

Effect of Ventusky-Assisted Problem-Based Learning on Students' Spatial Thinking in Atmospheric Dynamics: A Quasi-Experimental Study

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ARTICLE INFO	ABSTRACT
Article History: Received: 2026-06-14 Accepted: 2026-09-15 Published: 2026-09-30 Keywords: Atmospheric dynamics; Problem-based learning; Spatial thinking; Ventusky Corresponding author: Yosafat Dalimunthe Email: yosafat.dalimunthe.2507218@students.um.ac.id DOI: 10.37905/jgej.v7i2.39802 Copyright © 2026 The Authors  This open access article is distributed under a Creative Commons Attribution-NonCommercial (CC-BY-NC) 4.0 International License	Spatial thinking is an essential competency in geography education, particularly for understanding atmospheric phenomena that are dynamic, spatially distributed, and difficult to observe directly. However, previous geography education studies have predominantly examined static geospatial platforms, while empirical evidence on the use of dynamic meteorological visualisation integrated with problem-based learning for developing students' spatial thinking remains limited. This study examined the effect of Ventusky-assisted problem-based learning (PBL) on students' spatial thinking skills in Atmospheric Dynamics. A quantitative quasi-experimental method with a posttest-only nonequivalent control group design was employed with 72 tenth-grade students at SMAN 2 Sampang, Indonesia. Thirty-six students in the experimental group received Ventusky-assisted PBL, whereas 36 students in the control group received conventional instruction. Spatial thinking was assessed using eight essay items representing comparison, aura, region, hierarchy, transition, analogy, pattern, and association. The experimental class had a considerably higher mean score (84.61) than the control class (72.33), with a p-value of $< .001$ and a Cohen's d effect size of 1.37, which is classified as very large. These findings indicate that integrating Ventusky's real-time meteorological visualisation into the PBL framework effectively facilitates spatial reasoning by allowing students to observe, analyse, and interpret dynamic atmospheric phenomena through authentic spatial data. This study indicates that the intervention group engaging with Ventusky-assisted PBL demonstrated significantly higher posttest spatial thinking performance than the nonequivalent comparison group, pointing to the pedagogical promise of contextualised atmospheric data visualisation in geography classrooms within unique geographic settings like Madura Island.

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1. Introduction

Spatial thinking is a fundamental competency that characterizes the discipline of geography. The National Research Council (2006) defines spatial thinking as a cognitive construct involving concepts of space, representational tools, and reasoning processes. In the Indonesian context, high school students' geography skills, particularly spatial thinking abilities, remain at an alarming level. This is largely due to the predominance of conventional, teacher-centred instruction that fails to actively engage students in higher-order cognitive processes, which directly impacts their overall academic achievement in geography (Ridha et al., 2020). The urgency of mastering these skills is increasingly pressing in the context of global climate change, which demands that the younger generation be able to critically and analytically read and interpret atmospheric spatial data (Amin et al., 2020).

Empirical data indicate a concerning cognitive deficit; for instance, Burns and Davenport (2025) recorded a decline in the average Spatial Reasoning Test scores among novice learners, dropping from 8.00 to 7.22. The primary obstacle lies in the ability to isolate a target element from its visual background, with accuracy rates stagnating between 40% and 60%. Furthermore, McNeal et al. (2018) reported that 70.2% of students were unable to employ "mental animation" to project weather dynamics onto static maps, and only 56.8% successfully applied skills, a result attributed to superficial map-reading approaches. This significant empirical gap highlights an urgent need for targeted pedagogical interventions to equip the younger generation with the spatial capabilities required to critically interpret complex atmospheric data amidst global climate change.

This issue is particularly evident in the Atmospheric Dynamics curriculum, which covers abstract, invisible, and dynamic phenomena such as global wind circulation, air pressure gradients, and cloud formation. These conditions have led to low spatial reasoning skills among students, as evidenced by

difficulties in reading maps, analysing spatial patterns, and understanding the distribution of geographical phenomena (Silviariza et al., 2021). Unlike lithospheric objects that can be directly observed, understanding atmospheric phenomena requires the ability to visualise the movement of air masses in three-dimensional space and across regions. According to Sun et al. (2024), the inherently three-dimensional nature of the atmosphere requires spatial thinking skills to understand the relationships between location, direction, patterns, and the movement of occurring phenomena. Therefore, without adequate spatial visualisation support, students tend to experience high cognitive load, resulting in suboptimal conceptual understanding of atmospheric dynamics (Davenport & French, 2020).

To overcome students' limited spatial thinking abilities, a learning paradigm that actively involves students in addressing geographical issues is required. One applicable paradigm is problem-based learning (PBL), which uses actual challenges as the starting point for learning, motivating students to establish hypotheses, acquire information, evaluate data, and find answers autonomously (Kriel & van der Merwe, 2025; Wahelo et al., 2025). In geography education, this process directly trains spatial thinking skills because students are required to understand the relationships between locations, distribution patterns, and interactions among phenomena within a geographical space (Fadjarajani et al., 2024). Research by Putra et al. (2021) indicates that problem-based learning with a spatial approach is more effective in enhancing spatial thinking skills compared to conventional instruction. However, the effectiveness of PBL in Atmospheric Dynamics requires media support capable of visualising abstract and dynamic atmospheric phenomena.

One such medium, Ventusky, is a promising tool because it presents global weather data interactively and in real-time, including wind direction and speed, temperature, precipitation, cloud cover, and air pressure (Purnomo, 2025). Furthermore, the use of authentic geospatial data can strengthen geospatial literacy and enhance students' awareness of environmental conditions and issues in their surrounding areas (B. R. Firdaus, 2026). Through its streamlined animation feature, Ventusky can dynamically display the movement of air masses, making it easier to observe and analyse atmospheric phenomena that are not visible to the naked eye. Findings by Kim et al. (2025) also indicate that real-data-based atmospheric data visualisation can enhance spatial reasoning skills, as understanding atmospheric dynamics fundamentally requires spatial reasoning to analyse the patterns of processes and relationships between phenomena occurring in geographical space.

The conceptual framework of this study is constructed based on the intersection of spatial thinking skill development, problem-based learning, and dynamic geospatial visualisation. The study is grounded in spatial thinking skills comprising eight key indicators: comparison, aura, region, hierarchy, transition, analogy, pattern, and association (Lee & Bednarz, 2012). These indicators represent students' ability to compare characteristics across regions, understand the influence of one location on another, identify common characteristics of an area, understand spatial hierarchies, analyse spatial changes, find similarities in conditions across regions, recognise patterns of phenomenon distribution, and connect various phenomena that tend to occur simultaneously within a space (Bednarz & Lee, 2019; Bendl et al., 2025). The integration of Ventusky into the problem-based learning (PBL) framework is designed to facilitate the development of all these indicators through investigative activities on atmospheric phenomena based on spatial and contextual data.

Ventusky's layering feature allows students to observe the interrelationships among various atmospheric variables, such as sea surface temperature, monsoon wind direction, and rainfall distribution, thereby helping them identify patterns of phenomenon distribution and spatial relationships (Anuar & Ali, 2025). The presentation of historical and predictive data also provides students with the opportunity to compare atmospheric conditions across regions and over time while analysing the changes that occur. Atmospheric phenomena that were previously abstract are now easier to see and explain because of interactive representations, which help students strengthen their spatial thinking abilities. Haris et al. (2025) show that using atmospheric data visualisations can increase learner engagement while improving spatial comprehension of atmospheric events. These findings are consistent with previous research indicating that problem-based learning approaches and the usage of geospatial technologies help students acquire spatial thinking and geographic skills (Wijayanto et al., 2023). Furthermore, using real-time meteorological data in problem-solving exercises allows students to correlate geographic ideas with environmental circumstances they face on a daily basis (Meechandee & Meekaew, 2025).

