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The Impact of Weather on Counter-UAS DTII: Effects on Detection and Effectiveness

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Abstract

The paper examines how meteorological conditions affect all components of the DTII chain (Detection–Tracking–Identification–Incapacitation) in counter-UAS operations and tests whether the Russian Armed Forces deliberately time mass Shahed strikes to exploit favorable atmospheric phenomena. The review section summarizes the weather vulnerabilities of radar, EO/IR, acoustic, and RF sensing, highlighting near-surface temperature inversions and radar ducting (range extension/radar "holes," increased false echoes, EO/IR degradation, and relatively improved acoustic propagation). The research section performs a hindcast analysis of strikes on Ukraine from August 1, 2024 to September 15, 2025 (strike counts from official Ukrainian releases/Telegram; weather from ICON and ERA-5 reanalyzes). "Salient strikes" are defined as episodes exceeding at least twice the monthly mean number of UAS. Over that period, 44,390 UAS were launched and 26,701 neutralized (~60%). Of 158 strikes with >100 UAS, 78% occurred under inversion; all 39 strikes with >200 UAS took place during inversion conditions. From February 2025 onward, the correlation is unambiguous: inversion days represent roughly half of the calendar but account for 76% of all launched UAS (February to September). City-level results show that 25/26 (96%) of Kyiv's largest strikes, 14/15 (93%) in Odesa, and 8/8 (100%) in Lviv coincided with inversions. We infer systematic Russian selection of "inversion windows," even though reported Ukrainian C-UAS effectiveness (~60%) does not markedly drop on those days. We recommend multi-sensor fusion, operational "risk-window" forecasting, and institutionalizing an "owning-the-weather" approach in C-UAS planning, alongside continued validation of system thresholds and methods.

Keywords: meteorology, reconnaissance, safety, UAV

1. Introduction

Dwight D. Eisenhower once remarked that the success of the D-Day landings was achieved thanks to "better meteorologists than the Germans had" (NASA Earth Observatory, 2025). Although more than eighty years have passed since that event, his observation remains valid. Accurate weather forecasting continues to be essential for securing and supporting military operations. Less well-known research into atmospheric turbulence drives the development of military laser systems, which are crucial for countering emerging threats from unmanned aerial systems (UAS).

Despite technological advances, many military operations remain weather-dependent, and recent conflicts suggest this dependence may even be increasing. The ability of armed forces to understand, forecast, and mitigate weather effects – especially in air and missile defense – has become a crucial factor in the age of mass UAS deployment.

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Within the Polish Armed Forces and NATO, meteorological data are typically used for operational planning and training simulations. However, years of conflicts in which NATO maintained technological superiority have reduced the perceived need to integrate weather intelligence into reconnaissance and decision-making. Consequently, meteorological analysis has gradually faded from doctrine and operational awareness.

Given rising global tensions and the growing parity between major military powers, meteorological information should again be treated as a vital component of military intelligence. The author argues that renewed focus and academic study are needed to reintegrate weather awareness into military science.

Accordingly, this study analyzes the meteorological conditions accompanying Shahed UAS attacks to identify potential weather-related patterns influencing operational intensity or vulnerability. The working hypothesis assumes that meteorological factors affect detection, tracking, identification, and neutralization (DTII) systems, suggesting that weather may correlate with Russian operational behavior.

The enduring influence of weather in warfare – recognized since Eisenhower's D-Day forecasts – remains evident today. As modern battlefields rely increasingly on sensors, communication networks, and autonomous platforms, precise meteorological insight becomes not just tactically useful but strategically essential.

2. Operational context

Meteorological conditions constrain the employment of many types of offensive and defensive weapons, with operations in the air domain being particularly sensitive to weather. The recent large-scale introduction of a new class of platforms operating in this domain – small, often very low-flying unmanned aerial systems (UAS) – has forced a search for effective countermeasures and defenses. This development represents a renewed blade-and-shield dynamic, but unlike classical armor-versus-projectile problems, the contemporary challenge lies in detecting and countering relatively small, low-altitude UAS that pose detection and engagement problems even for the world's most advanced militaries – a fact underscored by numerous U.S. and NATO analyses.

