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DOI: 10.35117/A_ENG_23_01_03

Are Urban Heat Islands a threat to air transport?

Abstract: Weather conditions always have a huge impact on air transport. Taking into account global climate changes, which have a great influence on such conditions, this problematic continues to be one of the most current research topics, especially in the context of the above-mentioned field of transport. This article attempts to present the issue of the Urban Heat Island (UHI) and its potential influence on air transport. The aspects of lightning discharges and torrential rains, which are often accompanying them, were also discussed. Additionally, infrastructural and procedural solutions reducing the negative effects of unfavourable weather conditions are described.

Keywords: Urban Heat Island; Air transport; Weather conditions

Introduction

Air transport is the most susceptible mode of transportation to various external disturbances. This vulnerability arises from the delicate structure of aircraft, the transition from rolling movement to flight, the limited and costly maintenance infrastructure, and human constraints. Despite continuous advancements, humanity has yet to fully conquer atmospheric conditions, which have a particularly strong impact on aircraft and infrastructure. Year after year, the changing climate increasingly and more intensively affects human activity, a consequence of destructive practices dating back to the 18th century [1]. As such, discussions on the impact of lightning discharges and the torrential rains that often accompany them on airport infrastructure, as well as the search for infrastructural and procedural solutions to mitigate the adverse effects, remain highly relevant and significant today. Furthermore, the primary aim of this research is to present the issue of the Urban Heat Island (UHI) phenomenon, as a factor that can significantly influence thunderstorm activity, thereby exacerbating its adverse impact on air transport.

Weather conditions

Lightning

A thunderstorm can be described as one or more sudden electrical discharges, manifested by a flash of light (lightning) and a loud, sharp, or rumbling sound (thunder). Thunderstorms are typically associated with convective clouds and are often accompanied by precipitation.In meteorological reports (METAR) and forecasts (TAF) issued for specific airports, aviation personnel pay special attention to the abbreviation Cb, which denotes the presence of cumulonimbus clouds and associated electrical discharges [2]. For a cumulonimbus cloud to form, the following fundamental conditions must be met:

- A deep layer of highly unstable air,
- Warm and humid air.

The "trigger mechanism" for initiating this process may include:

- Surface layer heating, • Orographic conditions,
- Fronts forcing upward air movement.

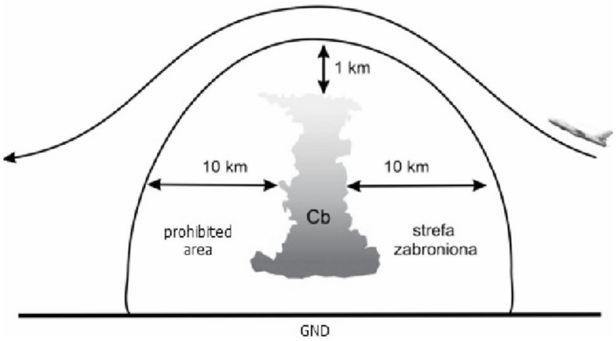
Not all cumulonimbus clouds produce thunderstorms; some merely bring heavy rain or hail. A single cumulonimbus cloud typically takes only an hour to form, grow, and dissipate, producing less than 30 minutes of thunder and lightning. If a thunderstorm lasts longer, it is likely due to the presence of multiple cumulonimbus clouds [3].

Lightning discharges can be classified based on their charge as positive (+) or negative (–). These are further divided into cloud-to-cloud or cloud-to-ground discharges. It is estimated that over 90% of negative discharges are of the cloud-to-ground type, with positive discharges considered the most dangerous [4]. Geographical latitude is closely linked to the frequency of ground discharges; the higher the latitude, the greater the number of ground discharges.

