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RESEARCH

Potential impacts of climate change on the siting of U-space infrastructure

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Abstract

The integration of Unmanned Aircraft Systems (UAS) into the U-Space system requires dedicated infrastructure planning, such as vertiports and aerial corridors, that is not only efficient but also resilient to future meteorological changes. In this study, focused on the Emilia-Romagna region, we develop a methodological framework based on Geographic Information Systemspatial analysis to estimate the annual hours of flight operability (flyability). The methodology is applied by comparing the current meteorological scenario, derived from historical climatological data, with a scenario featuring a temperature increase of +6 °C. This increase is not presented as a most likely projection, but rather as a high-end sensitivity analysis designed to assess how the spatial distribution of flyability may respond to strong warming conditions. The procedure starts from the creation of a Digital Elevation Model (DEM), from which additional thematic layers such as aspect and surface roughness are derived. The influence of local meteorological conditions is simulated using a Random Forest predictive model, designed to identify the areas with the highest probability of exceeding the maximum operational thresholds for drones, mainly related to wind, rainfall, and temperature. As a result, we obtain raster maps that quantify, for each territorial pixel, the annual hourly fraction available for UAS flight. The comparative analysis highlights a heterogeneous reduction in flight hours in the stress-test scenario, with particularly pronounced decreases in hilly and foothill areas. Conversely, coastal plains maintain high levels of operability. Based on this evidence, we propose two guidelines for U-Space planning: (i) preferentially select sites that preserve high flyability even under future climate scenarios; (ii) adopt targeted adaptation strategies in the most vulnerable areas, such as alternative routes, satellite vertiports, energy storage systems, and real-time meteorological monitoring.

Keywords Climate change · Drones · U-Space · SIFET · Urban air mobility

Potenziali impatti del cambiamento climatico sul posizionamento delle infrastrutture U-space

Parole chiave Cambiamento climatico · Droni · U-space · Vertiporti · Mobilità aerea urbana

Introduction

The integration of drones into passenger transport, both in urban and extra-urban contexts, is emerging as a highly topical issue, driven by rapid technological progress and by the need to reduce traffic congestion and emissions in metropolitan areas through electric-propulsion solutions, as well as to connect remote areas where the construction of additional infrastructure would be even more expensive (Cunietti et al. 2024). The design of the infrastructure supporting the so-called U-Space – namely the system of vertiports (take-off and landing points) and aerial corridors (predefined flight paths) – requires a multidisciplinary approach capable of integrating technical, environmental and regulatory aspects. Meteorological conditions and the effects of climate change play a crucial role: changes in temperature, prevailing winds and extreme weather events can compromise both safety and operational efficiency, influencing the choice of optimal locations (Cunietti et al.

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2025). This becomes even more relevant when considering infrastructure involving high financial investment and a significant social impact such as this.

This study, developed within a broader research context as part of a PhD program, examines how an increase in temperatures, as is occurring due to climate change, could modify the location of optimal flight corridors in Emilia-Romagna. Through spatial analysis, climate data are processed and represented cartographically to identify the most suitable areas. The production of clear and easily interpretable thematic maps is essential to assess the variability of operational conditions and to provide an effective and readily understandable decision-support tool. Ultimately, the objective is to identify locations with lower meteorological risk for the siting of vertiports.

Analysis of meteorological components

In the design and management of U-Space infrastructure, atmospheric conditions play a crucial role in determining not only flight safety but also operational continuity and the energy efficiency of the vehicles. This section provides an integrated overview of the main meteorological components – wind and turbulence, precipitation and icing phenomena, visibility, temperature and humidity – which, individually and in combination, constrain drones' performance limits and influence vertiport siting and maintenance strategies.

Wind and turbulence

Strong winds destabilize drones, making it difficult to maintain stable trajectories (Wang et al. 2019). To counter gusts and turbulence, the aircraft must consume more energy, significantly reducing battery life and thus the operational range. Moreover, sustained winds or sudden gusts (especially in urban areas, generated by buildings) can push the drone off course and compromise accuracy, for example in automated mapping or delivery missions (Cammelli 2022). In densely built-up urban environments, strong wind gradients are observed between ground level and flight altitude: short-lived gusts and vortices generated by urban obstacles represent specific threats that traditional airports do not usually encounter.