An additional complication for detection, tracking, identification, and neutralization (DTII) systems is the meteorological environment in which operations occur. Although manufacturers frequently emphasize the influence of certain meteorological parameters on the performance of sensor and effectors, the precise nature and magnitude of these effects are not comprehensively described in the open literature. This study first aims to present the principal methods of detection, tracking, identification, and neutralization, along with their meteorological limitations, and then to analyze operations in Ukraine to provide evidence that the Armed Forces of the Russian Federation exploited weather conditions when conducting UAS attacks. The purpose of this article is to initiate an empirical research program and a broader discussion of the operational significance of meteorological conditions for counter-UAS efforts and the tactical role of specific systems in the attack concepts employed by the Armed Forces of the Russian Federation.

3. Methodology

The methodological approach of this study comprises two complementary parts. The first part is a focused literature and technical specification review intended to synthesize the principal methods for detection, tracking, identification, and neutralization (DTII) of unmanned aerial systems (UAS). Open, publicly available information was collected from leading military and industry journals, defense-industry product specifications from NATO member-state suppliers, and reports published by relevant national and international institutions. Emphasis was placed on manufacturer-declared meteorological limitations for sensors and effectors and on documented counter-UAS (C-UAS) concepts observed in both NATO and non-NATO armed forces. Sources were identified through targeted queries in indexed journals and professional defense outlets; selection prioritized primary technical documentation, official institutional reports, and peer-reviewed analyses where available. Extracted claims about weather sensitivity were catalogued and compared across systems and modalities to produce a structured, comparative summary of declared meteorological vulnerabilities.

The second, empirical part of the study analyzes meteorological conditions associated with high-intensity UAS attacks attributed to the Armed Forces of the Russian Federation (AFRF) in Ukraine. Attack events were compiled from official publications of the Ukrainian Armed Forces and corroborating open-source reports disseminated on widely-used messaging platforms (Telegram channels operated by reputable institutions and correspondents). For the purposes of this analysis, "high-intensity" attacks were operationally defined as episodes in which the number of UAS employed exceeded twice the modal count observed in routine harassment strikes; such episodes were selected to focus on clearly distinguishable surges in operational tempo. Each candidate event was geolocated and time-stamped to the nearest available reporting precision, and events with clearly ambiguous timing or location were flagged and treated cautiously in subsequent analyses.

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Meteorological forcing for each event was reconstructed using archived reanalysis and operational model data. Hourly and sub-daily fields were obtained from ECMWF ERA5 reanalysis and the ICON model archives for the period from August 2024 through to September 15, 2025. Variables extracted included near-surface and low-level wind speed and direction, wind shear and low-level jet indicators, temperature and dew point (for relative humidity and fog potential), cloud base and total cloud cover, precipitation occurrence and intensity, boundary-layer height, and turbulence proxies (e.g., Richardson number or shear-based indices where available). Synoptic context was described using standard pressure-field composites, and mesoscale features relevant to UAS operations (temperature inversions, stable surface layers, frontal passages, and low cloud/fog regimes) were identified.

Analytical methods combined descriptive synoptic composites, event-based conditional sampling, and basic inferential statistics to test for associations between selected meteorological states and the occurrence of high-intensity UAS attacks. Composites of meteorological fields were produced for attack versus non-attack control days, and contingency-table analyses (χ^2 tests) and logistic regression models were used to evaluate the strength and significance of hypothesized relationships. Where sample sizes permitted, sensitivity analyses tested alternative thresholds for "high intensity" and alternative temporal windows around reported event times. All analyses explicitly accounted for uncertainty in event timing and location by propagating temporal/spatial windows through the compositing and statistical procedures.

Finally, the study acknowledges limitations inherent to open-source operational reporting and reanalysis/model resolutions. Telegram and other open channels can contain reporting delays, incomplete event metadata, or potential biases. As a result, official sources were cross-checked where possible and ambiguous events were excluded or treated separately. Reanalysis and model archives provide consistent meteorological fields but have finite spatial and temporal resolution that may underrepresent very shallow or highly localized phenomena (e.g., narrow fog banks, shallow temperature inversions). These limitations inform the interpretation of the results and the cautious framing of any causal claims. The primary intent is to establish initial empirical evidence and to propose hypotheses and methodologies for subsequent, more detailed investigation.

