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Building Meteorological Backup Artillery Products: Leveraging Upper Air Data

Tvorba záložních meteorologických produktů pro dělostřelectvo: Radiosondážní Měření

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Abstract: Accurate meteorological data is crucial for precise artillery fire, yet its availability can be compromised in combat conditions. This study investigates the impact of limited meteorological information on artillery accuracy and explores potential mitigation strategies. By analysing upper-air data from a single weather station, we simulated various scenarios of reduced meteorological support. Our findings highlight the significance of meteorological factors on artillery performance and the potential consequences of inadequate data. We developed a foundational framework for offline artillery support products, emphasizing the need for robust methods to estimate atmospheric conditions in data-scarce environments. Future research will focus on incorporating advanced modelling techniques and additional data sources to enhance the accuracy and applicability of these products.

Abstrakt: Pro přesnou dělostřeleckou palbu jsou klíčové meteorologické údaje, jejichž dostupnost však může být v bojových podmínkách omezena. Tato studie zkoumá vliv omezených možností v oblasti meteorologických informací na přesnost dělostřelecké palby a zkoumá možné strategie jejich zmírnění. Analýzou radiosondážních měření ve vyšších vrstvách atmosféry jsme simulovali různé scénáře omezené meteorologické podpory. Naše zjištění zdůrazňují význam meteorologických faktorů pro výkonnost dělostřelectva a potenciální důsledky nedostatečných údajů. Vyvinuli jsme základní rámec pro offline produkty dělostřelecké podpory a zdůraznili potřebu robustních metod pro odhad atmosférických podmínek v prostředí s nedostatkem dat. Budoucí výzkum se zaměří na začlenění pokročilých modelovacích technik a dalších zdrojů dat s cílem zvýšit přesnost a použitelnost těchto produktů.

Keywords: Artillery Meteorological Support; Fire Accuracy; METCM; Meteo-11; Upper-Air Sounding.

Klíčová slova: meteorologická podpora dělostřelectva; přesnost palby; METCM; Meteo-11; radiosondáž atmosféry.

INTRODUCTION

Artillery remains a critical component of modern warfare, providing decisive firepower in support of ground forces. Its role has evolved from a supporting element to a primary strike capability, as evidenced by its increasing prominence in contemporary conflicts (Maksymov, 2023). The integration of artillery with emerging technologies, such as unmanned systems, underscores its continued relevance in the evolving battlespace (Nordlöf, 2024).

To maximize artillery effectiveness, precise and timely fire is essential. Achieving this requires a deep understanding of the factors influencing projectile trajectory, including meteorological conditions. Research has demonstrated that incorporating meteorological data into firing data calculations can significantly enhance engagement accuracy (Bellucci, 1963; Zhang et al., 2019). Incorporating meteorological data through simulation calculations can significantly improve firing accuracy (Zhang et al., 2019). This approach is supported by Bellucci (1963), who compared errors in a target location with and without meteorological corrections, demonstrating a notable enhancement in the target location accuracy, particularly for the upwind targets.

On the other hand, with regard to technical developments of the modern artillery, the meteorological situation does not constitute an error in determining the coordinates of the target. Rather, it represents an error in the conditions for determining the elements for firing, where inaccurate elements will cause the target to be missed (Ivan et al., 2021).

Several studies (Bellucci, 1963; Khalil, 2021) suggest using a standard atmosphere model during artillery ballistic performance to address the spatial and temporal complexities of the meteorological conditions (Khalil, 2021). Understanding the mathematical model describing projectile motion and meteorological conditions during flight is crucial for preparing firing tables for spin-stabilized artillery projectiles, as emphasized in NATO standardization documents (NATO, 2018). Additionally, Hou et al. (2022) discuss the design of an operational application system for the cruise missiles supported by the meteorological and marine information, showcasing the expanding role of the meteorological support in the battlefield environment (Hou et al., 2022).

In terms of artillery system design, Mao & Xu (2023) stress the importance of optimizing structural parameters of the upper carriage to withstand the impact loads accurately (Mao & Xu, 2023). Kim & Park (2020) performed numerical simulations to evaluate protection levels for artillery positions under explosion scenarios, underscoring the significance of considering meteorological factors for safety and effectiveness in the artillery deployments (Kim & Park, 2020). Advanced technologies such as meteorological radars can offer real-time data on precipitation events and convective cell structures, providing additional data for artillery operations (Capozzi et al., 2022). Additionally, leveraging high-resolution urban observation networks, as proposed by Park et al. (2016, 2017), can further enhance meteorological information services tailored to specific user needs, including those in the artillery domain.

1. To what extent can the ground-level meteorological measurements be used to accurately predict atmospheric conditions at the altitude relevant to the artillery fire?
2. How does the accuracy of the developed model influence artillery fire outcomes in terms of the shell impact?
3. Can the proposed method enhance artillery effectiveness in various operational environments, including those with the limited meteorological resources?

By improving the understanding of the atmospheric data influences on the artillery fire, this research aims to enhance the effectiveness and precision of artillery systems, especially in environments with limited meteorological support. To achieve this, we propose a theoretical and technical framework for retrieving atmospheric parameters aloft, combined with the integration of meteorological data and standard artillery reports. This study is directly focused on the effect on artillery fire.

While previous studies have explored the impact of atmospheric conditions on artillery fire, there is a limited understanding of how to effectively predict and account for these factors in real-time operational environments. By addressing this gap, this research develops operational products to enhance lethality and survivability in diverse operational environments with limited meteorological support.

The paper is structured as follows. First, we introduce the artillery and meteorological datasets, including data preprocessing and standardization. Next, we conduct an exploratory analysis to identify potential relationships and patterns. In Chapter 3, we develop and implement statistical models to predict atmospheric parameters at altitude based on ground-level measurements. The performance of these models is evaluated using appropriate metrics. Finally, we discuss the implications of our findings for artillery operations and propose directions for future research.

By providing a robust methodology and in-depth analysis, this study seeks to advance the understanding of atmospheric data influences on artillery fire and contribute to the development of improved artillery systems.