Although various studies have demonstrated the effectiveness of problem-based learning models and geospatial technologies, a distinct research gap remains regarding the integration of dynamic meteorological platforms into geography education. Previous studies have predominantly relied on Google Earth, ArcGIS, or similar platforms, which are highly effective for analysing static lithospheric objects and mapping disaster mitigation (Bernhäuserová et al., 2022; Kholoshyn et al., 2025; Nirwansyah, 2022). However, these conventional GIS platforms lack the conceptual capacity to visualise continuous, fluid meteorological movements in real-time. Ventusky fills this gap by offering real-time atmospheric data, streamline visualisation, interactive meteorological layers, historical data tracking, and accurate weather forecasting features. Conceptually, Ventusky differs from traditional mapping tools because its specific alignment with Atmospheric Dynamics transforms abstract, invisible variables into observable and interactive spatial phenomena. Therefore, the explicit novelty of this study lies in testing the effectiveness of Ventusky-assisted problem-based learning to reduce spatial misconceptions and develop students' spatial thinking skills specifically in abstract atmospheric material.

The urgency of this study is heightened by the fact that it is being conducted on Madura Island, a coastal island region characterised by rich cultural diversity and unique environmental conditions, specifically in Sampang Regency, one of the regions in East Java that is highly vulnerable to drought (A. Firdaus et al., 2021; Masruroh et al., 2025). These conditions provide real-world problems closely tied to students' lives, making them a relevant context for problem-based learning. Using Ventusky, students can observe monsoon wind patterns, rainfall distribution, and the atmospheric characteristics affecting the Madura region. They can then analyse the spatial relationships between these phenomena. These activities have the potential to develop various indicators of spatial thinking skills, such as comparison, patterns, regions, hierarchy, transitions, analogies, and associations, in a contextual learning situation. Based on these considerations, this study aims to analyse the effect of the Ventusky-assisted PBL model on students' spatial thinking skills regarding Atmospheric Dynamics in geography instruction. It is hypothesised that the integration of Ventusky within the PBL framework will significantly improve students' spatial thinking skills compared to conventional teaching methods. Ultimately, this article contributes conceptually and practically by providing geography educators with a validated, technology-driven instructional framework to effectively teach abstract spatial phenomena.

2. Method

2.1 Research Design

This study took a quantitative approach, employing a quasi-experimental method with a posttest-only nonequivalent control group design (Krishnan, 2019; Sugiyono, 2013). The researcher adopted this strategy because the school had already established intact classes, making it impossible to adequately randomise the participants. Because a pretest was not administered, an initial test was conducted on students' previous midterm Geography scores. The homogeneity of variance test indicates that the data variance between the experimental and control groups is homogeneous ($p = .612$) prior to the intervention. While establishing initial homogeneity helps reduce baseline differences, the lack of a pretest on the primary spatial thinking construct limits the ability to track individual gains. Consequently, posttest differences should be interpreted with caution, as potential selection bias and unmeasured confounding variables inherent to nonequivalent quasi-experimental designs cannot be entirely ruled out.

The study divided participants into two groups: an experimental class that received instruction utilising the Ventusky-assisted problem-based learning (PBL) model, and a control class that received conventional instruction. The control class received conventional geography instruction characterised by teacher-centred lectures, textbook readings, and static printed weather maps, without access to digital geospatial tools or the Ventusky platform. Both groups covered identical core curriculum topics on Atmospheric Dynamics across two 90-minute instructional sessions (totalling 180 minutes). To minimise instructor bias, both classes were taught by the same geography teacher. Furthermore, to maintain treatment fidelity and prevent cross-group contamination, the Ventusky platform was utilised exclusively during experimental class hours, and control group students were limited to non-digital instructional materials. A schematic summary of the posttest-only nonequivalent control group research design is presented in Table 1.

Table 1. Posttest-Only Nonequivalent Control Group Research Design

Group	Treatment	Posttest
Experiment	X ¹	0
Control	X ²	0

Description:

Experiment: Learning using the problem-based learning (PBL) model assisted by Ventusky

Control: Learning using the conventional model.

X₁: Treatment using the PBL model assisted by Ventusky

X₂: Treatment using the conventional model

0: Spatial thinking ability test

2.2 Time and Location of the Study

This study was conducted during the even semester of the 2025–2026 academic year at SMAN 2 Sampang, East Java, Indonesia. SMAN 2 Sampang was selected based on objective geographic and instructional criteria. As shown in Figure 1, Sampang Regency is situated in an arid coastal region of Madura Island bordering the Madura Strait. The school's proximity to the coastal area provides an authentic, real-world context directly suited for studying Atmospheric Dynamics, particularly coastal weather phenomena, monsoon wind variations, and local microclimates. Additionally, the school possessed adequate digital infrastructure (Wi-Fi and student devices) necessary for interactive web-based mapping. To the authors' knowledge, limited empirical research has evaluated the integration of dynamic visualisation platforms, such as Ventusky, within high school geography instruction in this specific regional context.

The study was conducted over three sessions, each allocated 2 × 45 min. The first and second sessions were used for learning activities, while the third session was used to administer a posttest of spatial thinking skills.