4. DTII

DTII (Detection, Tracking, Identification, and Incapacitation) defines the core functions of counter-UAS operations. Detection is the essential capability, enabling the discovery of a UAS within a designated airspace using radar, acoustic, optical, or radio-frequency methods – each with meteorological limitations that affect performance. Tracking maintains a continuous record of the UAS trajectory, providing real-time position data to support situational awareness and enable timely counteraction. Identification classifies detected UAS by model or distinctive features, allowing assessment of endurance, range, or operational intent. In some systems, analysis of command-and-control links provides metadata such as battery state, flight direction, and even the approximate operator location (Lee et al., 2022). Incapacitation involves kinetic or non-kinetic methods – such as jamming, interception, or cyber interference – applied after detection and identification to neutralize or disable the platform (Markarian & Staniforth, 2021; Michel, 2019).

In practice, detection, tracking, and identification functions are commonly integrated within a single sensor suite, while incapacitation is carried out by associated effectors. Counter-UAS systems can be categorized as: fixed ground systems for permanent sites, mobile systems mounted on vehicles, man-portable devices resembling rifles, UAS-mounted effectors, and swarm-based platforms operating cooperatively (Michel, 2019; Chiper et al., 2022).

The principal detection modalities include radar, acoustic, electro-optical/infrared, and radio-frequency sensors, often combined into hybrid configurations to enhance reliability and mitigate environmental constraints.

5. Weather Effects on Primary Detection Methods

Radar methods are highly sensitive to precipitation and atmospheric propagation conditions such as humidity, temperature inversions, and ducting. These factors can shorten detection range, distort altitude estimates, and increase false alarms. Heavy rain or wet snow cause signal attenuation and clutter, while inversions and ducting may refract radar beams, producing under- or over-detection.

Acoustic methods are degraded by wind, rain, and background noise, which mask or scatter sound waves. However, calm, humid nights with surface inversions enhance detection by improving sound propagation and reducing ambient interference.

Radio-frequency (RF) methods are the least weather-sensitive. Their performance is mainly influenced by refraction effects (inversions, ducting) and, at frequencies above 10 GHz, by attenuation due to rain or moisture. In most conditions, these impacts are minor compared with radar or optical limitations.

Electro-optical (EO) and infrared (IR) methods are the most weather-dependent. EO sensors are impaired by low light, cloud, haze, fog, smoke, or rain, while IR performance declines with high humidity, fog, or warm backgrounds that reduce thermal contrast. Consequently, EO/IR sensors are usually integrated into multi-sensor architectures rather than used alone.

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Table 1. An analysis of the influence of selected meteorological factors on UAS detection systems

PARAMETER / DETECTION METHOD	RADAR	ACOUSTIC	RADIO	EO AND IR
ILLUMINATION	no influence	no influence	no influence	negative influence
CLOUD COVER	indirect influence	no influence	no influence	negative influence
FOG AND HAZE	indirect influence	positive influence	no influence	negative influence
PRECIPITATION	negative influence	negative influence	negative influence	negative influence
HUMIDITY	negative influence	positive influence	no influence	negative influence
TEMPERATURE	indirect influence	no influence	no influence	negative influence
TEMPERATURE INVERSIONS	negative influence	positive influence	negative influence	no influence
STRONG WIND	no influence	negative influence	no influence	no influence

Source: the authors' own work.

The analysis indicates that meteorological factors that degrade radar and EO/IR performance often have the opposite effect on acoustic detection systems. Conditions such as fog, low clouds, and temperature inversions, which attenuate or scatter electromagnetic and optical signals, tend to enhance the propagation of sound waves and thereby improve acoustic detection range and reliability.