1 DATA AND METHODS

NATO has established a comprehensive framework for meteorological data exchange, specifically tailored for ballistic and special purposes:

1. STANAG 4103 outlines the format of meteorological messages,
2. STANAG 4061 defines the standard ballistic meteorological message.
3. STANAG 6022 standardizes gridded data meteorological messages to facilitate large-scale data.

However, the complexities of combat environments often present challenges that might exceed these standards. To address this, we identified various scenarios based on differing levels of data availability, ranging from complete data sets to prolonged periods without any data. Figure 1 illustrates these scenarios.

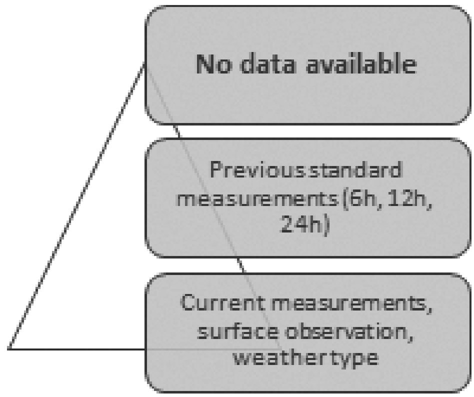


Figure 1: Outline of the research based on the data available from the most limited (top) to almost full availability (bottom). In this study, "No data available" solutions are proposed

In this paper, we have focused on the case where no data is available and how to deal with this situation. For the model case we chose measurements from two stations conducting radiosounding measurements. However, the data are in the standardized TEMP report format WMO (World Meteorological Organization), so it was necessary to set up a methodology to convert to standard levels METCM or METB3 artillery reports and the nationally used METEO-11 meteorological report.

1.1 Issued Meteorological Report METCM

The initial step involves assessing the feasibility of issuing an empirical/statistical or model artillery meteorological report. In the Czech Republic, the METEO-11 report, utilizing elevation values from Table 1 is commonly used. In contrast, NATO employs the METCM or METB3 report. A detailed comparison and conversion between these two reports can be found in the study by Šilinger et al. (2014).

Table 1: Altitude ranges of individual standard layers of the METEO-11 meteorological report

Layer code	Height over station [m]	Mean height [m]	Layer code	Height over station [m]	Mean height [m]

02	0 - 200	100	40	3 000-4000	3 500
04	200 - 400	300	50	4 000-5 000	4 500
08	400 - 800	600	60	5 000-6 000	5 500
12	800 - 1 200	1 000	80	6 000-8 000	7 000
16	1 200 - 1 600	1 400	10	8 000-10 000	9 000
20	1 600 - 2 000	1 800	12	10 000-12 000	11 000
24	2 000 - 2 400	2 200	14	12 000-14 000	13 000
30	2 400 - 3 000	2 700	18	14 000-18 000	16 000

A discrepancy was identified between the altitude levels used in artillery reports and standard meteorological measurements. To reconcile this disparity, adjustments were necessary to align the data. This involved interpolating values for non-standard levels based on the available meteorological parameters. Careful consideration was given to ensure that these adjustments did not compromise the accuracy and reliability of the subsequent statistical analysis.

The primary objective was to accurately estimate atmospheric conditions at the specific altitudes relevant to artillery fire. This step was crucial for establishing a robust foundation for the statistical modeling process.

1.2 Upper-Air Measurements Data

Standard upper-air measurements in the form of TEMP reports, as defined by the WMO standards (WMO, 2017), were obtained from the stations Praha-Libuš (WMO: 11520) and Prostějov (WMO: 11747). These measurements were collected using radiosondes carried by ascending balloons. While these data served as the primary dataset, additional ad hoc measurements are conducted during irregular chemical and artillery tests.

Table 2: Basic data of the upper-air measurement stations

ID	lat	lon	alt	Name	From	To	Country
EZM00011520	50.0078	14.4469	302.0	PRAHA-LIBUS	1969	2024	CZE
EZM00011747	49.4525	17.1347	214.8	PROSTEJOV	2003	2024	CZE

The measurements are performed at least twice a day in 00 and 12 UTC, irregularly or on demand also at 06 or 18 UTC. They follow standard procedures according to WMO regulations (WMO, 2017) and contain, among other values, the following information that were used in the research:

1. pressure and height of a given pressure level,
2. wind direction and speed,
3. temperature and dew point temperature deficit.

1.3 Upper-Air Levels Interpolation

Not all pressure levels provide all information within the measurement. In some levels where the pressure level was missing, a suitable method for determining the altitude of the pressure level had to be determined. To use the height data, the three methods used to interpolate between height standard levels using the so-called barometric formula were tested:

1. determination of the layer thickness using the basic siplified form of the barometric formula,
2. determination of the layer thickness using the Babinet formula,
3. determination of the altitude using the sea level pressure reference value,
4. linear interpolation.

Both methods are used in meteorology (Lente & Ösz, 2020), for example to convert pressure to sea level or in aviation. They are particularly suitable for determination in the lower to mid-troposphere, but may have a higher error than measurements at high altitudes.

$$\Delta z = \frac{RT}{gM} \ln \frac{p_0}{p_1} \qquad [1]$$

where:

R is the universal gas constant (approximately 8.314 J * (mol * K)$^{-1}$).

T is the temperature in Kelvin.

g is the acceleration due to gravity (approximately 9.80665 m * s^{-2}).

M is the molar mass of air (approximately 0.0289644 kg*mol^{-1}).

P_0 is the pressure at initial level (for altitude above mean sea level, 1013.25 hPa).

P_1 is the pressure at the given altitude.

The Babinet formula, traditionally employed in synoptic meteorology for analysis using synoptic maps and aerological data, remains relevant. Interestingly, when applying the same input values to equation 1, comparable results are obtained. Thus, the Babinet form (Lente & Ösz, 2020) can also be used:

$$\Delta z = 16000 * (1 + 0.004\, T_m) \frac{p_0 - p_1}{p_0 + p_1} \qquad [2]$$

where:

T_m is the mean temperature in the layer.

