating that students were generally within the low to at best moderate range.

The students' low pretest performance suggests that even those pursuing a Master of Arts in Teaching Science degree appear to have very limited, fragmented understandings of basic Earth system concepts. Their scores suggest the existence of robust misconceptions regarding albedo, positive feedback, and the Arctic energy budget. These misconceptions probably stem from students' tendency to perceive Earth system processes as linear cause-and-effect relationships rather than interrelated, recursive systems. The prevalence of a linear thought process is congruent with broader patterns of student learning regarding earth and climate system science, whereby individuals often learn isolated pieces of information rather than interacting elements.

The pretest or baseline profile, shown in Table 1, suggests broader issues concerning climate literacy and teacher content knowledge. This limited pretest performance indicates that a large proportion of teachers-in-training do not possess a systems-level understanding of climate feedback mechanisms, despite being prepared to serve as disseminators of climate science knowledge. Within the context of graduate education, the presumption that students arrive with existing knowledge of these systems does not appear to hold, as evidenced by the results of this study. The need to directly present foundational concepts of mechanisms such as feedback and albedo is further evident through these students' scores.

The current pretest results have direct implications for designing science teacher education curricula. First, they indicate the failure of traditional text-based approaches to build comprehensive knowledge of climate mechanisms. Second, they supported the development of a structured, inquiry-based 5E lesson utilizing authentic satellite data from Google Earth Engine for graduate students. This lesson is envisioned not as a remedial or add-on curriculum element but rather as a standard component of graduate climate coursework. Thus, the pretest suggests the necessity of countering specific misconceptions with graduate-level climate science curriculum development and approaching these concepts from a systemic viewpoint without relying on pre-existing deep knowledge in the field.

3.2 Students' conceptual understanding of albedo, positive feedback processes, and temporal scaling after the 5E Google Earth Engine activity using post-test results.

Participant	**Pretest (/20)**	**Posttest (/20)**	**Gain**	**% Gain**	**Interpretation**
R1	3	17	+14	+70.00%	Large Gain
R2	7	19	+12	+60.00%	Large Gain
R3	5	18	+13	+65.00%	Large Gain
R4	8	16	+8	+40.00%	Moderate Gain
R5	8	14	+6	+30.00%	Moderate Gain
R6	9	19	+10	+50.00%	Large Gain
R7	12	19	+7	+35.00%	Moderate Gain
R8	2	15	+13	+65.00%	Large Gain
R9	10	17	+7	+35.00%	Moderate Gain
R10	6	19	+13	+65.00%	Large Gain
R11	8	20	+12	+60.00%	Large Gain
Mean	7.09	17.55	+10.45	+52.27%	
SD	2.95	1.92			
Wilcoxon T			0.00	Z = -2.934	p = .001*
Effect Size			r = .885		Large Effect

p < .05. Classification: ≥50% gain = large; 25–49% = moderate; below 25% = small.

Table 2. Changes in Conceptual Understanding: Pre-Post Comparison

Table 2 demonstrates large student gain in conceptual understanding of albedo, positive feedback, and Arctic albedo feedback as a result of the 5E Google Earth Engine lesson. The students' mean pretest score was 7.09 (scores ranged from 2-12) indicating their understanding of climate feedback was low; the students' mean posttest score was 17.55 (scores ranged from 14-20) and reflected an average gain of 10.45 points, or 52.27 percent, a gain designated as "large gain." The gain for seven students was 50 percent or more, including all the "highly accurate" post-test participants (R1, R2, R3, R6, R8, R10, R11); all other participants made moderate gain of 30-40 percent. The standard deviation decreased from 2.95 to 1.92, reflecting that student scores were more clustered around a high score, indicating that student understanding was higher and more consistent after the BSCS 5E intervention using Google Earth Engine.

Inferential statistics provide strong evidence for this large gain. T=0.00, Z=2.934, and p=.001 from a Wilcoxon signed rank test suggest a statistically significant change from pre-test to post-test, with significance accepted at the .05 level. The large effect size (r =.885) further indicates a substantial and educationally significant impact of this lesson on students' understanding. Both descriptive and inferential statistics indicate that the students progressed from largely inadequate to significantly improved understanding. Their performance progressed from isolated concepts to a holistic, systems-based understanding of the Arctic albedo feedback cycle.