Preliminary observations also highlight the influence of cloud cover, fog, temperature inversions, and humidity on radar performance. These phenomena are typically associated with high-pressure (anticyclonic) conditions characterized by atmospheric stability, increased humidity in the lower troposphere, and frequent shallow inversions that can cause anomalous propagation effects such as subrefraction or ducting. Conversely, extensive cloudiness, precipitation, and strong winds – conditions generally linked with low-pressure (cyclonic) systems – can lead to increased radar clutter and signal attenuation, as well as reduced visibility and thermal contrast for EO/IR systems.

6. The Impact of Meteorological Conditions on the Operations of the Armed Forces of the Russian Federation (AFRF)

The primary assumption of this study is that the Armed Forces of the Russian Federation (AFRF) use forecast meteorological information over target areas to select the timing and location of attacks to exploit adverse weather conditions that degrade UAS detection systems. To test this hypothesis, we performed a retrospective analysis of meteorological conditions at attack locations and then collated these meteorological data with quantitative measures of strike magnitude and air-defense effectiveness reported by the Armed Forces of Ukraine.

By way of background, a quantitative review of daily UAS strike waves over Ukraine shows a dramatic increase in the number of platforms employed. Prior to August 25, 2024, no single strike wave exceeded 100 UAS daily. By August 6, 2025, that threshold had been surpassed – one wave employed more than 800 platforms – and by the later period, approximately every second wave exceeded 100 UAS. Such a rapid escalation in UAS employment (and likely production) presents a significant challenge for detection and defeat systems. Given the observed change in attack intensity and the greater variability of strike sizes, this study restricts its event sample to attacks occurring between August 2024 and September 15, 2025. Major strikes were operationally defined as episodes in which the number of UAS employed exceeded twice the monthly mean number of platforms used in attacks for that month.

According to reports published by the Armed Forces of Ukraine, between August 1, 2024 and September 15, 2025 a total of 44,390 Shahed-136/131 unmanned aerial systems (UAS) were launched against targets in Ukraine. During the same period, 26,701 of these UAS were reported as shot down or otherwise neutralized, corresponding to an interdiction effectiveness of 60%.

Because this study seeks to examine the influence of meteorological conditions on the scale of AFRF employment, the first analytical step was to pair counts of launched UAS with the prevailing pressure regime at the attacked location. To identify the dominant synoptic regime, hourly sea-level pressure (SLP) fields from the ECMWF ERA5 reanalysis were inspected for each event location and time. Events were then classified into two categories on the basis of the dominant SLP value: "low-pressure" episodes when the prevailing SLP was < 1015 hPa, and "high-pressure" episodes when the prevailing SLP was > 1015 hPa.

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During the preliminary stage of analysis, it was observed that all high-intensity attack episodes corresponded to periods dominated by high-pressure systems. Based on this finding, it was hypothesized that specific meteorological parameters commonly associated with anticyclonic conditions – namely fog and haze, cloud cover, and temperature inversions – may have been intentionally exploited in operational planning. Consequently, a detailed examination of the occurrence and frequency of these three parameters was conducted for the entire study period. The comprehensive analysis indicates that the only consistently recurring element across all examined events is the presence of temperature inversions in the lower atmosphere. Therefore, the subsequent sections of this article focus specifically on the influence of atmospheric inversions, excluding secondary phenomena typically associated with them – such as low cloud bases, haze, and fog.

7. Influence of Temperature Inversions and Ducting on Radar Detection

Given the finding that lower-atmosphere temperature inversions are the principal exploited phenomenon, it is necessary to examine more closely how inversions affect radar beam propagation. Below, the inversion and the related phenomenon of ducting are described, followed by their operational implications for counter-UAS radar performance.

Temperature inversion. In a standard tropospheric profile, temperature decreases with altitude (International Organization for Standardization, 1975). Under a temperature inversion, however, a layer exists in which temperature increases with height (Kaczorowska, 1986). A surface (near-ground) inversion occurs when this phenomenon is present within the mixing layer (typically up to ~1,500 m); for the purposes of this study, we limit discussion to inversions reaching no higher than about the 950 hPa level (approximately 400–500 m). Inversions alter the refractivity gradient of the lower atmosphere and thereby change the curvature of electromagnetic rays. In practice, this can bend radar rays toward the surface, which, on the one hand, may extend radar ranges well beyond the geometric horizon, and, on the other, can produce false echoes (ghost targets) when energy scatters from the ground and returns to the antenna. From a counter-UAS perspective, these conditions can allow detection of distant objects at ranges beyond normal while simultaneously producing large numbers of false alarms from remote objects or ground clutter – an outcome that degrades overall detection performance (Skolnik, 1990).