Due to the numerous risks associated with flying in or near storm clouds, both civil and military organizations worldwide have implemented relevant regulations and recommendations, such as:

- Points 4 and 5 of Paragraph 51 of the Polish Armed Forces' Flight Regulations (RL-2010):

"Flying in highly developed cumuliform clouds and approaching storm clouds within a horizontal distance of less than 10 km is prohibited. Flying beneath highly developed cumuliform clouds producing heavy rain, hail, snow, or lightning is also prohibited."
"Flying over storm clouds encountered in flight is permitted with an altitude margin of no less than 1,000 meters." (Fig. **1**), [5]



1. Range of maximum approach to Cb clouds (Source: based on: Meteorology for pilots – a guide, Headquarters of the Hydrometeorological Service of the Polish Armed Forces, Warsaw 2011)

- EASA Training Materials for Pilots:

„It is recommended to avoid any storm cloud at least 10 nautical miles away if it is high, growing rapidly or has an anvil at the top. Flying over cloud tops should be done with a height difference of at least 5,000 feet (…)" [6]

Recommended avoidance distances, based on airborne weather radar ranges, are shown in (Table 1).

Tab. 1. Recommended minimum distances for avoiding thunderstorms (based on: Meteorology - EASA aircraft training, Mark Wickson, 2015))

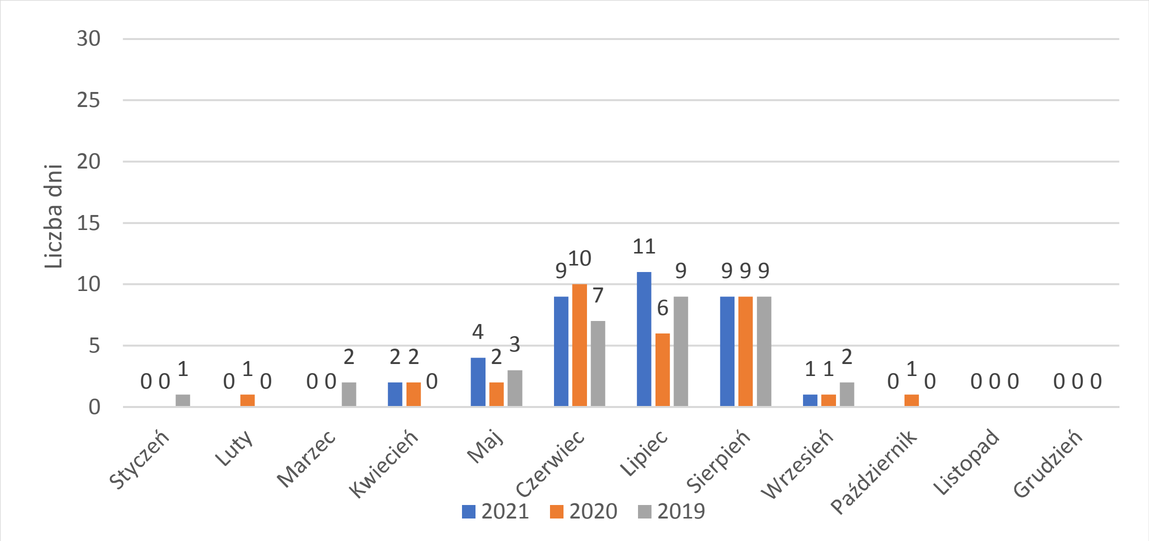
Height	**Distance**
0 – FL250	10NM
FL250 – FL300	15NM
Above FL300	20NM

As part of "The Earth Networks Airport Operations Weather Safety Audit," a survey was conducted in which airport operators, airlines, and ground handling agents in the United States identified lightning as having the most significant impact on their operations (75.4%) [7]. For safety reasons, airports enforce a minimum distance for lightning strikes from the airport. In the survey, 54.4% of respondents indicated 5 nautical miles as the threshold below which ground operations are suspended. At EPKK airport, this distance is set at 5 km, approximately 2.70 nautical miles (Fig. **2**), as specified in the Airport Operations Manual (INOP) [8].

2. Area 5 km from the EPKK airport reference point (Source: Google Earth)

Of course, entities operating at the airport may impose their own, stricter limits; however, the distance specified in the INOP serves as a non-negotiable threshold. If lightning occurs within this range, all ground handling operations must be suspended until the storm moves away.

The chart in (Fig. **3**) depicts the typical storm season for Kraków-Balice Airport (EPKK), occurring from June to August.