These relationships were applied to each layer and then the cumulative sum of the heights of all lower levels from that measurement was calculated. As a second alternative, the calculation from the mean sea level was tested, i.e., calculating the elevation of a given pressure level from a pressure p_0 = 1013.25 hPa. The results of the comparison in standard pressure levels by the elevation indicated by the measurement are shown in Figure 2.

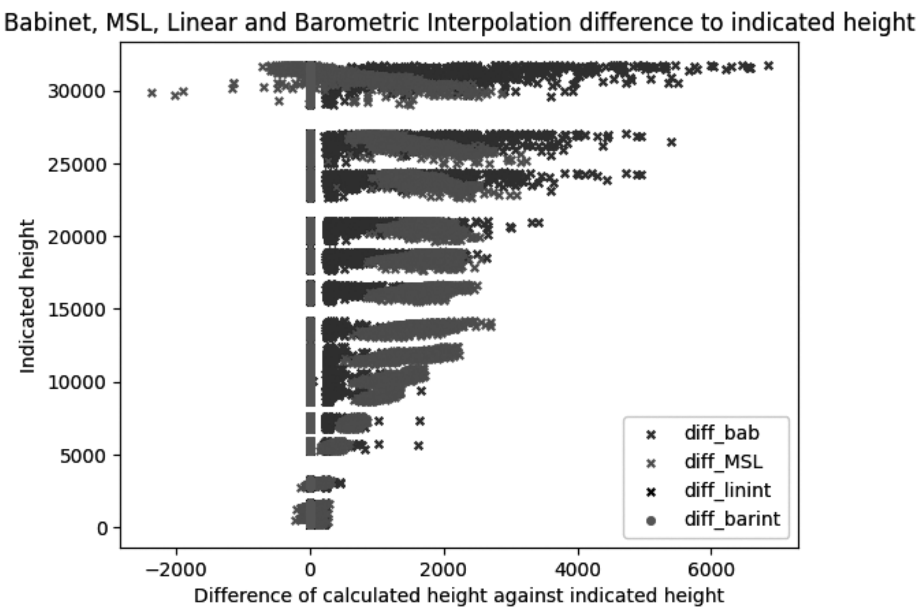


Figure 2: Comparison of indicated and calculated altitude differences (in meters) using the Babinet equation (blue crosses), mean sea level pressure as a reference value for the barometric equation (green), linear interpolation (black crosses), and barometric interpolation (red dots). Data from Prostějov, WMO: 1747, year 2020.

The graph illustrates that normalizing to standard pressure provides advantages by reducing the error variance caused by calculating cumulative frequencies. However, it is evident that the calculation cannot be universally valid for the entire height of the measured part of the atmosphere, as originally anticipated. As a result, alternative methods were proposed, which are always related to the level where the measurement is available.

One of these methods is linear interpolation, which exhibits no error at specific points since it is based on them directly. However, its accuracy could decrease if pressure levels are further apart. Nonetheless, for this specific application, linear interpolation may still be sufficient.

For this study, the application of the barometric formula for individual layers was chosen, as it is meteorologically justified. Within each layer, the level that last indicated the measured height was used as the reference level. Consequently, in this method, the primary source of inaccuracy is introduced solely by the shape of the barometric formula itself, including factors such as the averaging of temperature and values of constants, among others.

The basic description confirming the correctness of the use of linear or barometric interpolation is supported by the Table 2. There are all datasets displayed, where the columns of interpolations (Barometric and Linear) show the greatest similarity with the set of measured heights ('height').

Table of differences between the indicated height and the modelled height in standard levels demonstrates the difficulty of using Babinet's formula and MSL reference value. It should be added here that the first two methods have not been calibrated to the indicated heights, hence the errors are much larger. However, the other indicators also show that it is necessary to use individual measurements to optimize the interpolation.

The table of differences between the indicated height and the modeled height at standard levels clearly illustrates the challenges in using Babinet's formula and reference value. It should be noted that the first two methods have not been calibrated to the indicated heights, resulting in significantly larger errors. However, other indicators also indicate the necessity of using individual measurements to optimize the interpolation.

Table 3: Comparison of the indicated height, Babinet equation interpolation, Mean sea level altitude calculation (MSL), Barometric interpolation of indicated heights and linear interpolation. The table displays mean, minimal value, Q1-Q3, 50 % standing for median value and maximal value. The columns indicated by delta stand for differences at levels with indicated heights

	Height	Babinet	MSL	Barometric	Linear	Δbab	ΔMSL	Δbarint	Δlinint
mean	13066	14536	14177	14748	14747	546	1028	0.0	0.0
std	8954	9489	9735	8809	8808	719	706	0.0	0.0
min	215	1	1.9	215	215	39	-2370	0.0	0.0
25%	5680	6031	5814	6923	6922	245	328	0.0	0.0
50%	11760	13722	12513	14295	14293	281	1176	0.0	0.0
75%	20275	22371	21809	22157	22155	335	1594	0.0	0.0
max	31750	36860	41046	31750	31750	6846	3236	0.0	0.0

In conclusion, relying solely on Babinet's formula and reference value for interpolation may not yield accurate results. Therefore, incorporating individual measurements is crucial to improve the accuracy of the interpolation process. Calibration based on these individual measurements can lead to better predictive outcomes and more reliable height estimations, enhancing the overall validity of the study's findings.

This is why barometric interpolation will be used to create the product. The errors it introduces into the determination of meteorological quantities at a given altitude will not be so significant that it is necessary to use a refinement of the barometric formula. However, disadvantages can be seen in the slightly more complex calculation process within the code. Thus, for simpler calculations and code sharing, the use of linear interpolation would be more readable.

1.4 Wind Data Handling

As the wind direction data is measured in degrees from the wind's origin, minor discrepancies can arise in directional analysis. For instance, north winds represented by

350° and 0° would average to 175°, incorrectly indicating a southerly wind. To address this, wind direction and speed are typically expressed using the zonal (u) and meridional (v) wind components:

$$\mathrm{u} = w_s * \sin\varphi \qquad [3]$$

$$\mathrm{v} = w_s * \cos\varphi \qquad [4]$$

Where:
w_s is wind speed;
ϕ is wind direction.