Precipitation: rain, snow, hail and ice formation

Rain can damage exposed electronic components (motors, circuits, sensors) and reduce rotor grip, while snow or ice accumulating on propellers and fuselage alters aerodynamics and stability (Lundby et al. 2019). Under icing conditions, small drones rapidly lose lift – a phenomenon that can lead to sudden aircraft failures (Pinto et al. 2021). In addition to mechanical risk, heavy rain or dense fog reduce visibility and can blind optical sensors and cameras, hindering autonomous navigation and the maintenance of visual contact required by regulations (for example, FAA Part 107 requires at least 3 miles of visibility and prohibits flight in clouds) (Gao et al. 2021a).

Fog and reduced visibility

Fog, mist and dust storms reduce visibility and can compromise both visual and instrument flights (Lundby et al. 2019; Gao et al. 2021a). Small drones generally do not have sophisticated radar; therefore, low-visibility conditions increase the risk of collision with obstacles that are not detected in time. In addition, lighting conditions (e.g. sun glare) can interfere with optical sensors and cameras, posing an operational hazard for small UAS (Lundby et al. 2019).

Temperature, air density and humidity

Extreme temperatures affect the efficiency of both propulsion systems and batteries. Under excessive heat, LiPo batteries tend to overheat, reducing the available capacity and accelerating chemical degradation (Lundby et al. 2019). Warmer air (or locations with low pressure/high altitude) is less dense, decreasing the lift generated by the propellers – drones must therefore work harder to stay airborne, consuming more energy. Conversely, intense cold can drastically reduce battery performance (lower deliverable capacity) and make some materials more brittle, requiring warm-up procedures and increased maintenance (Gao et al. 2021b).

High geographic altitude (mountain areas, plateaus) involves thinner air, like the effect of heat: studies have shown that very high-altitude areas make flight more demanding than low-lying regions, due to reduced lifts and often stronger winds along ridges (Sushma et al. 2025). This implies payload limitations and the need for alternative routes to avoid reliefs under adverse conditions.

Operational and design implications

Climatic phenomena show seasonal and geographical variability even over relatively small areas. For example, coastal regions may be characterized by almost constant sustained winds (e.g. daytime sea breezes) or sudden gusts during Mediterranean summer thunderstorms, while inland areas may experience larger diurnal temperature ranges and morning fog (Wang et al. 2019). Global studies have quantified drone "flyability" (the percentage of time during which drones can fly while complying with weather limits): in hot, dry continental climates, the operational window is maximized, whereas high-latitude or oceanic areas suffer from large annual fractions of adverse weather (Gao et al. 2021b). It is not sufficient to assess only the flight hours possible under current meteorological conditions: it is essential to estimate how these operational windows will evolve in the future. From this perspective, such results not only inform present-day analysis, but also provide valuable insights into the evolution of atmospheric phenomena under a scenario of progressive temperature increase.

From a maintenance standpoint, more extreme climatic conditions imply greater wear on equipment: frequent flights in coastal saline environments or in the presence of sand can wear down motors and moving parts; prolonged exposure to UV radiation and high temperatures degrades airframes and plastic components; freeze–thaw cycles can damage joints and circuits. In addition, the need to interrupt operations frequently due to bad weather calls for more flexible maintenance plans (for example, additional inspections after flights in heavy rain). These aspects are driving the development of more robust drones (e.g. "weather-resistant" models with waterproof housings, extended temperature ranges and anti-icing capabilities) and integrated monitoring systems (such as sensors for detecting abnormal vibrations due to wind).

In summary, UAM planning must align with cities climate-change adaptation goals, ensuring that new infrastructure is both resilient to changing climatic conditions (withstanding extreme events) and consistent with adaptation strategies (not exacerbating local environmental conditions and, ideally, helping to improve them).

Currently, the most widespread commercial drones have declared operating limits of around 0–40 °C, maximum wind speeds of about 10 m/s and no tolerance to rain, whereas more advanced models tolerate between −20 and −45 °C, winds up to roughly 14 m/s and moderate rainfall. However, even with improved hardware, the spatial planning of routes and sites will still need to account for these climatic variables to ensure safety and continuity of service.