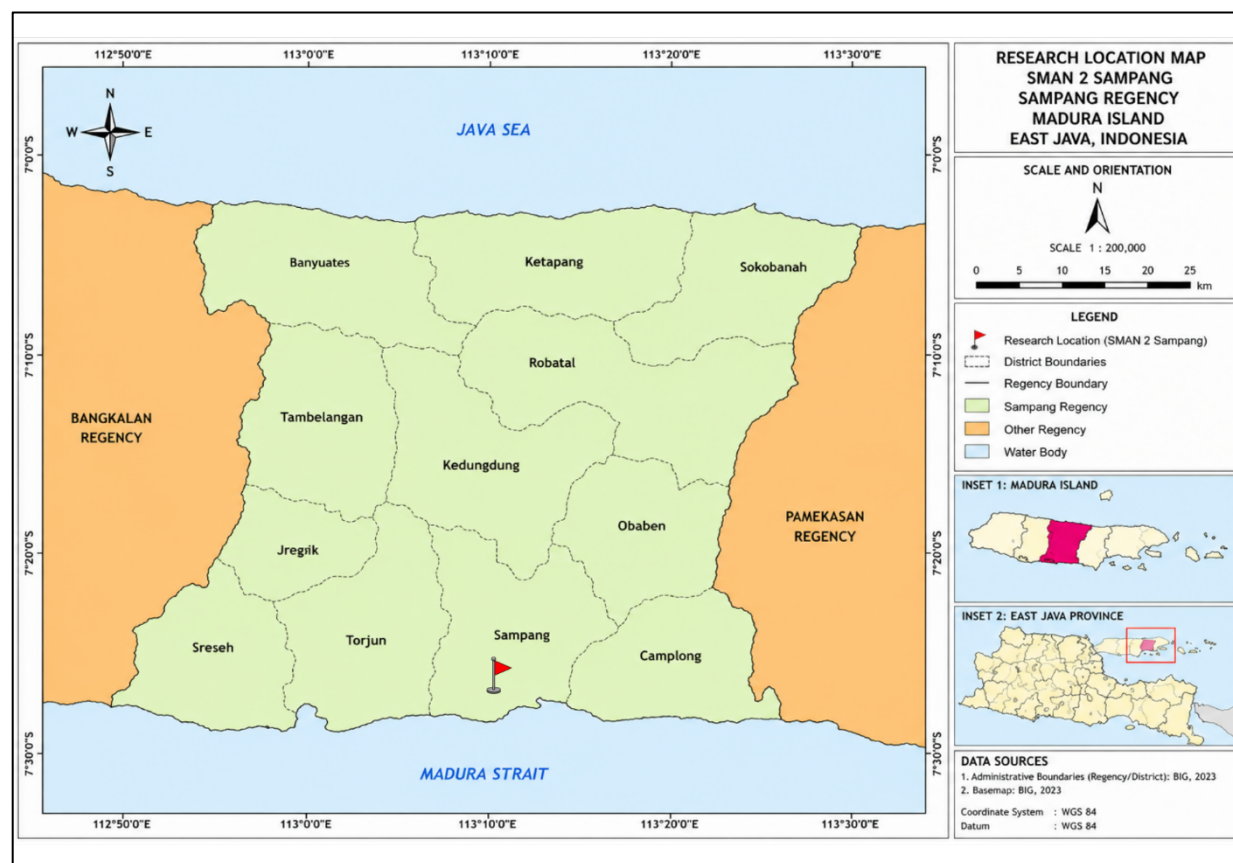


Figure 1. Research location map

2.3 Research Subjects

The research subjects were 10th-grade students at SMAN 2 Sampang. The sample was determined using a purposive sampling technique, selecting classes taught by the same geography teacher to minimise instructor bias. To justify the sample size adequacy and address the methodological limitations of using intact classes, a sensitivity power analysis was conducted prior to data collection using G*Power 3.1.9.7. For a two-tailed independent-samples t-test with $\alpha = .05$, statistical power ($1 - \beta$) = .80, and an allocation ratio of $N1/N2 = 1.0$ ($N = 72$ total; 36 students per group), the analysis indicated that the sample size was sufficient to detect a medium-to-large effect size of Cohen's $d \geq 0.67$. This statistical justification should nevertheless be interpreted alongside the intact-class design and single-school setting, which are common administrative constraints in educational research (Creswell & Creswell, 2017; Shadish et al., 2002). Methodologically, the posttest-only nonequivalent control group design is appropriate when random assignment is impractical but requires cautious interpretation of causal claims (Krishnan, 2019). Prior to data collection, formal institutional permission was granted by the school administration. Informed consent was obtained after a comprehensive briefing was provided to teachers and students before the study commenced. Participation was entirely voluntary, and participants were explicitly informed of their right to withdraw from the research at any stage without any penalty or adverse consequences. Participants had broadly similar demographic characteristics and were drawn from local coastal areas of Madura. The study involved 72 students, with 36 students in Class X-1 designated as the experimental group (Ventusky-assisted PBL) and 36 students in Class X-2 designated as the control group (conventional instruction). The designation of Class X-1 as the experimental group and Class X-2 as the control group was established prior to the intervention through a simple cluster-level random assignment between the two intact classes. Meanwhile, Class X-3, consisting of 23 students, was used to conduct validity and reliability tests on the research instruments.

2.4 Experimental Procedure

Learning activities in the experimental class followed the problem-based learning syntax, which was systematically structured and allocated across two 90-minute meetings (totalling 180 minutes). The explicit time allocation and student activities for each phase of the PBL cycle are detailed as follows: (1) Orienting students to the problem (allocated 20 minutes in Meeting 1): Students were presented with a contextual atmospheric problem regarding the recurrent severe droughts and shifting monsoon wind patterns affecting agriculture in Sampang Regency, stimulating initial spatial thinking questions. (2) Organising students for learning (allocated 20 minutes in Meeting 1): Students were divided into heterogeneous groups of 4–5 to formulate specific, localised investigative questions and outline their enquiry. (3) Guiding individual and group investigations (allocated 75 minutes total; 50 minutes in Meeting 1 and 25 minutes in Meeting 2): During this core phase, groups utilised Ventusky via their smartphones or laptops. They specifically activated the 'Temperature', 'Wind' (at 10 m and 850 hPa), and 'Precipitation' layers to observe historical and real-time air mass movements over Madura Island, compiling spatial and temporal atmospheric data. (4) Developing and presenting work products (allocated 45 minutes in Meeting 2): Each group spent 20 minutes synthesising their spatial data findings into a digital geographic report and a simple spatial pattern map, followed by 25 minutes of class presentations where groups shared their models and solutions. (5) Analysing and evaluating the problem-solving process (allocated 20 minutes in Meeting 2): The teacher facilitated a comprehensive reflection and evaluation session to solidify key spatial concepts (such as spatial hierarchy and transition), assess group solutions, and connect Madura's localised microclimates to global atmospheric trends. A summary of the timeline, activities, and media integration for each PBL phase is provided in Table 2.

Table 2. Detailed Time Allocation and Media Integration for the Ventusky-Assisted PBL Syntax

Meeting	PBL Phase & Duration	Key Learning Activities	Ventusky Integration & Media
Meeting 1 (90 min)	Phase 1: Orienting students to the problem (20 minutes)	Students are presented with a real-world, contextual geographic problem about recurrent severe droughts and changing monsoon wind patterns in Sampang Regency. Students raise initial questions.	Static introductory weather maps and slideshows.
	Phase 2: Organising students for learning (20 minutes)	Students form heterogeneous groups of 4–5. The teacher guides them to narrow down the problem, distribute team roles, and plan their investigation focus.	Digital worksheet (LKPD) outlining spatial analysis steps.
	Phase 3: Guiding investigations (Part A) (50 minutes)	Groups conduct active inquiries on localized temperature variations and wind directions. They collect initial spatial data on atmospheric variables over Madura.	Ventusky platform: Web/app access to Temperature, Wind, and Precipitation layers.
Meeting 2 (90 min)	Phase 3: Guiding investigations (Part B) (25 minutes)	Groups finalise their atmospheric data collection. They observe seasonal trends and transition patterns using historical wind and rainfall data.	Ventusky platform: Interactive time slider and layered meteorological variables.
	Phase 4: Developing and presenting work products (45 minutes)	Groups compile their spatial data findings into a digital geographic report and simple spatial pattern map (20 min). They present their reports to the class for peer evaluation (25 min).	Report templates, simple map plotting tools, or digital presentation slides.
	Phase 5: Analysing and evaluating the problem-solving process (20 minutes)	Teacher facilitates a reflection session. Students evaluate their proposed solutions, correct misconceptions, and synthesize spatial concepts (hierarchy, pattern, association).	Interactive whiteboard; Ventusky platform used for teacher explanation.

2.5 Research Instruments

The spatial thinking instrument was created using eight indicators: comparison, aura, region, hierarchy, transition, analogy, pattern, and association, adapted from the spatial thinking framework proposed by Lee and Bednarz (2012). Prior to empirical testing, the instrument underwent a content validation process involving expert judgement by a single validator, a professional lecturer with expertise in the fields of atmospheric science and atmospheric dynamics. This validation assessed the appropriateness of the content and concepts, the relevance of the geographical context, and the alignment of each test item with the specific spatial thinking indicators being measured. Based on the validator's assessment and verbal feedback, revisions were made to the instrument, particularly regarding content clarity, the accuracy of atmospheric concepts, and the alignment of the question contexts with the targeted indicators. As the validation process involved only one expert, the assessment could not be compared with that of other evaluators, and inter-rater reliability was not calculated. This stage of validation aimed to establish evidence of the instrument's content validity based on the professional judgement of a subject-matter expert before the instrument was used in empirical testing.

The instrument blueprint detailed eight indicators into eight corresponding essay items, with a maximum total score of 32. Each item presents a brief contextual problem based on atmospheric phenomena in the Madura region, requiring students to apply both spatial and critical thinking skills. A standardised analytical scoring rubric was utilised, grading responses from 0 (incorrect/no response) to 4 (comprehensive spatial analysis) per item. To allow for standardised reporting, students' raw scores (ranging from 0 to 32) were converted to a 0–100 scale using a linear conversion formula:

$$\text{Final Score} = \frac{\text{Total Raw Score}}{32} \times 100$$

Rounded to two decimal places and applied identically across both groups. To minimise evaluator subjectivity during essay scoring, a single researcher evaluated all posttest responses strictly guided by the pre-established analytical rubric. Scoring consistency was controlled through a blind-scoring

procedure (concealing student identities and group designations) and an intra-rater reliability check on a random 20% subset of responses. However, because a second independent evaluator was not utilised, inter-rater reliability was not calculated, which is a methodological limitation acknowledged in this study.

The instrument was subsequently tested empirically on 23 students from Class X-3 who were not included in the research sample. Item validity was analysed using Pearson's product-moment correlation. All eight items yielded calculated r -values exceeding the critical value of .413; consequently, all items met the validity criteria and were retained. The instrument's internal reliability was analysed using Cronbach's Alpha, yielding a coefficient of .768, which indicates adequate internal consistency. All posttest responses were then scored by the researcher using a predetermined analytic scoring rubric. Inter-rater reliability was not calculated because the scoring was performed by a single rater, and no independent assessment from a second rater was available. This condition is acknowledged as a research limitation, particularly given that rubric-based scoring of essay responses still allows for evaluator subjectivity. A summary of the instrument blueprint and its item validity is presented in Table 3.