Radar ducting. Ducting is an extreme form of refractive trapping. When a strong vertical gradient of temperature and humidity forms near the surface (for example under a pronounced inversion), radar energy can become confined within that layer and propagate as in a guided mode or duct (Banafaa & Muqaibel, 2025). The review of radar ducting in this study produced several operationally relevant observations:

- Effects on range and coverage. Ducting can significantly extend radar detection range because guided signals travel far beyond standard model predictions. At the same time, ducting can create localized "radar holes" or shadowed sectors where the direct radar signal does not penetrate, rendering targets within those holes effectively invisible to the radar. The latter effect – an extended interval during which a low-flying UAS flying inside a radar hole may remain undetected – is especially important for counter-UAS operations.
- False returns and misinterpretation. Energy trapped in ducts and reflected from the surface can generate spurious returns and produce errors in estimated range or angle of arrival (AoA). Radars may thus display apparent objects where none exist, or report incorrect bearing/elevation, complicating operator interpretation and automated tracking.
- Frequency dependence. The effective thickness of a ducting layer influences which frequencies are trapped: thicker ducts can guide lower-frequency energy (hundreds of MHz), whereas thinner ducts preferentially affect higher bands (GHz). Systems operating in roughly the 1–30 GHz range are therefore particularly susceptible to ducting effects.
- Radio-link extension. Ducting also favors extended RF reach between a UAS and its ground controller. In practice, the same refractive conditions that disrupt radar geometry can permit command-and-control links to operate at greater range than under standard propagation.

Operationally, the concurrence of these two refractive effects creates a coupled advantage for an attacker using small UAS. Ducting and surface inversions can both (a) reduce effective detection, tracking, and localization performance for defenders and (b) extend the controllable range of the UAS, enabling mission execution at distances that would otherwise be impractical. In the context of the Ukraine conflict, such regimes could be exploited to extend the effective management range for UAS directed toward western Ukraine, to increase UAS survivability by keeping platforms in radar shadow zones, and to complicate attribution and engagement decisions for defender forces.

These physical mechanisms do not guarantee success for attackers – local duct geometry, temporal variability, and the heterogeneity of sensor networks all modulate effects – but they do present a plausible, meteorologically grounded pathway by which operators can selectively reduce defender DTII effectiveness while maintaining or extending UAS operational reach.

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8. An analysis of the period from August 1, 2024 to September 15, 2025, aimed at determining the meteorological conditions associated with the operational activity of the Armed Forces of the Russian Federation (AFRF)

Between August 2024 and September 2025, the Armed Forces of the Russian Federation (AFRF) conducted 158 attacks involving more than 100 unmanned aerial systems (UAS), 14 attacks involving over 200 UAS, 9 attacks involving more than 300, 8 attacks involving over 400, and 8 attacks in which more than 500 UAS were employed. The progressive increase in AFRF operational engagement throughout the conflict is illustrated in the accompanying figure.