These results have several implications for climate change education and graduate science teacher training. Integrating a highly relevant and interactive technology tool with research-supported pedagogy for developing deeper conceptual understanding in the GEE 5E models may provide an answer to the common difficulties in students' conceptualization of climate feedback processes. This learning will likely help MATs be better prepared to teach this difficult and central concept in future classrooms, thereby improving secondary science students' climate change literacy.

3.3 Patterns in students' perceptions of temporal scaling, digital twin representations, active learning, and geospatial literacy

Item	Survey Focus	WM	DR
Theme A: Digital Twins and Temporal Scaling			
Item 1	Temporal scaling allowed us to observe decades of decay in seconds.	3.91	Agree
Item 2	The 1996 visual baseline helped to grasp the speed of deglaciation.	4.00	Agree
Item 3	A digital twin creates a high-fidelity connection to a remote location.	4.00	Agree
Item 4	Satellite timeline manipulation has helped identify tipping points.	4.27	Agree
Item 5	The ice-to-water transition is the most visible climate feedback indicator.	4.00	Agree
Theme A Mean		**4.04**	**Agree**
Theme B: Impact of Visual Interventions			
Item 6	Active learning helps retain more information than static modules.	4.27	Agree
Item 7	Scrubbing through the timeline deepened the understanding of thermal absorption.	4.00	Agree
Item 8	Visual intervention acts as a pedagogical scaffold.	4.18	Agree
Item 9	The score gain was a direct result of interacting with the time-series tool.	4.09	Agree

Item	Survey Focus	WM	DR
Item 10	The interactive tool allowed mastery of complex concepts through direct observation.	4.36	Agree
Theme B Mean		**4.16**	**Agree**
Theme C: Student Engagement with Real-World Data			
Item 11	Satellite archives create a sense of authentic research.	4.18	Agree
Item 12	It has moved from conceptual confusion to data curiosity.	3.91	Agree
Item 13	The urgency of visual data motivated persistence through difficult tasks.	3.91	Agree
Item 14	Motivation increased because the data were globally relevant.	4.55	Strongly Agree
Item 15	Professional tools helped in developing a stronger research identity.	4.18	Agree
Theme C Mean		**4.15**	**Agree**
Theme D: Localized Urgency and Geospatial Literacy			
Item 16	The GEE bridged the distance gap between Arctic melt and local resilience.	4.55	Strongly Agree
Item 17	Geospatial literacy aligns with the Philippine National Adaptation Plan (NAP).	4.27	Agree
Item 18	The observation of global tipping points has increased the urgency of Mindanao/Region XII.	4.00	Agree
Item 19	Satellite data integration is essential for modernizing the science curriculum.	4.55	Strongly Agree
Item 20	Experience improved geospatial literacy for disaster resilience through the following:	4.36	Agree
Theme D Mean		**4.38**	**Agree**
Grand Mean		**4.18**	**Agree**

Scale: 4.50–5.00 = Strongly Agree; 3.50–4.49 = Agree; 2.50–3.49 = Neutral; 1.50–2.49 = Disagree; 1.00–1.49 = Strongly Disagree. WM-Weighted Mean, DR-Descriptive Rating

Table 3. Student Perceptions: Survey Results by Themes.

In Table 3, students perceptions of the 5E Google Earth Engine intervention are summarized by four themes. A Grand Mean of 4.18 on a scale where a

"Agree" was 4 and a "Strongly Agree" was 5 shows the intervention was seen as successful and educational for teaching about arctic albedo feedback, temporal scaling, and geospatial literacy.

For Theme A (Digital Twins and Temporal Scaling), a mean score of 4.04 shows that students agreed that temporal scaling and digital twin representations enhanced their ability to visualize long-term Arctic sea ice decline and comprehend de-glaciation and potential tipping points. Students described witnessing "decades of decay in seconds" and using 1996 baselines for tracking change, demonstrating that the satellite time line allowed a paradigm shift from static understandings of climate to a process-based approach.