Table 3. Blueprint and Item Validity Results of the Spatial Thinking Instrument

Item No.	Spatial Indicator	Brief Problem Context	$r_{\text{calculated}}$	r_{critical}	Decision
1	Comparison	Comparing temperature and topographical effects between coastal Madura and mountainous Malang.	.554	.413	Valid
2	Aura	Interpreting the inland reach and limit of sea breezes on humidity in Sampang.	.741	.413	Valid
3	Region	Evaluating drought vulnerability across Madura's districts based on rainfall data.	.606	.413	Valid
4	Hierarchy	Inferring the dominant influence of global, regional, and local winds on dry weather.	.647	.413	Valid
5	Transition	Explaining sudden weather changes (wind, rain, temperature) during the transition season.	.668	.413	Valid
6	Analogy	Identifying climatic similarities between Madura and other arid regions in Indonesia.	.632	.413	Valid
7	Pattern	Analysing the spatial distribution pattern of rainfall from southern mountains to northern coasts.	.701	.413	Valid
8	Association	Associating low topography, high temperature, and low rainfall with severe drought risks.	.439	.413	Valid

Note. Maximum score per item = 4. Total maximum score = 32. Cronbach's alpha = .768.

2.6 Data Analysis

Data were analysed using SPSS version 25. The students' spatial thinking abilities were presented using descriptive statistics, which included the mean, standard deviation, minimum, and maximum values. Prior to hypothesis testing, preparatory tests such as normality and homogeneity were conducted. Because the sample size in each group was less than 50 students, the normality test was performed using the Shapiro-Wilk procedure. Data were considered normally distributed if the p -value was greater than 0.05. Levene's test was used to conduct the homogeneity test, and the data were considered homogeneous if the significance value exceeded 0.05.

Because the research design involved comparing the means of two independent and unrelated groups (experimental and control), the independent-samples t -test was used to evaluate data that met normality and homogeneity assumptions, with a 5% significance level ($\alpha = 0.05$). To provide greater statistical transparency, exact p -values are reported (e.g., $p < .001$ rather than 0.000), alongside 95% confidence intervals (CI) for the mean differences. Decisions were made by comparing the significance score to the selected error threshold. To improve the interpretation of the hypothesis testing results, an effect size analysis was performed using Cohen's d . The effect size was calculated by dividing the mean difference between the two groups by their pooled standard deviation to estimate the magnitude of the effect of the problem-based learning model supplemented by Ventusky media on students' spatial thinking abilities.

3. Results and Discussion

3.1 Results

3.1.1 Description of Spatial Thinking Skills Data

Spatial thinking skills data were obtained through tests administered to students after the learning process in the experimental class using the Ventusky-assisted problem-based learning (PBL) model and the control class using conventional learning. The test was designed to measure students' ability to analyse spatial patterns, relationships, and geographic phenomena. The results provide an overview of the effectiveness of the learning interventions in developing students' spatial thinking skills. The descriptive statistics for students' spatial thinking skills are presented in Table 4.

Table 4. Descriptive Statistics of Students' Spatial Thinking Skills

Class	N	Mean	Median	Standard Deviation	Minimum	Maximum
Experimental	36	84.61	84.00	7.817	66	100
Control	36	72.33	72.00	10.040	50	91

The control group received conventional instruction. According to Table 4, the average spatial thinking capacity of students in the experimental class was 84.61, whereas that of students in the control class was 72.33. These findings show that the average spatial thinking capacity of students in the experimental class was greater than that of the control class. The 12.28-point difference in mean scores suggests that the incorporation of Ventusky into the learning process provided students with greater opportunities to observe, understand, and analyse atmospheric events geographically. Students could detect spatial patterns, investigate relationships between geographic phenomena, and analyse atmospheric conditions across different locations by visualising real-time geospatial data. This interactive learning environment allowed students to relate theoretical concepts to real-world conditions, ultimately supporting the development of spatial thinking and decision-making abilities. Furthermore, the incorporation of Ventusky helped students develop a deeper understanding of spatial interrelationships and geographic processes, both of which are important components of spatial reasoning. Consequently, students in the experimental class demonstrated a greater capacity to assess and solve spatially oriented problems than those in the control class who received conventional instruction without the use of geospatial technology.

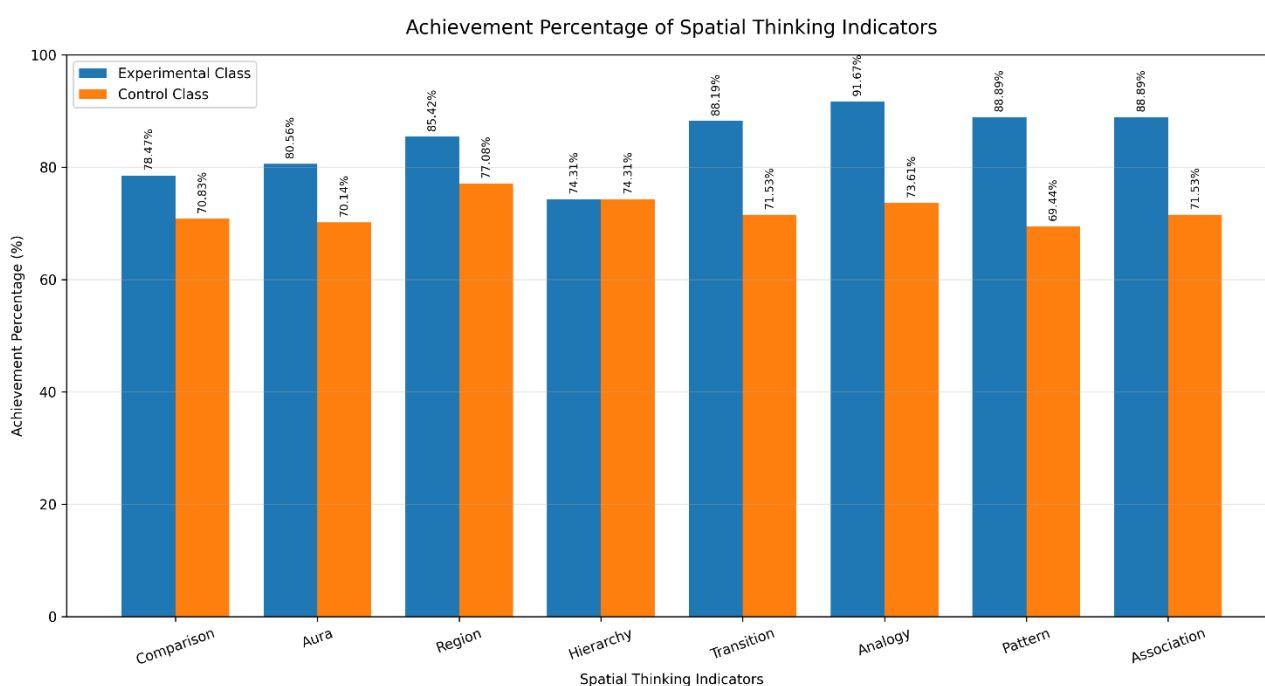


Figure 3. Achievement Percentage of Spatial Thinking Indicators.

The descriptive achievement percentages across all eight spatial thinking indicators for both the experimental and control groups are visually illustrated in [Figure 3](#). The experimental group consistently demonstrated higher descriptive performance across nearly all indicators, exhibiting particularly strong advantages in spatial Analogy, Pattern recognition, Association, and temporal Transition relative to the control group. In contrast, both groups displayed virtually identical descriptive performance on the Hierarchy indicator, which represented the lowest achievement mark for the experimental class.