The meteorological convention for wind is that the *u* component is positive for westerly flow (west to east) and the *v* component is positive for southerly flow (south to north).

2 EXPLORATORY ANALYSIS

The primary goal of this chapter is to identify patterns in wind components with respect to altitude and time at each station. We aim to understand

1. how temperature and wind components vary with height,
2. examine yearly and monthly fluctuations.

To achieve this, we will analyze standard deviations of grouped wind component data at different levels, categorizing the data based on time of day, time of year, and surface conditions. By uncovering significant trends, seasonal patterns, or diurnal variations in wind components, this exploratory analysis is intended to lay the groundwork for subsequent modeling, clustering and analysis, contributing to a comprehensive understanding of meteorological conditions at the study sites.

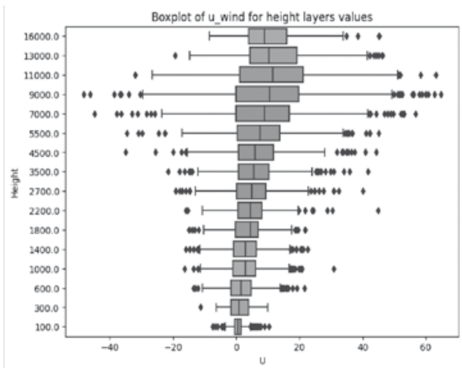
2.1 Wind Variations with Height

For a basic overview of how the wind generally behaves aloft, the stations Prostějov (WMO: 11747) were used. The following procedure was used for the exploratory analysis of wind elements:

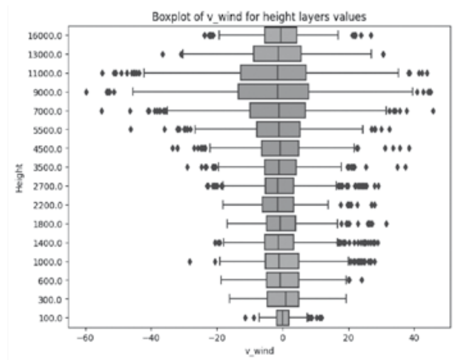
1. Only a value from each term was selected from the levels listed in Table 1. Since the levels have different number of measurements, at different heights and intervals, the height value closest to the mean height of the given level was chosen.
2. Box plots of the values were created and displayed in Figure 3:
   a) for the u wind component,
   b) for the v wind component,
   c) wind speed,

d) wind direction.

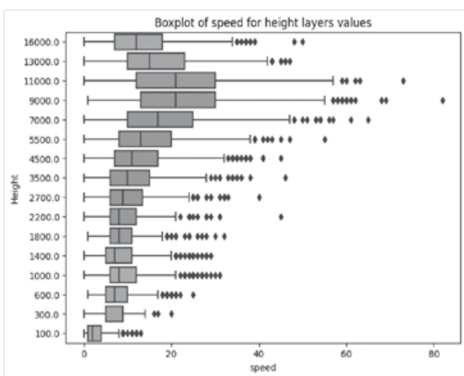
3. Trend analysis was created for the period of measurements in Prostějov. The purpose was to see if there is any significant trend or fluctuation in the data, or if it is possible to use e.g. the last five years of measurements and thus reduce the volume of data.



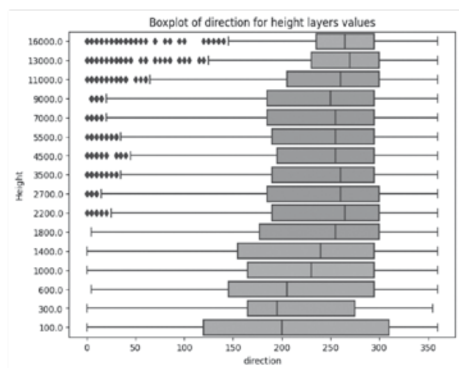
(a)



(b)



(c)



(d)

Figure 3: Boxplot for METEO-11 layers mean heights (a) u component of wind, (b) v component of wind, (c) wind speed, (d) wind direction. Data: Prostějov 2020.

From the graph in the Figure 3, it can be seen that the wind direction at altitude is more oriented towards the west and northwest directions, with easterly flow being rather sporadic. It is also apparent that the wind direction near the ground can be the most fluctuant and therefore the good results cannot be expected when only generating reports using statistical boxplots.

2.2 Temperature Variations with Height

Generally, the temperature exhibits a gradual decrease with increasing height, adhering to the values defined by the dry-adiabatic and saturated-adiabatic temperature gradients. Nevertheless, deviations in temperature, such as inversions or other anomalies, can be observed in upper-air measurements. These variations are the most notable discrepancies from the statistical trends. The Figure 4 illustrates the temperature profile in relation to height using data from the five-year dataset recorded in Prostějov.