Theme B (Impact of Visual Interventions) received a mean score of 4.16, indicating strong agreement with visual and interactive components as drivers of learning. Students agreed that direct interaction with the visualization tools made content stick better than in static lessons, that actively scrubbing through the timeline built comprehension of heat absorption, and that the visual interface enabled understanding complicated concepts. The highest mean was a WMS of 4.36, "I could master complex concepts by direct visual experience," demonstrating the value of having direct visual access to climate phenomena that were previously abstract.

Theme C (Student Engagement with Real World Data) was rated 4.15 and was seen as helping students see authentic research behind real-world data sets, clearing prior confusion, and motivating them. Participants noted that "use of real-world tools also helped reinforce their identities as science teachers/researchers" which may have been particularly crucial at the graduate level, where identity as a scientist can be tenuous. This data may imply that students came to see themselves as "scientists" rather than merely as consumers of scientific data.

Theme D (Localized Urgency and Geospatial Literacy) received the highest mean score (4.38). Here, many items were marked "Strongly Agree." Students believed the lesson helped "connect melt in the Arctic to local threats and dangers" and "reinforced the argument that integration of satellite data is crucial for updating science curriculum" and that it provided them with "geospatial literacy in regard to disaster resilience." The data imply that students now see not only global processes but also their localized and immediate relevance to their own lives.

Overall, these data indicate that the 5E Google Earth Engine intervention not only enhanced a conceptual understanding of Arctic albedo feedback and stimulated student engagement in the classroom, but ultimately aided students in identifying as researchers, future scientists, and professionals.

3.4 Qualitative Analysis of Students' Reasoning on Arctic Albedo Feedback

Reasoning Indicator	Evidence Source	Respondents	Sample Response
Identified albedo as a surface reflectivity property	Observation log entries	R1, R2, R3, R4, R5, R6, R7, R8, R9, R10, R11 (11/11)	"Ice reflects, dark ocean absorbs — the shift from white to blue is the key trigger."
Described the feedback as circular, not linear	Feedback loop diagrams	R1, R2, R3, R4, R6, R8, R9, R10, R11 (9/11)	"Ice loss does not just stop at melting; it actively fuels ocean warming, which loops back to accelerate the melt." — R11
Identified a specific tipping point year from GEE data	GEE observation log	R3, R4, R5, R7, R8, R9, R10, R11 (8/11)	"The scrubbing showed the most visible white-to-blue transition occurring between 2007 and 2012."

Reasoning Indicator	Evidence Source	Respondents	Sample Response
Connected ice loss to thermal absorption quantitatively	Feedback loop diagrams	R4, R5, R6, R7, R9, R10 (6/11)	"Darker grid cells expand and heat indices rise in tandem — the parameters are directly coupled." — R6
Articulated the self-amplifying nature of the system	Observation log entries	R4, R5, R6, R7, R10, R11 (6/11)	"It is a runaway loop. The visual synchronization of ice retreat and warming indicators makes the self-amplifying nature effortless to see." — R10

Table 4. Qualitative Analysis of Students' Reasoning on Arctic Albedo Feedback

Table 4 presents the qualitative analysis of student reasoning on the Arctic albedo feedback mechanism, as evident in the observation log entries and feedback loop diagrams. The results indicate that student thinking has evolved from the identification of albedo as a property of a surface to explaining the feedback mechanism as a self-reinforcing climate feedback, suggesting a developmental trajectory from recognition to system-based reasoning, which is a challenge in teaching climate change science.

At the most basic level, all 11 students identified albedo as a characteristic of surface reflectivity in their observation logs. All students consistently compared the ice-covered and dark ocean surfaces and differentiated them by comparing their reflectivity. Such consistency suggests that the use of Google Earth Engine's visualization capabilities has made it easier for students to connect surface reflectivity as the key property. This aspect is important because the difference in reflectivity is an important concept for developing an understanding of how the loss of ice causes further warming.