3. Number of storm days recorded by the Kraków-Balice meteorological station in 2 years 2019-2021 (own study based on IMGW-PIB)

Rainfall

Fully developed cumulonimbus clouds are always accompanied by rainfall, often including hail. Particularly significant for air transport are intense downpours, especially those of a torrential nature.

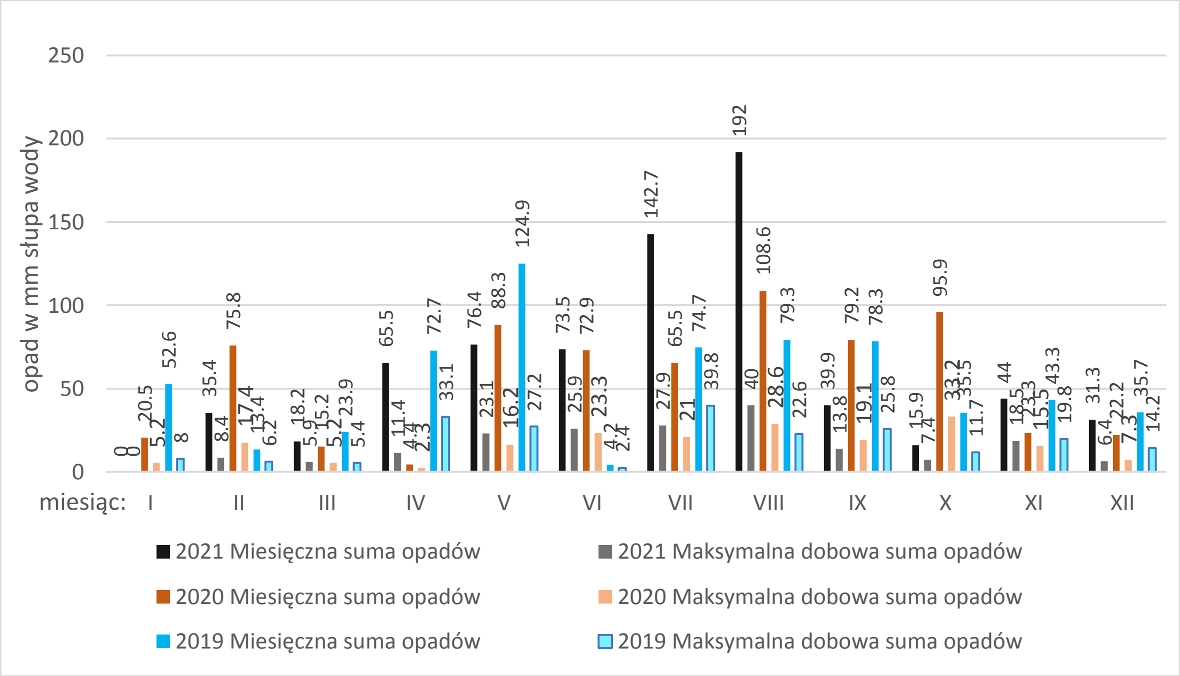
Rainfall, combined with excessive rubber deposits left during aircraft landings, can significantly reduce traction. It is crucial to note that modern airport surfaces are vast expanses of concrete or asphalt, which do not absorb water in any way.

The landing process does not end at touchdown but continues until the aircraft's speed is reduced to a safe level. Airport operators are internationally mandated to report the condition of runway surfaces. Studies and measurements have shown that over 90% of runway excursions occurred under conditions other than “dry.” The introduced Global Reporting Format (GRF) regulations require, among other measures, the assessment of contamination thickness. Under these regulations, during rainfall, particular attention is given to surface water layers exceeding 3 mm in thickness.

Cumulonimbus clouds deliver exceptionally large volumes of water in a very short time. Such rainfall is characterized by large droplet sizes and high intensity over a relatively small area (Fig. **4**).

4. Spot rainfall south of EPKK airport, 23-05-2021 (Source: Bylica A.)

Due to the geographical latitude at which the EPKK airport is located, it can be assumed that the period of the greatest rainfall, both monthly and daily, occurs from April to September, with particular emphasis on the period from May to August, the thesis is confirmed by (Fig. **5**).