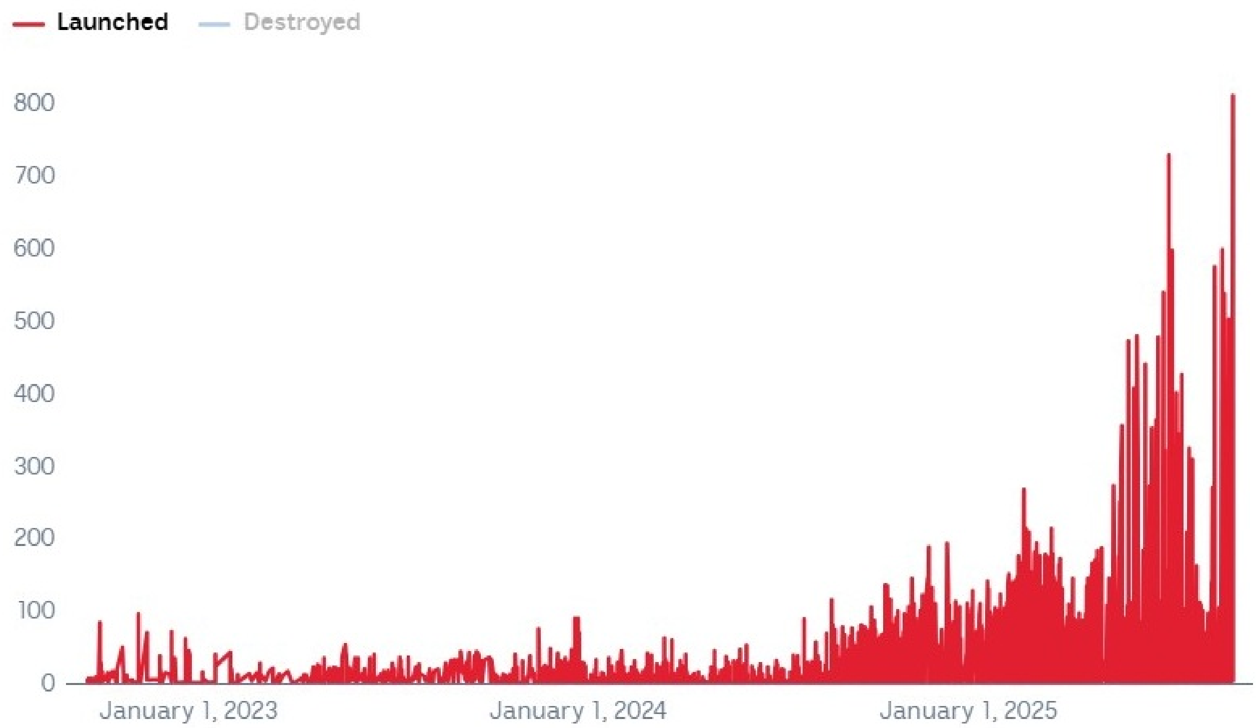

Figure 1. Increase in the number of unmanned aerial systems (UAS) attacking Ukraine between 2022 and 2025. Adopted from: Center for Strategic and International Studies (CSIS), *Russian Firepower Strike Tracker: Analyzing Missile Attacks on Ukraine*. Copyright by Publisher.

Of the 158 attacks in which more than 100 unmanned aerial systems (UAS) were employed, 124 attacks (78%) occurred under inversion conditions. Furthermore, all 39 attacks involving more than 200 UAS were conducted during periods characterized by temperature inversions.

An analysis of the most significant events reveals a clear temporal relationship. Up to January 2025, identifying a consistent dependence between attack occurrence and meteorological conditions was difficult: among 16 attacks involving more than 100 UAS during this period, 7 occurred under inversion conditions, while 9 took place in the absence of inversions or other related phenomena. Beginning in February 2025, however, all major attacks took place under inversion conditions. It must be noted that the scaling up of UAS use by the Armed Forces of the Russian Federation (AFRF) may partially obscure the overall pattern.

Additionally, due to the regional approach applied in assessing inversion conditions – and in order to avoid classification errors near boundary situations and to focus on those scenarios where radar ducting was likely – it was assumed that an inversion occurred when the reanalysis data showed a temperature increase of at least 0.5°C within the SFC–975 hPa layer.

The subsequent analysis, therefore, focused on the period from February to September 2025, which exhibited both the highest AFRF UAS activity and the strongest correlation with the preliminary findings.