However, to statistically differentiate simple descriptive gains from true inferential differences, Welch's t-tests with Holm-adjusted p-values were performed. As detailed in [Table 5](#), after applying Holm's adjustment for multiple comparisons, statistically significant differences between the two groups were confirmed for only four indicators: Transition ($p = .047$, $d = 0.63$), Analogy ($p = .009$, $d = 0.81$), Pattern ($p = .020$, $d = 0.73$), and Association ($p = .036$, $d = 0.67$). In contrast, the posttest differences for Comparison, Aura, Region, and Hierarchy were not statistically significant ($p > .05$). These results indicate that while Ventusky's dynamic visualisation layers substantially strengthened students' capabilities in temporal transitions, spatial analogies, pattern recognition, and intervariable associations, visualisation alone was insufficient to produce statistically detectable improvements in spatial hierarchy, regional classification, or basic spatial comparisons without additional explicit instructional scaffolding.

Table 5. Between-Group Differences in Spatial Thinking Indicators

Indicator	Exp. M (SD)	Ctrl. M (SD)	Mean diff.	t	df	p (Holm)	d	Result
Comparison	3.14 (1.05)	2.83 (1.16)	0.31	1.17	69.28	.489	0.28	Not Significant
Aura	3.22 (0.87)	2.81 (1.24)	0.42	1.66	62.62	.412	0.39	Not Significant
Region	3.42 (0.97)	3.08 (0.97)	0.33	1.46	70.00	.445	0.34	Not Significant
Hierarchy	2.97 (1.16)	2.97 (1.16)	0.00	0.00	70.00	1.000	0.00	Not Significant
Transition	3.53 (0.74)	2.86 (1.29)	0.67	2.69	55.60	.047	0.63	Significant (Medium-to-Large)
Analogy	3.67 (0.59)	2.94 (1.12)	0.72	3.43	52.81	.009	0.81	Significant (Large Effect)
Pattern	3.56 (0.91)	2.78 (1.20)	0.78	3.10	65.25	.020	0.73	Significant (Medium-to-Large)
Association	3.56 (0.91)	2.86 (1.15)	0.69	2.84	66.44	.036	0.67	Significant (Medium-to-Large)

The indicator-level findings suggest that Ventusky particularly supported students in developing aspects of spatial thinking related to Analogy, Pattern, Transition, and Association. Its interactive thematic layers and dynamic visualisation enabled students to compare atmospheric conditions across locations, recognise spatial patterns, observe temporal changes, and relate multiple meteorological variables within a geographical context. These features made abstract atmospheric processes more visible and helped students connect different spatial and temporal information during analysis. In

contrast, the Hierarchy indicator was less responsive to the use of Ventusky alone. Although the platform provides zooming, temporal controls, and multiple meteorological layers, interpreting relationships across different spatial scales from broader atmospheric systems to local weather phenomena requires students to integrate information across scales rather than simply observe individual visualisations. This suggests that the use of Ventusky for developing hierarchical spatial reasoning may benefit from more explicit guidance and scaffolding during learning.

3.1.2 Prerequisite Test Analysis

The Shapiro-Wilk test was used to test for normality because the sample size for each group was less than 50 students. Data were considered normally distributed if the significance value (p-value) was greater than 0.05.

Table 6. Results of the Normality Test of Spatial Thinking Ability

Group	Shapiro-Wilk	df	Sig.
Experimental	0,978	36	0,668
Control	0,951	36	0,113

Table 6 shows that the significance value (Sig.) for the experimental group is 0.668 and for the control group is 0.113. According to the test criteria, the data are normally distributed if the significance value is greater than 0.05. The significance value for the experimental class is $0.668 > 0.05$, and the significance value for the control class is $0.113 > 0.05$. Thus, it can be concluded that the spatial reasoning ability data for both groups are normally distributed. These results indicate that the normality assumption has been met, so the analysis can proceed to the homogeneity test stage as one of the requirements for using parametric tests.

The homogeneity test was conducted using Levene's test to determine the equality of variance between the experimental and control groups.

Table 7. Results of the Homogeneity of Variance Test

Variable	Levene Statistic	df1	df2	Sig.
Spatial Thinking	1,566	1	70	0,215

Based on the homogeneity test results in Table 7, a p-value of 0.215 was obtained. Data are considered homogeneous if the significance value is greater than 0.05. A significance value of $0.215 > 0.05$ indicates that the variance of spatial thinking ability data in the experimental and control classes is homogeneous. Thus, the homogeneity assumption was met, allowing the analysis to proceed using the independent-samples t-test.

3.1.3 Hypothesis Test Result

Hypothesis testing was conducted using an independent-samples t-test to determine the difference in spatial thinking skills between students taught using Ventusky-assisted problem-based learning and those taught using conventional methods.

Table 8. Results of the independent-samples t-test on Spatial Thinking Skills

Variable	t	df	p	Mean Difference	95% CI Lower	95% CI Upper
Spatial Thinking Skills	5.790	70	< .001	12.28	8.05	16.51

Hypothesis testing was conducted using an independent-samples t-test to determine the difference in spatial thinking skills between students taught using Ventusky-assisted problem-based learning and those taught using conventional methods. Table 8 shows a p-value of $< .001$, indicating high statistical significance and aligning with the reporting protocol described in the Methods section. These findings show that there is a substantial difference in spatial thinking skills between students in the experimental and control groups. Therefore, the null hypothesis was rejected, providing support for the alternative hypothesis. The mean difference of 12.278 (95% confidence interval [CI]: 8.05 to 16.51) suggests that students who received Ventusky-assisted problem-based learning had superior spatial thinking skills compared with those who received conventional instruction. The interval does not contain zero, further confirming the robust effect of the intervention.

3.1.4 Effect Size

In addition to testing statistical significance, this study also calculated the magnitude of the treatment effect using Cohen's *d*.

Table 9. Effect Size Calculation Results

Statistics	Value
Cohen's <i>d</i>	1.37
Category	Very Large

In addition to testing statistical significance via the independent-samples *t*-test, the magnitude of the difference between the two instructional approaches was quantified using Cohen's *d*, as presented in Table 9. The computation yields a Cohen's *d* value of 1.37, which falls into the "very large" category (Sawilowsky, 2009). This result suggests that Ventusky-assisted problem-based learning produced a large standardised difference in students' spatial thinking skills.

This finding suggests that the observed difference is not only statistically significant but also has substantial practical significance for geography education. The large effect size indicates that the use of Ventusky as a tool for visualising atmospheric phenomena helps students understand the spatial relationships among atmospheric phenomena more deeply than conventional teaching methods.

3.2 Discussion

3.2.1 The Effect of Ventusky-Assisted PBL on Students' Spatial Skills

The indicator-level findings suggest that Ventusky particularly supported spatial thinking processes involving spatial analogy, pattern recognition, temporal transition, and intervariable association. Its interactive thematic layers and dynamic visualisation allow students to move beyond merely observing atmospheric phenomena toward identifying spatial distribution patterns, analysing temporal weather shifts, and correlating multiple meteorological variables across space and time. Conversely, basic spatial comparison did not show statistically significant differences, indicating that simple comparative tasks were already accessible through conventional media. These findings align with recent research emphasising that dynamic geospatial technologies most effectively enhance complex spatial reasoning when embedded within appropriate inquiry-oriented pedagogical processes (Erdem et al., 2026; Mašterová, 2023). Similarly, recent reviews indicate that geospatial technologies can strengthen spatial thinking, enquiry, and problem-solving when their use is pedagogically structured rather than treated merely as a technological addition (Bondarenko, 2025). However, the weaker development of hierarchical spatial reasoning suggests that visualisation alone may not be sufficient for students to integrate atmospheric processes across scales. This finding is consistent with recent work describing geographical thinking as a complex cognitive process that requires students to connect and interpret spatial relationships rather than simply recognise geographic information (Sinton, 2023).