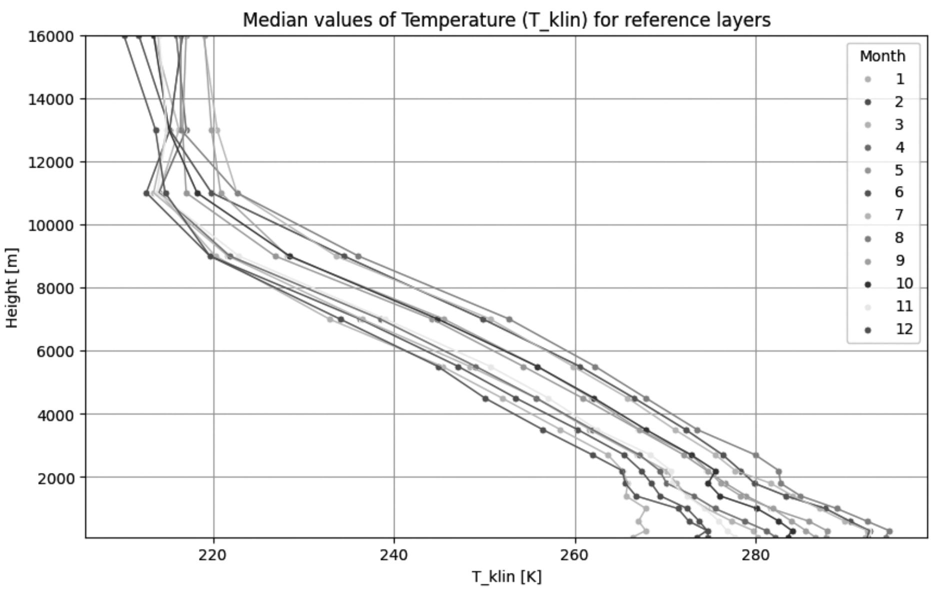


Figure 4: Median values of linearly interpolated temperature [K] in standard METEO-11 layers by months with an obvious tropopause effect (Data: Prostějov)

The graph validates the anticipated trend driven by physical mechanisms. Naturally, the median smoothens out the exceptional impact of inversions, which becomes apparent only through a partial increase in variability in the lower atmospheric layer, particularly during autumn and spring months. In addition, the approximate height of the tropopause is clearly discernible from the graph. We could also anticipate that for future models, it would be convenient to model warm months (6, 7, 8), transition months (5 and 10) and cold months separately due to the temperature effect on the trajectory.

2.3 Annual Course of the Wind Indicators

The exploratory analysis examined the wind indices and their mean and standard deviation at different levels. Their annual course for a five-year section at the Prostějov station is shown in Figure 4.

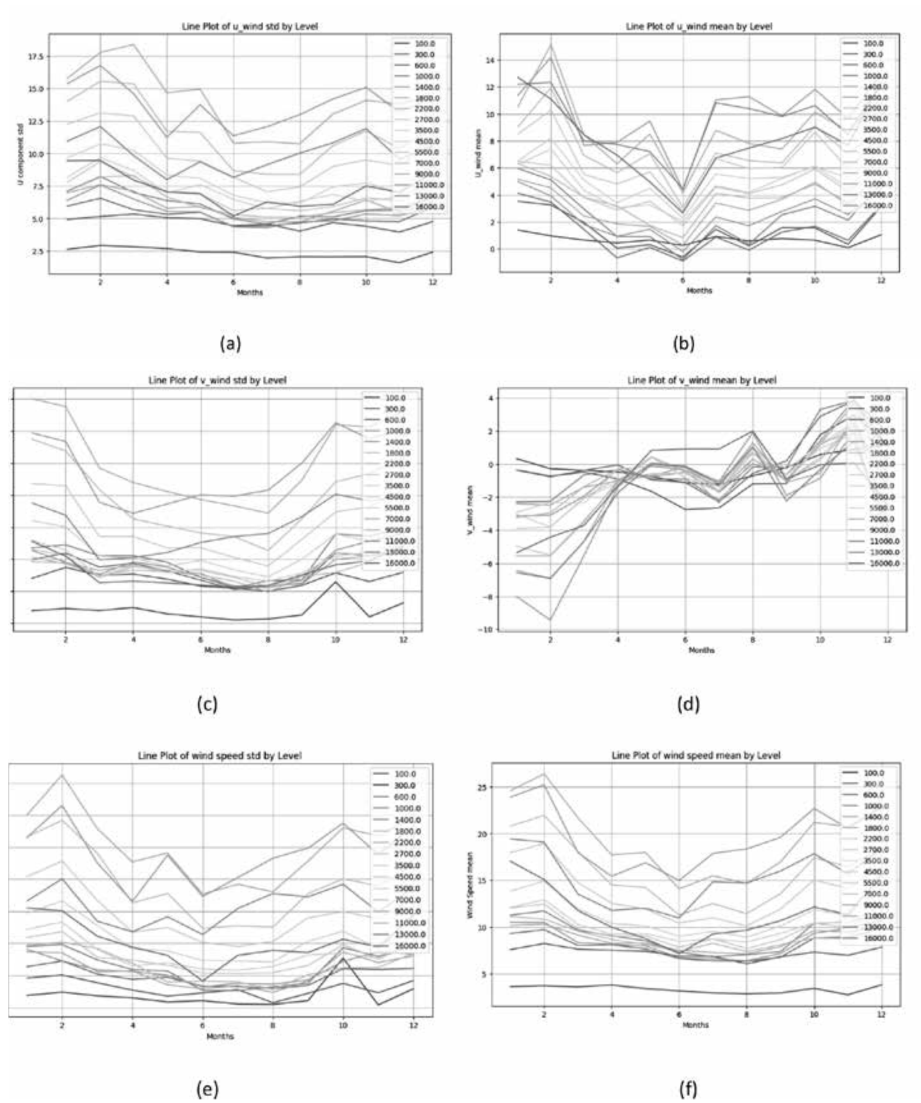


Figure 5: Overview of the annual course of the mean and standard deviation of the u, v wind components and wind speed at Prostejov station in 2018-2022

There is quite obvious trend within the data of wind speed measurements. Therefore, it would be reasonable to split the problem by months or season. From the figures, we can guess that the most problematic and variable months in terms of wind distribution will be the winter months (namely February, when wind speeds are both highest and at the same time we register a high standard deviation). Summer, on the other hand, will probably have the most outlying values due to convection. Especially with the future use of numerical models, the main drawback for summer months could be lower predictability.

3 RESULTS

Two stations in the Czech Republic, Prostějov and Prague-Libuš, were used as test stations for the Scenario 1 where no data would be available.

The simplest way to acquire at least a minimal weather estimation would be to use measurements from standard levels and possibly their linear interpolation. As the pre-processing of data for the creation of analogue tools is not time-limited for field use, two main scenarios based on measurement site were created for use in the absence of any data:

1. use of the last five years of measurements,
2. use a set with similar surface conditions

3.1 Statistics-Based Approach

The statistics from the last five years of measurement provide a valuable starting point to understand the problem. Based on the exploratory analysis, it is evident that the problem can be categorized according to the basic variables observed at the ground level:

1. Sector of prevailing wind direction (N, NW, W, SW, S, SE, E, NE);
2. Wind speed (at intervals of five meters per second up to 30 m/s or more);
3. Temperature (intervals of five degrees Celsius over the detected range of values);
4. Month of the operation.