Table 2. Occurrence of Distinct UAS Attack Events and Presence of Temperature Inversions (Aug 2024–Sep 2025)

Month	Number of Distinct Events	Inversion Occurrence
Aug 2024	6	6 / 6
Sep 2024	6	4 / 6
Oct 2024	4	2 / 4
Nov 2024	4	1 / 4
Dec 2024	5	2 / 5
Jan 2025	3	1 / 3
Feb 2025	3	3 / 3
Mar 2025	7	7 / 7
Apr 2025	6	6 / 6
May 2025	5	5 / 5
Jun 2025	7	7 / 7
Jul 2025	6	6 / 6
Aug 2025	4	4 / 4
Sep 2025	3	11 / 3

Source: the authors' own work.

a. Major Strikes on Selected Ukrainian Cities

Twenty-five out of twenty-six (96%) of the largest attacks on Kiev were conducted under inversion conditions. Fourteen out of fifteen (93%) attacks on Odessa were conducted under inversion conditions.

Eight out of eight (100%) attacks on Lviv occurred under high-pressure conditions accompanied by temperature inversions.

b. Analysis for the period February–September 2025

Events with a temperature inversion at the primary strike location occurred on just over half of the days in the study window (118 of 228 days). However, those 118 inversion days accounted for 25,233 of the 33,484 UAS employed during the period – approximately 76% of all UAS used between February and September 2025.

Air-defense effectiveness during inversion days was essentially in line with the period average: overall interdiction success for the full period was 60%, and the reported success rate during inversion conditions was approximately 61% (Ukrainian Armed Forces data). Statistical analysis revealed no robust difference in air-defense effectiveness between inversion and non-inversion situations. Nevertheless, the marked tendency since February 2025 to concentrate large-scale attacks under surface inversion regimes suggests that the Armed Forces of the Russian Federation regard these conditions as operationally favorable for massed UAS strikes.

City-level analyses support the inference that meteorological conditions were used in target selection – likely because inversions and related refractive regimes can extend command-and-control range or alter the local probability of successful engagement – thereby influencing route planning and target choice.

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7. Conclusions

Throughout January 2025, no consistent correlation was observed between UAS strike activity and large-scale weather conditions. However, from February 2025 onward, the link became clear: the Armed Forces of the Russian Federation (AFRF) systematically exploited surface temperature inversions when conducting massed UAS attacks. This suggests a deliberate use of meteorological conditions to degrade enemy detection capabilities. The lack of an observable reduction in air-defense success during inversion events may indicate either operational advantages not reflected in available data or inaccuracies in reported defeat rates. Nonetheless, the persistence of this pattern implies that AFRF considers such conditions tactically beneficial. Identifying the adversary's preferred weather conditions allows forecasting of periods and regions with elevated strike risk. A test forecast for September 15–21, 2025 identified 19–21 September as the most favorable window, with southeastern and northwestern Ukraine showing inversion layers exceeding 5 °C. Consistent with this prediction, on the night of September 19–20, AFRF launched a major strike using 579 Shahed-class UAS against southeastern Ukraine.

These findings demonstrate that retrospective meteorological analysis can reveal adversary behavioral patterns, supporting the concept of owning the weather. While this method has inherent uncertainty, regular updates can significantly improve counter-UAS planning and situational awareness. Temperature inversions likely reduce radar effectiveness by bending beams and creating shadow zones, allowing low-altitude UAS to evade detection. Although such conditions can enhance acoustic sensing, AFRF operational choices prioritize radar and EO/IR degradation over potential acoustic exposure. This highlights the importance of a multi-sensor detection architecture, combining radar, acoustic, RF, and EO/IR systems to offset meteorological weaknesses.

Integrating weather intelligence into operational planning enables pre-positioning of counter-UAS assets along the most probable attack routes. In conditions of mass UAS use and limited defensive resources, meteorological forecasting supports an economy-of-force approach, focusing protection where conditions favor enemy operations. Continued monitoring of this correlation will allow prediction of likely attack directions and more efficient allocation of mobile interception units.

The analysis indicates that elevated UAS activity correlates with anticyclonic, inversion-dominated conditions. Further studies should explore the influence of weather on other weapon systems, especially during precipitation, fog, or low cloud bases, which may further degrade radar performance. The results, based on ERA5 and ICON reanalysis data, underline the need for deeper investigation in three areas:

1. Quantifying meteorological impacts on specific AFRF systems and sensors, identifying mitigation techniques.
2. Continuously tracking AFRF operational patterns to validate and update findings.
3. Institutionalizing meteorological intelligence as a permanent component of reconnaissance and defense planning.