5. Monthly and maximum daily precipitation totals at Kraków-Balice Airport in 2019-2021 (Own study based on IMWM-PIB)

The volume of precipitation is also influenced by increased storm activity during this period (Fig. **3**). According to Chomicz's classification, heavy rainfall includes precipitation with a total expressed in mm (yield) over time (t, mm) exceeding the value $u_0 = 1.0t^{0.5}$. Torrential rains are defined as those with a yield greater than $u_0 = 1.0t^{0.5}$(Table 2). Based on rainfall intensity, the most commonly recorded categories of rain fall into levels 4 and 5 according to the Chomicz scale.

Tab. 2. Chomicz Scale (Chomicz 1951) (Source: Hydrology – auxiliary materials, Dr. Eng. Marek Bodziony, Cracow University of Technology, Cracow 2006)

Stopień skali	Współczynnik wydajności opadu ∝	Kategoria deszczu	
		Określenie	Znak literowy
0	0.0 - 1.0	zwykły deszcz	
1	1.01 - 1.40	silny deszcz	A_0
2	1.41 - 2.00	deszcz ulewny – I st	A_1
3	2.01 - 2,82	deszcz ulewny – II st	A_2
4	2.83 - 4.00	deszcz ulewny - III st	A_3
5	4.01 - 5.65	deszcz ulewny - IV st	A_4
6	5.66 - 8.00	deszcz nawalny - V st	B_1
7	8.01 - 11.30	deszcz nawalny – VI st	B_2
8	11.31 - 16.00	deszcz nawalny – VII st	B_3
9	16.01 - 22.61	deszcz nawalny – VIII st	B_4
10	22.62 - 32.00	deszcz nawalny – IX st	B_5
11	32.01 - 45.23	deszcz nawalny – X st	B_6
12	45.24 - 64.00	deszcz nawalny – XI st	B_7

Airport infrastructure, on which aircraft operate, has very limited capacity for draining rainwater. Generally, water runoff is achieved through surface gradients in compliance with regulations such as Annex 14 to the Chicago Convention or European Regulation 139/2014. Modern runways and taxiways are designed with dual-slope gradients, with a peak at the geometric center. However, older runways built under previous regulations, using a single-slope gradient for water drainage, are still in operation. An example of such an airport is EPKK.

On aircraft aprons and other paved areas, linear drainage systems are typically installed, toward which the surfaces are sloped. Due to the low taxiing speeds of aircraft, linear drains are often located within inner-apron taxiways. Runway drains are positioned at the edges, outside the areas where aircraft typically operate. The absence of an internal drainage system on the runway surface means that during torrential downpours, the volume of water to be quickly drained often exceeds the drainage system's capacity.

The time required to drain water depends on surface macrotexture, slope steepness, and the quality of joint sealant construction. Wind is a variable factor that can either aid or disrupt water runoff. When aligned with the flow direction, wind can accelerate drainage, while sufficiently strong opposing winds can cause water accumulation. To improve drainage efficiency, airport operators often employ grooving techniques. Grooves cut into the pavement direct water flow, reducing the likelihood of pooling.

Enhancing drainage parameters comes at the expense of the pavement's durability, which is weakened by the grooving process. There are two primary types of grooves: square and trapezoidal. Studies have shown that trapezoidal grooves are more effective in preventing aquaplaning at higher aircraft rolling speeds and during torrential rain [9]. Naturally, aquaplaning is a complex phenomenon influenced by wheel speed, tire pressure, tread, pavement macrotexture, and the thickness of the water film. Moreover, aquaplaning can be categorized into two types: viscous and dynamic, with an additional process known as "reversed rubber hydroplaning" [10]. Airport operators must pay special attention to maintaining the cleanliness of grooves, particularly square-profile grooves, whose sharper edges tend to accumulate more rubber.

Urban Heat Island (UHI)

The Urban Heat Island (UHI) phenomenon can be defined as a climatic effect characterized by elevated air temperatures in urban areas compared to adjacent suburban or rural regions [11]. First described in 1833, UHI is influenced by factors such as:

- Homogeneous artificial surfaces,
- Albedo of artificial surfaces,
- Urban geometry,
- Disruptions to city "ventilation corridors,"
- Presence of industry,
- Heavy traffic,
- Anthropogenic factors,
- High-rise buildings,
- Topography.