By promoting interval values, specific model situations were defined, dividing wind and temperature values with height into categories. Users can then utilize appropriate tables or charts based on the estimation of these values.

However, the example of the 2018-2022 data reveals the limitations of this approach. With multiple intervals for temperature, wind direction, and wind speed, the number of tables becomes extensive. For instance, considering the Prostějov station, there would be approximately 12 intervals of temperature, 8 intervals of wind direction, and 7 intervals of wind speed, resulting in 672 tables or reports of 16 rows of height levels (multiplying by 12 for each month separately).

Therefore, four visualization solutions are proposed:

1. A book of tables categorized by prevailing direction and speed.
2. A comprehensive chart or set of charts resembling postage stamps.
3. A simplified visualization using an aggregating tool to reduce the number of charts.
4. An interactive application displaying a graph or table relevant to the observed conditions.

Each visualization tool has its advantages and disadvantages. A book of tables provides detailed information but may become overwhelming due to its volume. Complex charts may be visually engaging but may lack clarity (Figure 6). A simplified visualization using aggregation may provide an overview but might lose critical details. The interactive application is efficient for personalized insights but may require more sophisticated implementation.

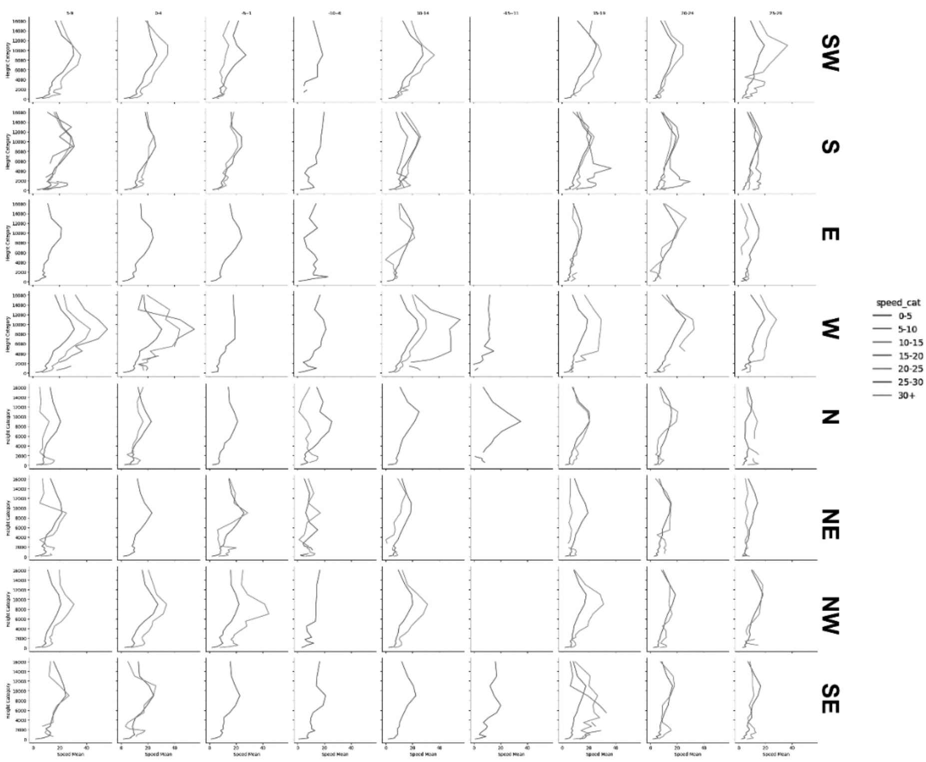


Figure 6: Example of 'Stamp plot' visualization of wind speed aloft based on temperature category (stamp title on the upper part), wind direction category (right legend), and surface wind speed category (represented by line colour). The plot demonstrates the disputable readability of the visualization.

Choosing the appropriate visualization tool depends on the specific needs and preferences of the users, considering the balance between detail and accessibility. The aim is to present the data effectively to facilitate understanding and informed decision-making.

3.2 Impact on the Artillery Fire Accuracy: No Current Data

To give an idea of the implications for the conduct of artillery fire, we have issued simulated reports of the average heights for 1st January, 1st March, 1st June and 1st September based on data from the last 10 years. We included the median values, and then the 25th and 75th percentiles of the temperature and wind values for the report calculations. These were compared to an actual report from the same day in 2022 that would be theoretically generated for Prostejov.

Fire parameters were estimated to the four cardinal directions: North (Figure 7), East (Figure 8), South (Figure 9) and West (Figure 10) for the base ranges of 6000, 7800, 10000, 10400, 12200, 13000, 13800, 14800, 17100, 18000, and 18500 metres. Finally, we calculated the mean absolute error (MAE) of the distance and the direction from the potential target.

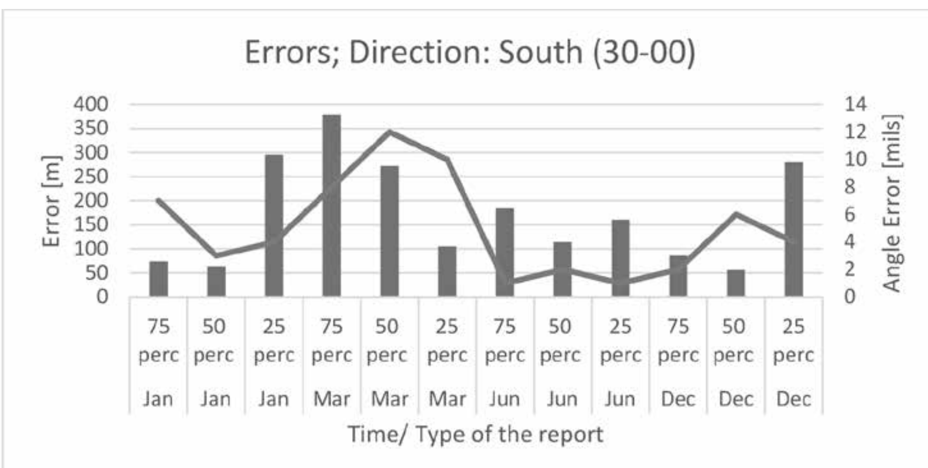


Figure 7: Mean error of the distance (blue bars) and direction (orange curve, right y axes) for the fire in the northern direction based on comparison of the 25, 50, 75 percentile of long-term values of wind and temperature.