Effects of meteorological conditions on drone performance and possible solutions

A global-scale analysis (ten-year historical data combined with typical drone weather tolerances) found that the most common drones (resistant to wind ≤ 10 m/s, temperature 0–40 °C, no rain) can operate on average only about 87% of the time, with minimum values of around 54% in unfavourable locations (Lundby et al. 2019). Local case studies confirm these variations: for example, in Denmark, an examination of weather conditions over an entire year for two cities showed that, depending on the type of drone employed, the cumulative possible flight time ranged from just 57.9% up to 97.4% of the year (Table 1).

Table 1 % of drone flyability in Lundby et al. (2019)

Denmark		
UAV tipology	**Odense**	**Svendborg**
Phantom 4	62.6%	57.9%
Cumulus V1	95.6%	92.9%
Wingcopter	97.4%	96.3%
Volocopter	85.3%	80.1%

In other words, local microclimate and vehicle robustness strongly determine operational availability: cities with strong winds or frequent precipitation can force operations to stop for almost half of the year if suitable equipment is not used (Gao et al. 2021b). This has economic and service implications: on-demand UAM services risk being unreliable if "uptime" (available flight time) is low. Looking ahead, climate change may amplify these challenges by intensifying unfavorable environmental conditions. For instance, more frequent heatwaves may further reduce battery performance, while an increase in extreme convective phenomena (severe thunderstorms, hailstorms) could narrow safe flight windows. As some authors note, climate change can both facilitate flight in certain cases (e.g. drier terrain with fewer obstacles) and hinder it through more frequent extreme events – introducing entirely new circumstances to which drone transport will have to adapt (Sushma et al. 2025).

However, in studies not directly focused on drones but on related domains such as wind energy, some authors observe that climate change will not necessarily impact operability negatively in every context: on drier, obstacle-free terrain, the number of flyable hours could increase (Lira-Loarca et al. 2025). In this study, conducted over a very long temporal scale (100 years), the authors show that in certain areas – for example in Northern Europe (Fig. 1) – rising temperatures may translate into a larger number of operable hours, a favorable condition for drones but unfavorable for wind power.

Innovative approaches to integrating climate data are emerging in the literature. For example, within the SESAR (Single European Sky ATM Research) CREATE (Climate Resilient ATM - Air Traffic Management) project, although focused on conventional aviation, models are being developed to improve the resilience of air traffic management to adverse weather conditions (Vaisala 2025).

Transferring these concepts to U-Space may lead to advanced GIS tools where each pixel carries information on current climate and possible future trends (e.g. maps of temperature increase or changes in wind regimes by 2050). The use of urban Digital Twins is another trend: high-resolution CFD (Computational Fluid Dynamics) simulations can model airflows around buildings and identify true "wind corridors" in cities (Vaisala 2025). This wind-engineering