As outlined in the section on Thunderstorm Formation, one of the key triggers for cumulonimbus (Cb) cloud formation is convective movement and warm air. Artificial surfaces and buildings, with their low albedo, absorb significant amounts of solar radiation and heat to high temperatures. Wind flow disrupted by buildings further enhances air heating within cities. Consequently, cities exhibit an atypical radiation balance, where reflected radiation is significantly lower and surface thermal radiation is greater compared to non-urban areas [12].

$R_n = K\downarrow - K\uparrow + L\downarrow - L\uparrow$

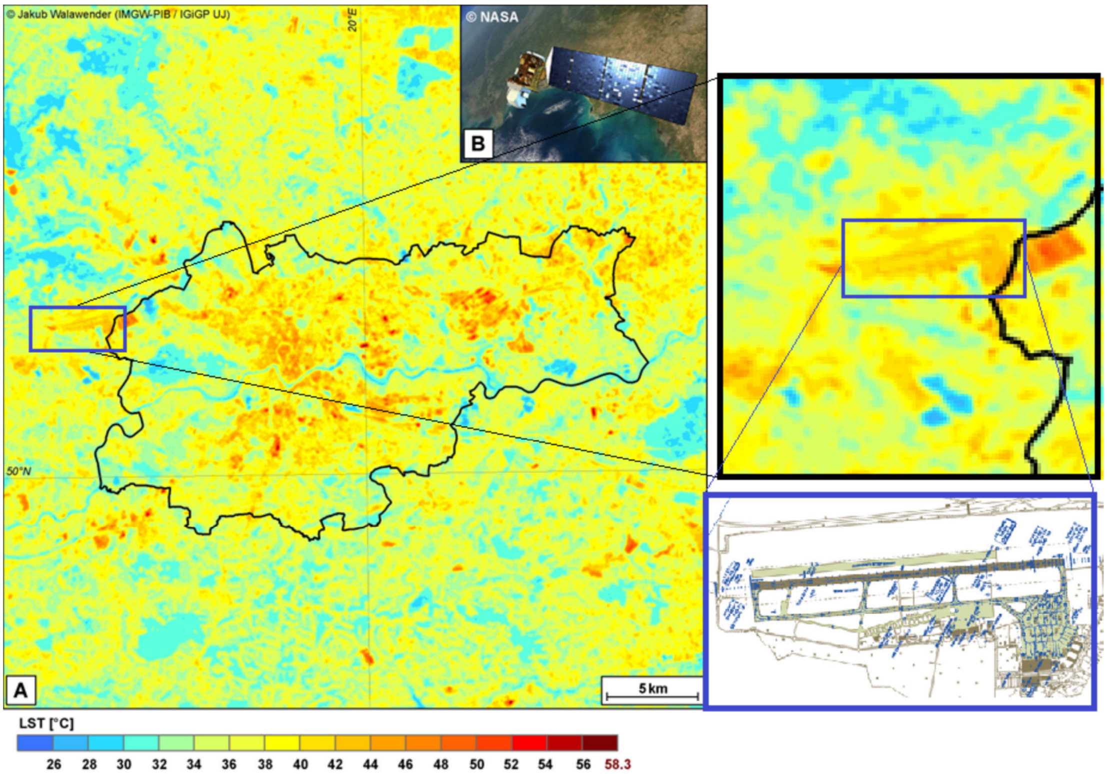
Rn – Surface radiation balance,
$K\downarrow$ – Incoming solar radiation,
$K\uparrow$ – Reflected solar radiation,
$L\downarrow$ – Atmospheric thermal radiation,
$L\uparrow$ – Surface thermal radiation.

Research conducted by F. Ali-Toudert and H. Meyer (2006) demonstrated the relationship between urban internal temperatures and the height and spacing of buildings, which form urban corridors [13].

Can Urban Heat Islands Affect Air Transport?