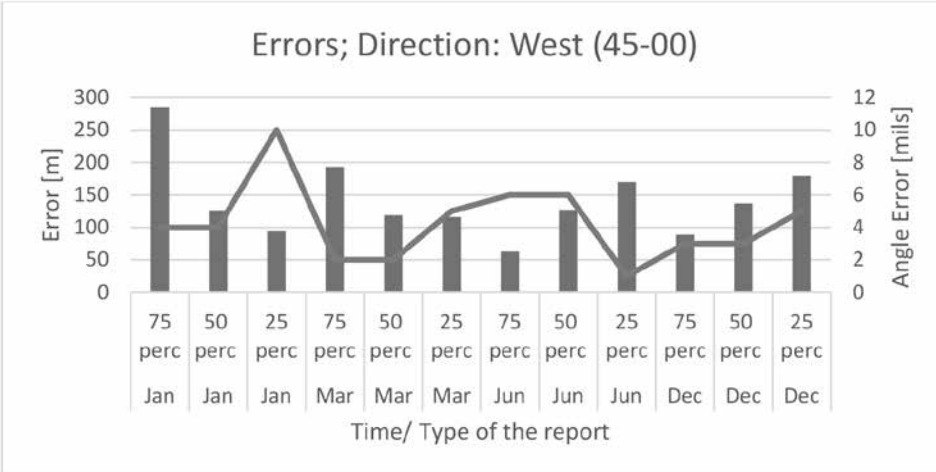


Figure 8: Mean error of the distance (blue bars) and direction (orange curve, right y axes) for the fire in the eastern direction based on comparison of the 25, 50, 75 percentile of long-term values of wind and temperature.

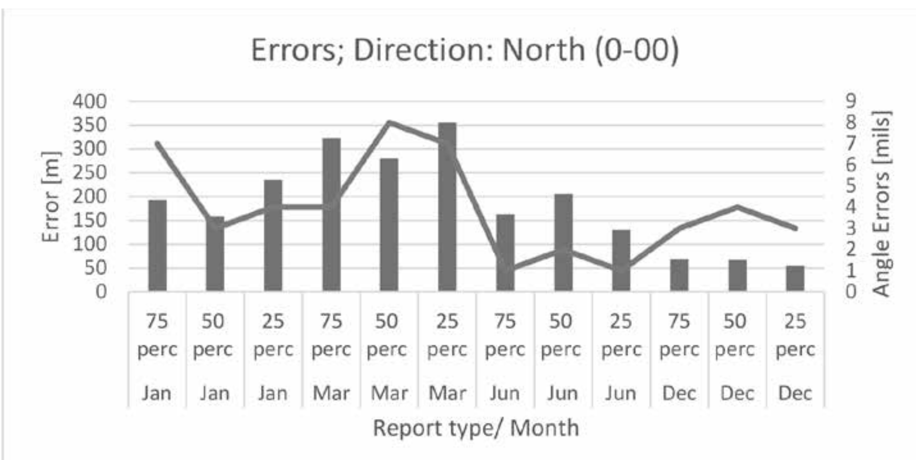


Figure 9: Mean error of the distance (blue bars) and direction (orange curve, right y axes) for the fire in the southern direction based on comparison of the 25, 50, 75 percentile of long-term values of wind and temperature.

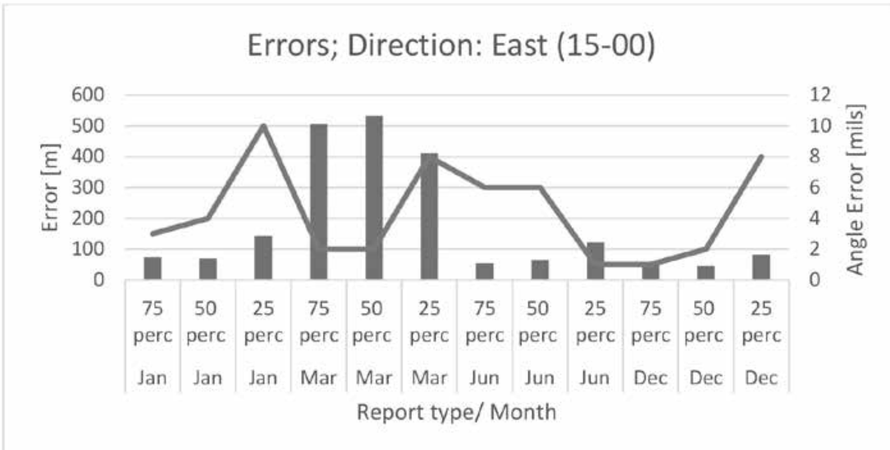


Figure 10: Mean error of the distance (blue bars) and direction (orange curve, right y axes) for the fire in the western direction based on comparison of the 25, 50, 75 percentile of long-term values of wind and temperature.

Even though one of the simulated products has always performed best, it is difficult to find a trend for these specific situations. Clearly, the accuracy of the method will vary considerably based on how average or satisfactory the conditions are at a given time for a given report.

As can be seen from the preceding figures, it is indeed possible to achieve average Errors below 50 meters, but that is only if we can effectively assess at least a trend in altitudes. This can be aided by estimates of ground level values, as demonstrated in the Figure 6. Even with efficient methods like probability stamp graphs, the number of potential scenarios can quickly escalate into the hundreds. Selecting the most probable outcome still leaves considerable uncertainty regarding the precise impact on the target. Nevertheless, this approach provides a solid baseline for decision-making in data-scarce environments. Its primary contribution lies in informing commanders about the potential accuracy and consequences of firing without adequate meteorological preparation.