Theoretically, a PBL model utilising geospatial technology forces learners to identify problems, analyse empirical data, and formulate evidence-based solutions, which trains multiple dimensions of spatial thinking (Nisa et al., 2021). Ventusky facilitates these cognitive mechanisms directly through its interactive features. For instance, the platform's animated wind streamlines and colour-coded temperature layers support the pattern and association indicators by allowing students to visually correlate low topography, high temperatures, and low rainfall specific to the Madurese climate. Furthermore, the temporal slider feature enables students to track sudden weather shifts, facilitating the transition indicator. Although the platform's zooming capabilities—from global atmospheric circulation to local sea breezes in Sampang—offer a theoretical framework for representing spatial hierarchy, the empirical findings reveal that visual interaction alone did not yield statistically significant gains in this dimension. This indicates that transitioning across spatial scales involves higher-order cognitive abstractions that cannot be developed through raw visualisation alone, but rather require explicit teacher scaffolding and structured enquiry prompts. These mechanisms align with Fadjarajani et al. (2024), who assert that problem-solving within PBL builds a cognitive vision of spatial interconnections within a geographic area.

Nevertheless, the improvement in spatial thinking skills observed in this study cannot be separated from the role of Ventusky as a geospatial technology that supports students' knowledge construction. Ventusky presents real-time meteorological data in the form of interactive maps, allowing students to

observe wind patterns, temperature distributions, precipitation, air pressure, and weather dynamics both spatially and temporally. Unlike conventional media, which tend to be static, Ventusky's interactive visualisations allow students to understand the relationships between atmospheric phenomena more concretely. This aligns with the findings of prior studies, which indicate that direct interaction with atmospheric visualisation platforms can enhance student engagement and understanding. Additionally, the use of real-world data in Ventusky enables students to analyse atmospheric phenomena within authentic and meaningful contexts. Sun et al. (2024) explain that weather data visualisation based on actual data is effective in developing spatial thinking skills because students are required to identify patterns, processes, and relationships between phenomena within a geographical space. Through the layering feature, students can integrate various atmospheric variables simultaneously, enabling them to compare conditions across regions, recognise patterns, and analyse complex spatial relationships. Thus, Ventusky functions not only as a visualisation tool but also as a tool for spatial thinking that supports the development of more in-depth spatial analysis skills.

The results of this study also reinforce the findings of Zain et al. (2025) and Purba et al. (2025), who stated that the integration of geospatial technology in learning can enhance students' spatial thinking skills. However, unlike previous studies that generally utilised Google Earth or ArcGIS for topics such as the lithosphere, land use, and disasters, this study integrates Ventusky as a real-time data-based meteorological platform for the topic of Atmospheric Dynamics. Ventusky's features, including streamlines, multi-layer atmospheric displays, and historical and predictive data, align with Purwanto et al.'s (2025) perspective that developing spatial thinking skills requires technology that enables students to actively interact with spatial data. From a novelty standpoint, this study shows that combining PBL with Ventusky can make geography learning more contextual and data-driven while supporting the development of 21st-century geospatial competencies. Furthermore, the use of eight spatial thinking indicators provides a more comprehensive assessment, while the Sampang Regency context enables students to relate atmospheric principles to real-world phenomena they encounter. These findings confirm that problem-based learning is more successful when supported by realistic situations that are closely matched with students' experiences (Mike et al., 2026).

Overall, the results show that advances in students' spatial thinking skills are attributable not only to the implementation of problem-based learning (PBL) but also to the use of Ventusky, a geospatial technology that enables students to interact directly with real atmospheric data. The combination of both creates a contextual, problem-based, and data-driven learning environment, enabling students not only to understand the concepts of Atmospheric Dynamics theoretically but also to identify patterns, analyse relationships between phenomena, and develop spatial reasoning based on real-world atmospheric conditions (de Miguel González et al., 2019). These findings confirm that the integration of innovative learning models with interactive geospatial technology has the potential to be an effective strategy for developing students' spatial thinking skills while supporting geography learning relevant to 21st-century competency demands. Furthermore, this study demonstrates that selecting geospatial technologies appropriate to the subject matter and students' environmental conditions can make learning more contextual, strengthen spatial literacy, and enhance students' sensitivity to local environmental dynamics and issues. Ventusky is well suited to examining atmospheric phenomena in Madura, a relatively hot and dry region.

3.2.2 Ventusky's Potential as a Geography Learning Medium for Atmospheric Dynamics

In addition to enhancing spatial thinking skills, this study demonstrates that Ventusky has broader pedagogical potential as a geospatial technology in geography education. Ventusky presents real-time meteorological data from various global weather models in the form of interactive visualisations that are easily accessible to students without requiring specialised technical skills. These characteristics support the development of geo-literacy, the ability to read, interpret, and analyse geospatial information as a critical 21st-century competency (Buasuwan et al., 2022). This finding aligns with Meechandee and Meekaew (2025), who demonstrated that the use of geospatial platforms based on real-world phenomena can enhance students' geo-literacy and learning engagement. In this study, visualisations of atmospheric conditions in the Madura region and Sampang Regency allow students to connect the concept of Atmospheric Dynamics with phenomena they experience firsthand, thereby making learning more contextual and meaningful (Susilawati & Hamisi, 2025).

The indicator-level findings show that the intervention was more strongly associated with several dimensions of spatial thinking, particularly Transition, Analogy, Pattern, and Association, whereas Comparison, Aura, Region, and Hierarchy did not show detectable between-group differences. This pattern suggests that Ventusky may be particularly supportive of spatial reasoning processes that require students to connect information across locations, time, and atmospheric variables. Its interactive maps, thematic layering, and historical and predictive data allow students to compare regional conditions, recognise spatial patterns, observe temporal changes, and relate multiple meteorological variables within a geographic context. These activities can support spatial thinking processes such as association and pattern recognition, consistent with Jo and Hong-Dwyer (2024), while the integration of spatial, temporal, and thematic information reflects the characteristics of effective geospatial technology as described by Kerski (2023).

The stronger performance in Analogy may be related to opportunities to compare climatic characteristics across regions, while Pattern and Transition can be supported by observing the distribution and temporal changes of rainfall, temperature, and wind. Similarly, the Association indicator may benefit from examining multiple atmospheric variables simultaneously. Recent empirical research by Lailissa'adah et al. (2025) also demonstrated the potential of Ventusky to support secondary students' interpretation of dynamic hydrometeorological phenomena. However, the absence of a detectable difference in Hierarchy suggests that visualisation alone may be insufficient for integrating atmospheric processes across spatial scales. In this respect, the PBL framework provides an important pedagogical structure by guiding students to investigate, interpret, and discuss atmospheric data rather than using Ventusky merely as a visualisation tool. This is consistent with the argument that geospatial technologies require appropriate pedagogical support to facilitate meaningful learning (Mašterová, 2023). However, the effectiveness of geospatial technology is not automatic and still requires support from appropriate learning strategies (Mutia et al., 2023). Thus, this study extends emerging empirical applications of Ventusky by examining its integration with PBL to support students' spatial thinking in Atmospheric Dynamics.

3.2.3 Research Limitations

Although this study shows that Ventusky-assisted PBL improves students' spatial thinking skills, several limitations that pose potential threats to internal validity should be acknowledged. First, the study utilised a posttest-only nonequivalent control group design. Without a pretest, the study could not directly establish the baseline equivalence of students' initial spatial abilities or definitively measure individual cognitive gains. Second, the study was conducted at a single school with a small sample size; hence, generalising the results to a larger population should be approached cautiously, as varying school infrastructures and technological access may influence outcomes (Andrade, 2021). Additionally, the two relatively short instructional sessions (three sessions including the posttest) mean that the study captures only short-term effects and does not evaluate the longitudinal retention of spatial thinking skills (McLaughlin & Bailey, 2023).

Third, spatial thinking skills were assessed solely through essay tests; thus, the study did not fully capture the spatial thinking processes occurring during investigative activities. This study also did not consider other variables that could potentially influence learning effectiveness, such as digital literacy, learning motivation, and students' perceptions of using Ventusky (Mašterová, 2023). Furthermore, as a real-time data-driven platform, Ventusky requires a stable internet connection; thus, its implementation may face challenges in schools with limited technological infrastructure. Given these limitations, future research is recommended to involve a broader and more diverse sample, use a pretest-posttest or longitudinal design, combine various methods of assessing spatial thinking skills, and explore the factors influencing the effectiveness of integrating geospatial technology into geography learning. Finally, the researcher assessed essay responses using a standardised rubric. Although this procedure maintained internal consistency, the absence of inter-rater reliability testing introduces a potential source of scoring subjectivity.