Airports are ideally located on terrain conducive to their operations, far from human settlements and areas where birds or other wildlife may pose a threat. Proximity to developed road and/or rail networks is also a key consideration. Airports are hubs of employment for thousands of people and serve as economic catalysts, encouraging nearby residential development. In Poland, as in many parts of the world, a noticeable trend involves urban encroachment upon airports that were located in remote areas 20–30 years ago. This phenomenon affects airports such as Warsaw-Okęcie (EPWA), Kraków-Balice (EPKK), and Poznań-Ławica (EPPO). While proximity to airports raises noise pollution concerns for residents, it also poses direct and indirect challenges for air transport. Specifically, UHI effects could potentially exacerbate adverse meteorological phenomena.

Given the UHI phenomenon, the question arises: can urban heat islands affect air transport? The mechanisms and conditions favoring Cb cloud formation are well understood, as is the process by which vast artificial surfaces—made of steel, asphalt, or concrete—absorb and store enormous amounts of thermal energy. Airports fit the description of areas resembling UHIs. Considering only the airport's terrain, the scale might appear micro; however, this scale expands significantly as the surrounding areas develop. Airports should not be underestimated as significant sources of long-term heat emission. The scale of this phenomenon is evident in (Fig. **6**), which highlights the runway, taxiways, and aprons.

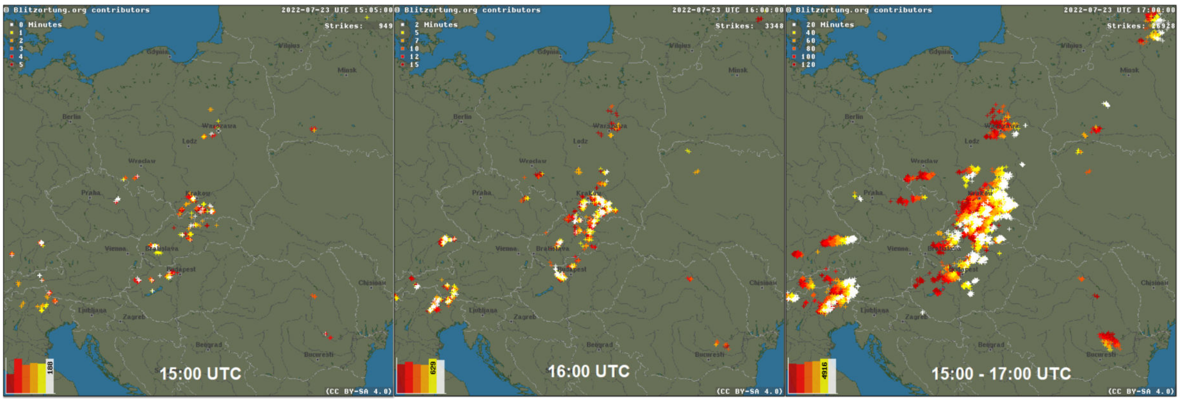


6. Satellite visualization of the temperature of the City of Kraków with the Kraków-Balice airport area highlighted (Source: Own study based on Jakub Walawander (IMGW-PIB / IGiGP UJ) and AIP POLSKA)