DISCUSSION AND CONCLUSIONS

In this study, we attempted to abandon the previous sources, to move away from the perfect assumptions of precise meteorological support and to look at the small nuances in the flight path from the ballistics point of view. Rather, it examined the impact of inadequate data on fire control. This builds a good foundation for operational products for use in combat. This approach is fully in compliance with the knowledge of contemporary wars and PACE (primary, alternate, contingency, emergency) procedures not only in the artillery field, which is being developed for continuous operations in degraded conditions.

Our study established three basic research questions.

1. To what extent can ground-level meteorological measurements be used to accurately predict atmospheric conditions at altitude relevant to artillery fire?
2. How does the accuracy of the developed model influence artillery fire outcomes in terms of target deviation?
3. Can the proposed method enhance artillery effectiveness in various operational environments, including those with limited meteorological resources?

Chapter 2.3 introduced four methods for converting height data, as meteorological reports, especially historical ones, often use different intervals. We tested the meteorologically established Babinet formula for conversion to sea level and compared it to linear and barometric interpolation, both initiated from points with matching pressure and height data. While barometric interpolation is theoretically more accurate, linear interpolation proved easier to calculate in practice, due to the assumption of the linear relationship between pressure and height at a specific level. The superior accuracy of barometric interpolation might become evident over larger distances between data points.

In Section 2.4 we briefly introduced the method of wind direction adjustment, where it was necessary to explicitly convert the units and values to vector values of the u and v components that are common in numerical meteorology.

Exploratory data analysis revealed distinct trends, particularly in wind variations with altitude, temperature, and time. Wind speeds generally peaked between 9 and 11 kilometres, decreasing thereafter. Additionally, wind direction exhibited a westward shift at higher altitudes, likely due to reduced surface topographical influences. These findings suggest that the uncertainty associated with trajectory estimation may be lower in these altitude ranges but multiplied by the wind speed.

Temperature profiles exhibited expected seasonal variations. Ground inversions were prevalent during winter months, while a consistent adiabatic lapse rate characterized summer conditions. Based on these observations, we propose segmenting future models into summer, transitional, and winter periods to account for distinct atmospheric characteristics.

In terms of wind characteristics over the course of the year, it was confirmed that the largest standard deviations and therefore the assumption of potentially most difficult modelling would be in the colder months and higher layers. Here again, we propose a split of future forecast models by month.

The results highlight two primary challenges.

1. Despite comprehensive elaboration, statistical procedures face difficulties in visual representation due to the vast number of potential scenarios.
2. While simple percentile-based methods can achieve reasonable accuracy with careful application, large error values remain probable. Selecting the optimal variant often becomes a matter of chance.

Nevertheless, the research underscores the critical importance of precise artillery and meteorological preparation. The developed statistical models offer two potential applications.

1. They can serve as a foundation for constructing more complex weather models and classification systems tailored to artillery needs.
2. They provide commanders with a tool to assess the potential impact of inadequate meteorological support on mission outcomes, such as target misses or discovering the own positions.

The current study was subject to the several limitations. Firstly, the availability and quality of meteorological data, can influence the accuracy of the analysis. Data measured in the 12 hour step, while valuable, may not fully represent the dynamic nature of atmospheric conditions. Additionally, the focus on a specific region limits the generalizability of the findings to other geographical areas.

To address these limitations and expand upon the current study, several avenues for future research can be explored.

1. Geospatial Interpolation: Incorporating geospatial interpolation techniques, such as Inverse Distance Weighting (IDW) or Splines can be employed to estimate meteorological parameters at locations with limited data availability by utilizing information from nearby stations.
2. Machine Learning: Advanced machine learning algorithms, including Bayesian Ridge Regression and Random Forest, can be applied to improve the accuracy and robustness of predictive models. As an initial experiment, we briefly tested prediction of the Temperature in all the levels based on the ground values. Bayes Ridge Regression reached mean absolute error up to 7-9 Centigrade on the one year of testing data. This confirms our anticipation that ML models can effectively guide the decision of selecting correct scenario.
3. Data Enrichment: Expanding the dataset to include additional variables, such as weather types, can enhance model performance by providing additional context and enabling more accurate classifications. Furthermore, integrating numerical weather prediction models, both global (as WRF, ECMWF, GFS) and local (HRRR, ALADIN, AROME, ICON), can improve the accuracy of forecasts. Satellite and radar data can also be incorporated to provide more comprehensive and up-to-date atmospheric information especially for the nowcasting (0-3 hours) updates.

It is anticipated that by continuing along these lines of research, the accuracy and applicability of artillery fire prediction models can be significantly improved, leading to increased operational effectiveness.

In collaboration with the artillery units, we will develop products and software for all proposed scenarios completely without data, up to a near-complete data base, and seek to improve rapid prediction for automated decision making during operations and fire control.

LIST OF ABBREVIATIONS

Abbreviation	Full Form
ALADIN	Limited area weather prediction model
AROME	A numerical weather prediction model designed by Méteo-France
ECMWF	European Centre for Medium-Range Weather Forecasts
GFS	Global Forecast System
HRRR	A numerical weather prediction model produced by the National Weather Service; High-Resolution Rapid Refresh
ICON	Icosahedral Non-hydrostatic Model
IDW	Inverse Distance Weighting
MAE	Mean Absolute Error
METB3	Meteorological artillery report used for manual calculations
METCM	Meteorological artillery report used in automated systems
ML	Machine Learning
MSL	Mean Sea Level
NATO	North Atlantic Treaty Organization
PACE	Methodology used to build a communication plan (following primary, alternate, contingency, emergency principles)
STANAG	Standardization Agreement
UTC	Coordinated Universal Time
WMO	World Meteorological Organization
WRF	Weather Research and Forecasting Model

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