Future research should also examine how weather analysis can reveal probable launch zones, approach corridors, and strike axes, enabling better deployment of mobile defenses and optimized sensor use under adverse conditions.

Finally, adopting the "owning the weather" concept – understanding, anticipating, and exploiting meteorological effects on both friendly and adversary capabilities – can transform weather from a limiting factor into an operational force multiplier, allowing commanders to seize or deny weather-driven tactical advantages.

Declaration of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

References

1. Banafaa, M., & Muqaibel, A. H. (2025). Tropospheric ducting: A comprehensive review and machine learning-based classification advancements. *IEEE Access*, 13, 22510–22545. https://doi.org/10.1109/ACCESS.2025.3537160
2. Chaari, M. Z. (2021). High power microwave for knocking out programmable suicide drones. *Security and Defence Quarterly*, *34*(2), pp. 68–84. https://securityanddefence.pl/pdf-135068-66456?filename=66456.pdf
3. Chen, Y., Li, Z., Li, L., Ma, S., Zhang, F., & Fan, C. (2022). An anti-drone device based on capture technology. *Biomimetic Intelligence and Robotics*, *2*(3), Article 100060. https://doi.org/10.1016/j.birob.2022.100060
4. Chiper, F.-L., Martian, A., Vladeanu, C., Marghescu, I., Craciunescu, R., & Fratu, O. (2022). Drone detection and defense systems: Survey and a software-defined radio-based solution. *Sensors*, 22, 1453. https://doi.org/10.3390/s22041453
5. International Organization for Standardization. (1975). *ISO 2533:1975 Standard atmosphere*. Geneva, Switzerland: Author.
6. Kaczorowska, Z. (1986). *Pogoda i klimat*, 2nd ed. Warszawa, Poland: Wydawnictwo Szkolne i Pedagogiczne. ISBN 83-02-02688-3
7. Kang, H., Joung, J., Kim, J., Kang, J., & Cho, Y. S. (2020). Protect your sky: A survey of counter unmanned aerial vehicle systems. *IEEE Access*, 8, 168671–168710. DOI:10.1109/ACCESS.2020.3023473
8. Lee, C. H., Thiessen, C., Van Bossuyt, D. L., & Hale, B. (2022). A systems analysis of energy usage and effectiveness of a counter-unmanned aerial system using a cyber-attack approach. *Drones*, 6, 198. https://doi.org/10.3390/drones6080198

Safety & Defense 11(2) (2025)
DOI https://doi.org/10.37105/sd.272

9. Manke, G. C. (2011, July). *Lasers in electronic warfare. In Proceedings of CLEO: Laser Science and Photonic Applications*, pp. 1–4. IEEE. doi: 10.1364/CLEO_AT.2011.ATuF1
10. Markarian, G., & Staniforth, A. (2021). *Countermeasures for aerial drones*. Norwood, MA: Artech House. ISBN 978-1-63081-801-2
11. Michel, A. H. (2019). *Counter-drone systems*, 2nd ed. Annandale-on-Hudson, NY: Center for the Study of the Drone at Bard College. https://dronecenter.bard.edu/files/2019/12/CSD-CUAS-2nd-Edition-Web.pdf
12. NASA Earth Observatory. (2025, September 23). *Forecasting D-Day*. https://earthobservatory.nasa.gov/images/145143/forecasting-d-day
13. NQDefense. (2024, November 27). *Anti-drone: Drone spoofing and countermeasure*. https://www.nqdefense.com/anti-drone-drone-spoofing-and-countermeasure
14. Rozenbeek, D. J. (n.d.). *Evaluation of drone neutralization methods using radio jamming and spoofing techniques*. https://www.diva-portal.org/smash/get/diva2:1460807/FULLTEXT01.pdf
15. Skolnik, M. I. (1990). *Radar handbook*, 2nd ed. New York, NY: McGraw-Hill. ISBN 0-07-057913-X