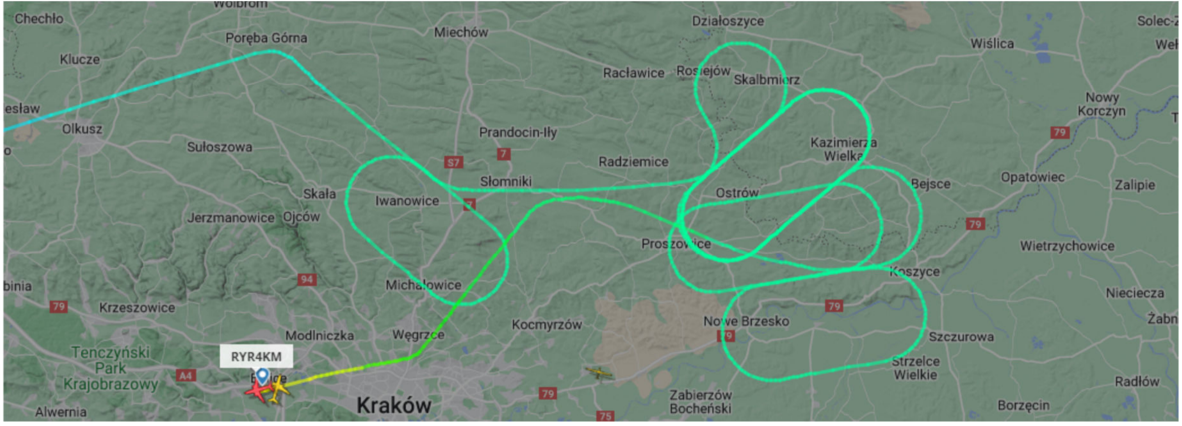
Of course, the strength of the Urban Heat Island (UHI) effect is also influenced by the terrain on which a city or airport is located. This topic is extensively discussed in the publication *"Urban Heat Island Against the Background of Natural Thermal Diversity of an Area Situated in a Concave Landform (Using Kraków as an Example)"* by Anita Bokwa (*Geographical Works, issue 122, Institute of Geography and Spatial Management, Jagiellonian University, Kraków 2009*). Based on the information presented, it should be acknowledged that the proximity of dense urban development, combined with the shape of the terrain, can significantly impact the course of atmospheric discharges. The accumulated heat energy acts as a driving force for already developed Cumulonimbus clouds, which cause the initial phenomena. Clouds moving over heated urban areas receive an energy boost in the form of convective movements of strongly heated air, which intensify atmospheric discharges and precipitation.

The movement of a storm over land is primarily determined by the interaction of its updrafts and downdrafts with steering winds in the mid-layers of the atmosphere, where the storm develops. The speed of individual storms typically ranges around 20 km (12 miles) per hour, but some storms move much faster. Under extreme circumstances, supercell storms can travel at speeds between 65 and 80 km (approximately 40 to 50 miles) per hour [14].

An example of rapid storm development is shown in (Fig. **7**), where, on July 23, 2022, a violent storm passing through the city of Kraków in southern Poland caused significant damage and forced the suspension of operations at EPKK/KRK airport. Some planes were left waiting in holding patterns for many minutes, as seen in (Fig. **8**), while others, due to low fuel levels, had to be diverted to alternate airports.



7. Development of thunderstorm cells passing through southern Poland on 23/07/2022 between 15:00 and 17:00 UTC (Source: own study based on www.blitzortung.org)



8. RYR4KM aircraft waiting for weather conditions to improve at EPKK airport on July 23, 2022. (Source: www.flightradar24.com)

Delays in air traffic are not solely caused by the impact of storm clouds on aircraft. Intense rainfall, which increasingly accompanies thunderstorms, forces airport infrastructure services to suspend airport operations. The suspension can be implemented in two ways:

First: Issuing an appropriate NOTAM message that closes the runway for a specified period. Unfortunately, a significant downside to this solution is its impact on aircraft intending to depart for the airport affected by the NOTAM, even if they are hundreds of kilometers away. An active NOTAM closing a runway triggers the imposition of flight SLOTs on all flight plans. For example, if a NOTAM closes the runway at EPKK for 20 minutes, a plane in Paris, approximately 2 hours away from Kraków, cannot take off on time due to the runway closure at EPKK, even though the NOTAM indicates that the runway will be reopened by the time the plane arrives in Kraków.

Second: Communicating with air traffic controllers to delay arrivals. This information is distributed via radio on the APP frequency. In cases of short-term suspension of air operations, this method has a strictly local impact.

Regardless of how airport operations are suspended, the negative consequences affect airport management, airlines, and ground handling agents on the apron and in the terminal. The accumulated traffic to and from the airport generates delays because staffing is planned according to the standard daily schedule and does not account for extraordinary situations. Additionally, airports with a high volume of air operations and poorly developed infrastructure — such as a limited number of parking stands—will be forced to queue aircraft waiting to access parking spots on taxiways, or pilots will decide to divert to alternate airports.

The **National Oceanic and Atmospheric Administration (NOAA)** points out that in the context of lightning-related hazards, the highest exposure to risk occurs just before and after a storm. However, the greatest risk of lightning strikes occurs during the main phase of the storm (Fig. **9**).