More encouraging is the structure of students' causal reasoning in feedback loop diagrams. Nine of the 11 students drew the ice albedo feedback as cyclical rather than a linear cause-and-effect relationship. This is important because students have been shown to struggle to see climate systems as a complex network of interacting feedback cycles, instead viewing them as one-directional. Thus, the data suggest that the 5E intervention and the use of the Google Earth Engine provided scaffolding to promote system-based reasoning and understanding of how the loss of ice, subsequent change in reflectivity, warming of the water, and further ice melt is a recursive system. The data suggest that continued support may be necessary because two students did not exhibit this thinking process.

The observation logs also revealed that eight students identified a distinct tipping point from the Google Earth Engine time series, most often from 2007 to 2012, when the transition from white to blue surface cover was most pronounced. This indicates that temporal analysis using satellite data is a successful teaching strategy for students to draw evidence-based conclusions about the critical periods of melting. This implies a shift from an individual snapshot to an ongoing, time-based environmental change process.

More advanced student reasoning included six students making direct connections between ice loss and thermal absorption, and six students using language that suggested they understood that the system was self-amplifying. These are evidence-based explanations that describe the system interaction and acceleration. The six students' responses fell into the category of higher-order reasoning associated with inquiry-based learning and systems-based, student-centered pedagogies, such as the 5E model.

Overall, there is a clear implication for science teacher education: utilizing geospatial data and time series analysis as a tool for developing systems-based reasoning and improving students' understanding of climate change. As graduate students, participants used these tools to deepen their understanding of a key climate feedback;

thus, future teachers can employ these methods to teach complex environmental science concepts through inquiry, observation, and data.

3.5 Integrate quantitative score gains and qualitative perception themes

Dimension	Quantitative Evidence	Qualitative Theme	Convergence
Knowledge Gain	Mean posttest score: 17.55/20; Mean gain: +10.45; p = .001, r = .885 (Large Effect)	All 11 respondents described moving from conceptual confusion to a clearer understanding after the GEE interaction.	Strong convergence: score gains confirmed by students' reports of a shift from passive to active understanding.
Systems Thinking	9/11 students scored ≥17/20 on posttest items related to feedback loops and circular systems	Theme Q2 (Emergent Theme: Visualization of Circular Feedback as a Self-Reinforcing Loop): All 11 respondents described the albedo effect as a loop, not a sequence.	Strong convergence: The test performance on systems thinking items aligns with the qualitative descriptions of circular reasoning.
Active Learning and Engagement	Theme C Grand Mean: 4.15 (Agree); Item 14: 4.55 (Strongly Agree)	Theme Q3 (Emergent Theme: Transition from Passive Student to Active Investigator): 11/11 described increased agency and professional confidence.	Strong convergence: Survey data and open-ended responses both confirm heightened engagement and research identity.
Temporal Scaling and Geospatial Literacy	Theme A Mean: 4.04 (Agree); Theme D Mean: 4.38 (Agree)	Theme Q1 (Emergent Theme: From Static to Dynamic Understanding): 11/11 described temporal compression as cognitively transformative.	Strong convergence: Perception scores and qualitative data confirmed that the time-slider bridged the conceptual gap between static textbook learning and dynamic data interaction.
Regional and Curriculum Relevance	Items 16, 19: WM = 4.55 (Strongly Agree); Item 18: WM = 4.00 (Agree)	Theme Q4 (Emergent Theme: Connecting Global Deglaciation to Local Urgency in Mindanao): All respondents connected Arctic melt to Mindanao climate risks and called for data-driven curriculum modernization.	Strong convergence: Quantitative and qualitative data both indicate the high perceived relevance of the intervention to the Philippine science education context.

Table 5 . Description of how the 5E Google Earth Engine intervention supports systems thinking and climate literacy among Master of Arts in Teaching Science students.

The mixed method integration of the quantitative and qualitative strands suggests that the 5E Google Earth Engine intervention significantly promoted systems thinking and climate literacy in MAT Science students. The numerical data converged with students' self-reported data across each of the aspects in Table 5, fulfilling several requirements of effective climate change instruction.

For knowledge acquisition, the dramatic, statistically significant difference in test scores corroborates each student's narrative of moving from confusion to clarity through the use of GE. This correspondence indicates that students not only acquire more factual information but also rethink their mental models of Arctic albedo feedback. This response directly addresses concerns regarding the pervasive confusion surrounding the nature of climate feedback loops.