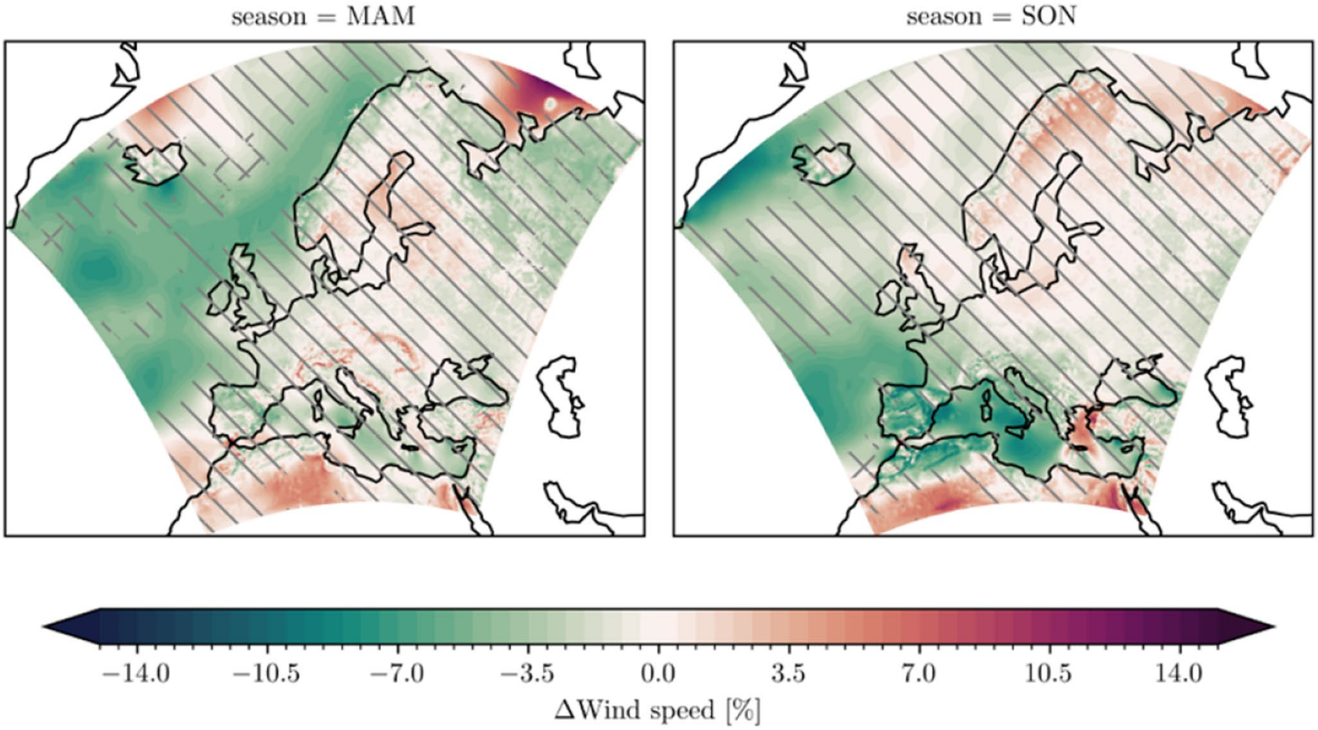

Fig. 1 % wind speed

study presented a framework for using high-resolution atmospheric simulations to identify local turbulent conditions and support the planning of safe drone operations in urban environments. This means being able to map zones of intense turbulence (e.g. upwind of high-rise buildings) and thus avoid placing aerial corridors there or instead implementing mitigation measures (barriers, operational limits).

In summary, the methodology consists of translating climate data into usable information layers: maps of risk, cost or climatic suitability. This can be done at multiple scales – from the regional scale (mean climate data or climate-change scenarios) down to the urban microscale (turbulence around individual buildings). Integrating these layers into multi-criteria decision-making processes and routing calculations makes it possible to identify infrastructure solutions that maximise operational resilience and safety, even under more extreme future climate conditions.

Traditionally, infrastructure siting is addressed with GIS methods and network models that account for planning constraints, service demand, obstacles, safety and regulations (Rikalovic et al. 2014). The same must be done for the planning of drone infrastructure such as vertiports and corridors. In this case, it becomes necessary to include climatic and meteorological criteria in spatial analysis models in order to find optimal and resilient solutions.

In the literature on urban climate adaptation, the UAM topic is emerging, and poor planning may exacerbate existing problems. Climate resilience of U-Space infrastructure refers to the ability of these systems to operate safely and effectively despite climatic disturbances, and to adapt to long-term changes. In the case of drones, a first approach is to develop thematic maps that highlight areas most vulnerable to specific climate hazards. For example, wind-risk maps can be created (zones with a high probability of winds>X m/s), along with fog-frequency maps or radar-based maps of thunderstorm cells. A Chinese research group has proposed generating a “risk map” for UAV operations by combining safety indicators in urban environments (Wang et al. 2024).

Although focused on population density and obstacles, a natural extension is to include meteorological parameters in such risk maps. In a GIS context, these vulnerability maps can be derived from climatic raster data combined with infrastructure locations: for each planned vertiport, the flood-risk layer, for example, can be overlaid to check whether the site is safe. A recent European project (HARMONIC Sesar Project 2023) is developing a decision-support GIS that includes a climate-resilience module: by selecting a corridor, the system returns an index based on how many days per year that route is affected by severe weather events, according to historical time series. This enables planners to evaluate alternatives: choosing a route with a higher resilience score, even at the cost of a few extra kilometers, may ensure greater long-term operational continuity.

The network’s rerouting capability is also assessed: can drones bypass a closed area by flying along other routes? Can adjacent vertiports compensate for the temporary unavailability of a main one? Using graph algorithms and GIS, vulnerable bottlenecks can be identified – that is, elements whose loss (even temporary) would isolate parts of the network. A geospatial approach is to calculate centrality and criticality indices for network nodes/edges based on traffic volumes and overlay them with the probability of climate-related failure (e.g. probability of closure due to weather). Infrastructure with both high criticality and high exposure should be redesigned or complemented with redundancies. For instance, if a single corridor crosses an area frequently affected by afternoon convective storms, it may be advisable to plan a parallel corridor further downstream as a backup during those hours.