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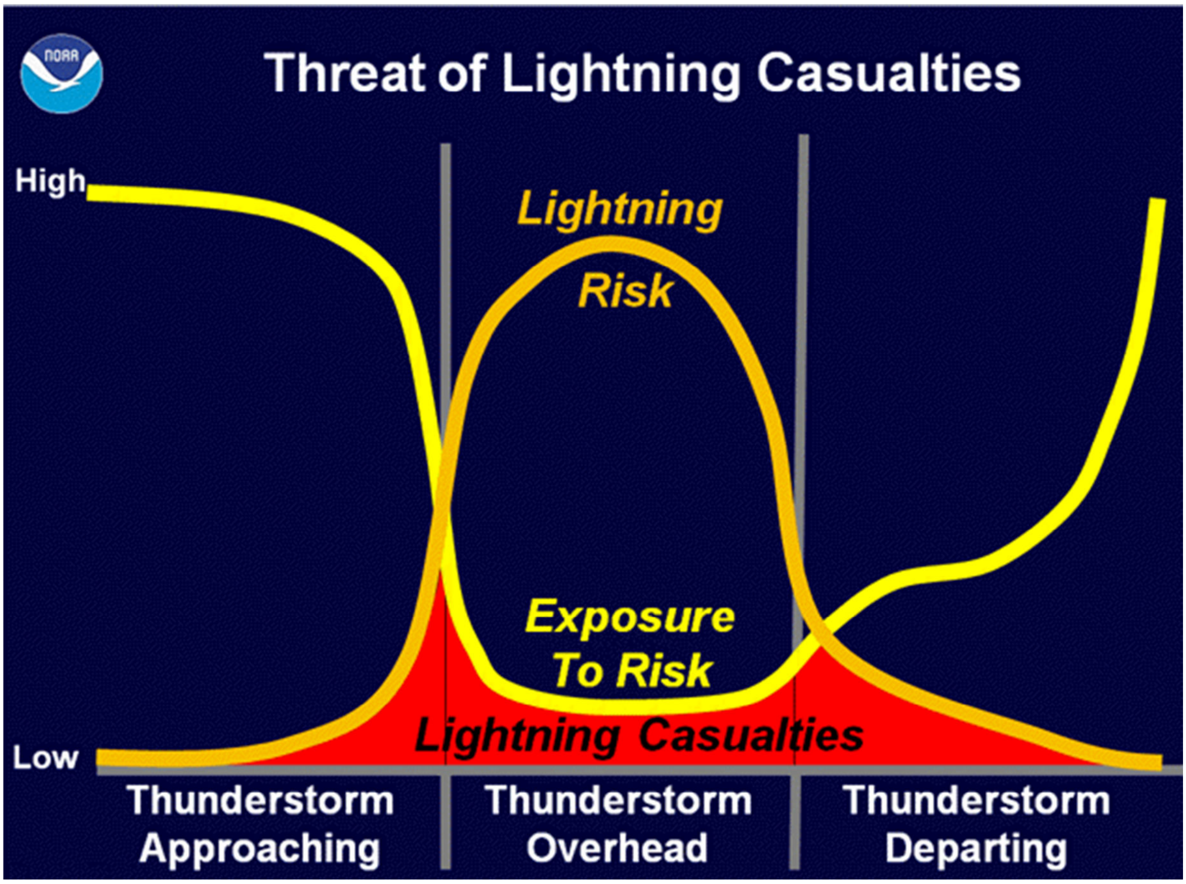

9. Threats from lightning strikes (Source: NOAA)

Taking into account NOAA's analysis, it is advisable for airport operators, air traffic control services, airlines, and ground handling agents to establish appropriate thresholds for the distance of lightning strikes from airports or aircraft.

Summary

Although the concept of the Urban Heat Island (UHI) effect has been known for a long time, it has not been previously examined in the context of its impact on air transport. Undoubtedly, the changing climate brings increasingly frequent and severe weather phenomena, including storms powered by heat energy. In this context, airports located within or near cities appear particularly vulnerable. Incoming unstable air masses receive additional energy, resulting in phenomena that are especially intense.

The sensitivity of air transport highlights the critical importance of precise and early forecasting of adverse weather events, as well as the continuous improvement of procedures to enhance safety both in the air and on the ground.

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