The implications for systems thinking were also consistent across the data. The high-performance post-test items on feedback loops are corroborated by students' universal description of the albedo feedback as a cyclical, self-sustaining cycle and not as a simple, linear cause-and-effect relationship. This pattern suggests that one critical limitation of conventional instruction, where feedback is rarely treated as a dynamically developing system, was addressed by this intervention.

The intervention also enhanced active learning, engagement, time scaling, and spatial literacy. With survey means from "Agree" to "Strongly Agree," and emergent themes on engaging in discovery and changing "from static to dynamic," students' responses revealed their satisfaction with authentic satellite data and professional tools. This finding is consistent with evidence identifying active and engaging pedagogy and the use of meaningful data as essential components of climate education.

Finally, the high student agreement with the items on regional importance and curriculum modernization, along with students' qualitative connections of Arctic de-glaciation to climate risks in Mindanao, shows that students recognize spatial and feedback-oriented instruction as pertinent to science teaching and resilience in the Philippines. This finding fulfills recent suggestions to include systems-oriented, context-relevant climate literacy in teacher education programs.

4. CONCLUSION AND RECOMMENDATION

The results of the study proved that the 5E Google Earth Engine intervention provided gains in conceptual knowledge and perceptions of Master of Arts in Teaching Science students' understanding of Arctic albedo feedback. Baseline measures indicated that the students lacked initial knowledge of albedo, the Earth's energy budget, and Arctic albedo feedback. This indicates that students held partial, unscientific conceptualizations, even as graduate students.

The students demonstrated significant gains in conceptual knowledge as a result of this intervention. The improvement in student scores from pretest to posttest and the resulting large effect size further indicated that students had achieved substantial conceptual change. Student understanding appeared to progress from partial, linear descriptions to coherent, systems-based descriptions of Arctic albedo feedback.

The positive feedback on student perceptions of temporal scaling, digital twin simulations, active learning, and authentic satellite data demonstrated student-like perceptions of effective learning environments. The students also indicated strengthened engagement with global climate change concepts, increased geospatial literacy, and enhanced awareness of how global climate processes are connected to local educational and environmental issues.

The qualitative data collected through observation logs and feedback loop diagrams supported these quantitative results. Student reasoning improved from a simplistic notion of albedo as a characteristic of the surface to coherent descriptions of ice albedo feedback as a circular, self-reinforcing process. An increase in student incorporation of tipping points, coupled effects, and recursive processes showed an improvement in students' systemic understanding of the climate system. Collectively, the data presented in Tables 1–5 provide evidence that the 5E Google Earth Engine intervention facilitated desired outcomes in initial understanding, conceptual change, perception of learning, reasoning improvement, and fostering systems-thinking approaches to learning about the climate system.

Drawing upon the conclusions made from this study and considering the research objectives of this study, the following recommendations were made. These recommendations for research should be concrete and address research in a way that lends itself to future endeavors.

Science Teachers. When teaching climate-related issues such as energy balance, albedo, and feedbacks within the system, teachers should design learning experiences that are data-driven, inquiry-based, and use visualizations such as the satellite imagery shown to them. Students should be given multiple opportunities to investigate, interpret, model, and present evidence of their understanding, such as constructing feedback loop diagrams, to better reinforce these systems-based thinking concepts.

School Administrators. Administrators should endeavor to provide teachers with technological resources, such as adequate Internet bandwidth and student devices and software, like Google Earth Engine, that can be used in an instructionally relevant and effective manner. Access to and use of such resources should be supplemented by professional development that supports teachers' effective integration of such resources into their curriculum.

Curriculum Planners. Climate feedback systems, geospatial literacy, and temporal scaling should be explicitly incorporated into science and teacher education programs. Learning outcomes should include students' ability to identify and explain relationships within a system, utilize environmental datasets, and understand how global climate processes impact local education and environmental issues.

Students. Science education students should be provided with more opportunities to use authentic datasets and inquiry technologies in their efforts to learn about complex, system-based concepts such as climate change.

Future Researchers. Additional studies should use these intervention techniques with diverse samples of science teachers and explore other climate-related topics.

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