4. Conclusion

This study demonstrates that high school students engaging with Ventusky-assisted problem-based learning (PBL) achieved significantly higher posttest spatial thinking performance than those receiving conventional instruction in Atmospheric Dynamics. Rather than a uniform improvement across all

dimensions, indicator-level analysis confirms that significant performance gains were specifically concentrated in spatial transition, analogy, pattern recognition, and association. Conversely, between-group differences for comparison, aura, region, and spatial hierarchy did not reach statistical significance, with spatial hierarchy representing the primary area where learners faced multi-scalar cognitive challenges. Theoretically, the key novelty of this study lies in showing that real-time meteorological visualisations can effectively scaffold problem-based enquiry by contextualising abstract atmospheric phenomena into observable spatial patterns, thereby selectively enhancing higher-order spatial reasoning.

Practically, given that these findings were derived from a single-school context over two instructional sessions (three sessions including the posttest), caution should be exercised when generalising these outcomes to broader populations. To optimise classroom implementation, geography educators must secure essential technical infrastructure, including stable internet connectivity and student device compatibility, while anchoring learning in contextualised, real-world atmospheric problems such as coastal drought dynamics in Madura. Furthermore, teachers should incorporate explicit, multi-scalar guided scaffolding to support complex spatial abstractions, particularly for indicators such as spatial hierarchy that do not improve through visual interaction alone.

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References

- Amin, S., Utaya, S., Bachri, S., Sumarmi, S., & Susilo, S. (2020). Effect of problem based learning on critical thinking skill and enviromental attitude. *Journal for the Education of Gifted Young Scientists*, 8(2), 743–755. <https://doi.org/10.17478/jegys.650344>
- Andrade, C. (2021). The limitations of quasi-experimental studies, and methods for data analysis when a quasi-experimental research design is unavoidable. *Indian Journal of Psychological Medicine*, 43(5), 451–452. <https://doi.org/10.1177/02537176211034707>
- Anuar, B. B., & Ali, A. B. (2025). Prediction of weather elements in southern region of Malaysia based on Navier-Stokes equation. *Proceedings of Science and Mathematics*, 31, 11–18. <https://science.utm.my/procscimath/2025-2/vol-31/>
- Bednarz, R., & Lee, J. (2019). What improves spatial thinking? Evidence from the Spatial Thinking Abilities Test. *International Research in Geographical and Environmental Education*, 28(4), 262–280. <https://doi.org/10.1080/10382046.2019.1626124>
- Bendl, T., Krajňáková, L., Marada, M., & Řezníčková, D. (2025). Geographical thinking in geography education: a systematic review. *International Research in Geographical and Environmental Education*, 34(4), 326–352. <https://doi.org/10.1080/10382046.2024.2354097>
- Bernhäuserová, V., Havelková, L., Hátlová, K., & Hanus, M. (2022). The limits of GIS implementation in education: A systematic review. *ISPRS International Journal of Geo-Information*, 11(12), 592. <https://doi.org/10.3390/ijgi11120592>
- Bondarenko, O. V. (2025). Teaching geography with GIS: a systematic review, 2010-2024. *Science Education Quarterly*, 2(1), 24–40. <https://doi.org/10.55056/seq.903>

- Buasuwana, P., Suebnusorn, W., Butkatunyoo, O., Manowalulou, N., Kaewchinda, M., Lalitpasan, U., Srilapo, N., Sarnswang, S., Suksiri, W., Wiboonuppatham, R., & Sripongpankul, S. (2022). Re-envisioning a "skills framework" to meet 21st century demands: What do young people need? *Frontiers in Education*, 7, 1004748. <https://doi.org/10.3389/feduc.2022.1004748>
- Burns, L. E., & Davenport, C. E. (2025). Characterizing the growth in spatial thinking skills in undergraduate meteorology students across the curriculum. *Bulletin of the American Meteorological Society*, 106(2), E275–E289. <https://doi.org/10.1175/BAMS-D-23-0324.1>
- Creswell, J. W., & Creswell, J. D. (2017). *Research design: Qualitative, quantitative, and mixed methods approaches*. Sage publications.
- Davenport, C. E., & French, A. J. (2020). The Fundamentals in Meteorology Inventory: Validation of a tool assessing basic meteorological conceptual understanding. *Journal of Geoscience Education*, 68(2), 152–167. <https://doi.org/10.1080/10899995.2019.1629193>
- De Miguel González, R., Donert, K., & Koutsopoulos, K. (Eds.). (2019). *Geospatial technologies in geography education*. Springer. <https://doi.org/10.1007/978-3-030-17783-6>
- Erdem, C., Kaya, M., Tunç Toptaş, H., & Altunbaşak, İ. (2026). Problem-based learning and student outcomes in higher education: a second-order meta-analysis. *Studies in Higher Education*, 51(4), 950–971. <https://doi.org/10.1080/03075079.2025.2498084>
- Fadjarajani, S., As'ari, R., & Putri, A. E. (2024). Model of problem-based learning in geography: Focusing on societal dynamics to enhance spatial thinking skills. *E3S Web of Conferences*, 600, 02011. <https://doi.org/10.1051/e3sconf/202460002011>
- Firdaus, A., Harisuseno, D., & Suhartanto, E. (2021). Studi analisa kekeringan dengan metode Standardized Precipitation Index (SPI) dan Palmer Drought Severity Index (PDSI) di DAS Kemuning Kabupaten Sampang. *Jurnal Teknologi dan Rekayasa Sumber Daya Air*, 1(2), 535–548. <https://jtresda.ub.ac.id/index.php/jtresda/article/view/96>
- Firdaus, B. R. (2026). Why geoliteracy matters: Strengthening disaster response and sustainable development through spatial thinking. *IOP Conference Series: Earth and Environmental Science*, 1586(1), 012036. <https://doi.org/10.1088/1755-1315/1586/1/012036>
- Haris, Syamsunardi, Mannan, A., & Rasjusti, N. I. (2025). Improving spatial thinking skills through GEE-integrated STEM learning: A quasi-experimental study among geography undergraduates. *Information Technology Education Journal*, 4(3), 507–518. <https://doi.org/10.59562/intec.v4i3.10463>
- Jo, I., & Hong-Dwyer, J. J. (2024). GIS learning and college students' acquisition and understanding of spatial concepts. *Journal of Geography in Higher Education*, 48(5), 763–774. <https://doi.org/10.1080/03098265.2023.2263748>
- Kerski, J. J. (2023). Teaching and learning geography with a web GIS approach. In A. Klonari, M. L. y Torres, & A. Kizos (Eds.), *Re-visioning geography: Supporting the SDGs in the post-COVID era* (pp. 113–135). Springer International Publishing. https://doi.org/10.1007/978-3-031-40747-5_7
- Kholoshyn, I. V., Bondarenko, O. V., Hanchuk, O. V., Varfolomyeyeva, I. M., & Panteleeva, N. B. (2025). Geospatial data in school geography courses: Sources, methodological features of use and implementation challenges. *Journal of Physics: Conference Series*, 3105(1), 012016. <https://doi.org/10.1088/1742-6596/3105/1/012016>
- Kim, J., Wang, K., Miller, J., Dorneich, M. C., Winer, E., Brown, L., & Caldwell, B. (2025). Creating augmented reality-based experiences for aviation weather training: Challenges, opportunities, and design implications for 3D authoring. *Ergonomics*, 68(3), 374–390. <https://doi.org/10.1080/00140139.2024.2329696>
- Kriel, C., & van der Merwe, C. D. (2025). Teaching geographic information systems in South African geography classrooms, using problem-based learning. *South African Geographical Journal*, 107(4), 586–602. <https://doi.org/10.1080/03736245.2025.2472665>
- Krishnan, P. (2019). A review of the non-equivalent control group post-test-only design. *Nurse Researcher*, 26(2), 37–40. <https://doi.org/10.7748/nr.2018.e1582>
- Lailissa'adah, L., 'Urfan, F., & Rahmati, R. (2025). Ventusky's influence on hydrometeorological disaster preparedness, considering learning styles and gender. *Jurnal Pendidikan Ilmu Sosial*, 34(2), 244–255. <https://doi.org/10.17509/jpis.v34i2.88815>
- Lee, J., & Bednarz, R. (2012). Components of spatial thinking: Evidence from a Spatial Thinking Ability Test. *Journal of Geography*, 111(1), 15–26. <https://doi.org/10.1080/00221341.2011.583262>
- Masruroh, U., Kriswahyudi, Y., & Setiadi, A. (2025). Pertanian regeneratif di lahan kering Madura:

- Implementasi, dampak, dan potensi replikasi. *Blantika: Multidisciplinary Journal*, 3(10), 1521–1531. <https://doi.org/10.57096/blantika.v3i10.443>
- Mašterová, V. (2023). Learning and teaching through inquiry with geospatial technologies: a systematic review. *European Journal of Geography*, 14(3), 42–54. <https://doi.org/10.48088/ejg.v.mas.14.3.042.054>
- McLaughlin, J. A., & Bailey, J. M. (2023). Students need more practice with spatial thinking in geoscience education: a systematic review of the literature. *Studies in Science Education*, 59(2), 147–204. <https://doi.org/10.1080/03057267.2022.2029305>
- McNeal, P., Ellis, T., & Petcovic, H. (2018). Investigating the foundations of spatial thinking in meteorology. *Journal of Geoscience Education*, 66(3), 246–257. <https://doi.org/10.1080/10899995.2018.1483119>
- Meechandee, S., & Meekaew, N. (2025). Integrating phenomenon-based learning and GIS to improve geo-literacy and student engagement: an action research approach. *Discover Education*, 4(1), 91. <https://doi.org/10.1007/s44217-025-00468-9>
- Mike, M., Bachri, S., Masruroh, H., Aliman, M., Wijayanto, B., Susetyo, B. B., & Khalidy, D. Al. (2026). Problem-based learning in geography education: The effect on spatial thinking and flood preparedness attitudes in senior high school student. *Jambura Geo Education Journal*, 7(1), 135–147. <https://doi.org/10.37905/jgej.v7i1.36032>
- Mutia, T., Rosyida, F., Alfyananda, P. K., Alfi, S., & Wulan, P. S. (2023). Media Google Earth dengan problem based learning berpengaruh terhadap kemampuan berpikir spasial siswa SMA. *GEOGRAPHY: Jurnal Kajian, Penelitian dan Pengembangan Pendidikan*, 11(2), 303. <https://doi.org/10.31764/geography.v11i2.16943>
- National Research Council. (2006). *Learning to think spatially: GIS as a support system in the K–12 curriculum*. The National Academies Press. <https://doi.org/10.17226/11019>
- Nirwansyah, A. W. (2022). Challenges in GIS practice in geography teacher training during COVID 19 pandemic: Students' perspective from private Islamic university in Indonesia. *Jurnal Pendidikan Geografi*, 27(2), 126–136. <https://doi.org/10.17977/um017v27i22022p126-136>
- Nisa, K., Soekamto, H., Wagistina, S., & Suharto, Y. (2021). Model pembelajaran EarthComm pada mata pelajaran geografi: Pengaruhnya terhadap kemampuan berpikir spasial siswa SMA. *Jurnal Ilmiah Pendidikan Profesi Guru*, 4(3), 500–510. <https://doi.org/10.23887/jippg.v4i3.40031>
- Purba, C. T., Purwanto, P., & Wijiyono, W. (2025). Implementasi pembelajaran geografi berbasis teknologi melalui pembuatan peta digital dengan Microsoft Excel untuk meningkatkan kemampuan berpikir spasial siswa kelas X SMA Negeri 1 Gondanglegi. *GEOGRAPHY: Jurnal Kajian, Penelitian Dan Pengembangan Pendidikan*, 13(1), 74. <https://doi.org/10.31764/geography.v13i1.29010>
- Purnomo, D. (2025). Peningkatan aktivitas dan hasil belajar geografi melalui pemanfaatan informasi geospasial berbasis aplikasi Ventusky. *Education Transformation: Jurnal Ilmiah Insan Pendidikan*, 3(2). <https://jurnal.bbgktjateng.org/index.php/edutrans/article/view/366>
- Purwanto, P., Utomo, D. H., Wiwoho, B. S., Susanto, A., Elvada, E., Purba, C. T., Zain, M. W. K., Maghfiroh, A., & Mellyana, I. M. (2025). GeoTPACK (geographical technology, pedagogical, and content knowledge) strategi meningkatkan keterampilan geografi berkelanjutan. *Jurnal Pendidikan Geografi Undiksha*, 13(1), 87–96. <https://doi.org/10.23887/jjppg.v13i1.85878>
- Putra, A. K., Sumarmi, S., Deffinika, I., & Islam, M. N. (2021). The effect of blended project-based learning with STEM approach to spatial thinking ability and geographic skill. *International Journal of Instruction*, 14(3), 685–704. <https://doi.org/10.29333/iji.2021.14340a>
- Ridha, S., Putri, E., Kamil, P. A., Utaya, S., Bachri, S., & Handoyo, B. (2020). The importance of designing GIS learning material based on spatial thinking. *IOP Conference Series: Earth and Environmental Science*, 485(1), 012027. <https://doi.org/10.1088/1755-1315/485/1/012027>
- Sawilowsky, S. S. (2009). New effect size rules of thumb. *Journal of Modern Applied Statistical Methods*, 8(2), 597–599. <https://doi.org/10.22237/jmasm/1257035100>
- Shadish, W. R., Cook, T. D., & Campbell, D. T. (2002). *Experimental and quasi-experimental designs for generalized causal inference*. Houghton Mifflin.
- Silviariza, W. Y., Sumarmi, S., & Handoyo, B. (2021). Improving critical thinking skills of geography students with spatial-problem based learning (SPBL). *International Journal of Instruction*, 14(3), 133–152. <https://doi.org/10.29333/iji.2021.1438a>
- Sinton, D. (2023). GIS, geospatial technology, and spatial thinking in geography education. In B. Warf

- (Ed.), *Oxford bibliographies in geography*. Oxford University Press.
<https://doi.org/10.1093/obo/9780199874002-0276>
- Sugiyono. (2013). *Metode penelitian pendidikan: Pendekatan kuantitatif, kualitatif, dan R&D*. Alfabeta.
- Sun, Y., Dyer, J., & Harris, J. (2024). Preparing teachers for teaching spatial computational thinking with Integrated Data Viewer visualization of weather data: A discipline-based perspective of computational thinking. *Journal of Educational Computing Research*, 62(4), 841–866.
<https://doi.org/10.1177/07356331241226746>
- Susilawati, S. A., & Hamisi, S. H. (2025). Integrating technology in Grade 10 geography: Enhancing basic concepts with geographic information systems. *Assyfa Learning Journal*, 3(1), 69–84.
<https://doi.org/10.61650/alj.v3i1.621>
- Wahelo, T. T., Mengistu, D. A., & Merawi, T. M. (2025). Geography teachers' implementation of problem-based learning for deforestation and climate change education in Metekel Zone Secondary Schools, Northwest, Ethiopia. *International Journal of Educational Development*, 117, 103314.
<https://doi.org/10.1016/j.ijedudev.2025.103314>
- Wijayanto, B., Sumarmi, S., Hari Utomo, D., Handoyo, B., & Aliman, M. (2023). Problem-based learning using e-module: Does it effect on student's high order thinking and learning interest in studying geography? *Journal of Technology and Science Education*, 13(3), 613.
<https://doi.org/10.3926/jotse.1965>
- Zain, M. W. K., Purwanto, P., & Wijiyono, W. (2025). Penerapan Geomedia untuk meningkatkan kemampuan berfikir spasial siswa di SMAN 1 Gondanglegi. *GEOGRAPHY: Jurnal Kajian, Penelitian Dan Pengembangan Pendidikan*, 13(1), 61. <https://doi.org/10.31764/geography.v13i1.29005>