Stress testing can be performed using climate-resilience indicators. In the transport literature, indicators such as robustness (the extent to which a network's performance degrades as stress increases) and recovery (how quickly it is restored) are commonly defined. For U-Space, geospatial indicators might include: the percentage of urban area served under a given weather scenario X, or the reduction in capacity (number of flights per hour) under strong wind conditions (20 m/s). By using projected climate data (e.g. 2050 scenarios), it is possible to estimate how these indicators will worsen if no measures are adopted. GIS can be used to show, for example, that by 2050 the area served by drones with a given reliability level may shrink if some zones become off-limits more frequently.

These analyses encourage solutions such as planning mobile or temporary vertiports that can be activated in emergencies (a concept discussed in some coastal cities, where during summer – with more stable weather – vertiports are used in tourist areas, whereas in winter – with storm surges and strong winds – operations are shifted to more sheltered inland sites). A relevant factor in emergencies is the planning and verification of alternative vertiports or emergency landing areas. Analogous to alternate airports for manned aviation in case of diversion, alternative en-route vertiports are being considered for drones, where they can land if the original destination is hit by sudden adverse weather (Mascio et al. 2025).

Design considerations for resilient vertiports

The authors argue that the climate resilience of U-Space infrastructure must be built ex ante, relying on an accurate use of spatial and climate data: from the identification and mapping of risks to the design of redundant networks, up to the simulation of stress-test scenarios. Geospatial techniques – such as risk maps, "climate cost surfaces" and integrated simulations – provide valuable quantitative tools to guide decisions and adapt the design of vertiports and corridors to future climatic "normals". As we have seen, the interaction between UAM/AAM planning and climate change is not limited to day-to-day operations but extends to the long-term adaptation of cities and territories. On the one hand, UAM is embedded in sustainable mobility strategies, in which electrically powered drones replace road vehicles, thus contributing to emission reduction and climate change mitigation.

On the other hand, however, climate change imposes adaptation challenges on UAM infrastructure itself. With rising temperatures and changing weather patterns, some sites may become less suitable, making siting a crucial factor. For example, a vertiport located on an inadequately ventilated rooftop in a Mediterranean city may experience excessively high air and surface temperatures in summer, penalising eVTOL (electric Vertical Take-Off and Landing) take-off performance. Planning should therefore incorporate microclimatic analyses (e.g. urban heat island models) to select sites with good natural ventilation or to provide passive/active cooling systems (such as "green vertiports" with green roofs to mitigate heat) (Prism Sustainability 2025). Moreover, extreme events such as intense cloudbursts and flash floods (increasingly frequent in Mediterranean climates) mean that ground vertiports or those near coasts/rivers should be designed with flood-protection standards and elevated platforms where necessary. Emerging guidelines suggest that vertiports, like traditional heliports, should have procedures for adverse weather: for example, operation suspension plans when wind exceeds thresholds, shelters for aircraft in case of hail, and enhanced drainage systems for heavy rainfall. Some bodies (NASA -National Aeronautics and Space Administration, EASA - European Union Aviation Safety Agency) are starting to compile lists of design considerations for AAM vertiports, including climate resilience: for instance, NASA mentions the need to address severe weather (thunderstorms, strong winds) with appropriate warning systems and protective structures. In Europe, a recent Eurocontrol study in collaboration with Vaisala identified various types of vertiport sites and their respective meteorological sensor requirements, highlighting how weather sensing will have to be adapted to the context (urban vs. rural, rooftop vs. open field) (Lundby et al. 2019). This has implications for planning: in areas where climate change may bring more fog or windstorms, it will be appropriate to equip vertiports with advanced sensors (LIDAR for wind shear, ceilometers for cloud base) and possibly locate them where a supporting meteorological observation network already exists.

Furthermore, the siting of corridors and vertiports must be coordinated with cities' climate adaptation strategies, as verified through spatial planning instruments and environmental constraints. For example, urban resilience plans may include "green corridors" or ventilation channels to mitigate the heat island. These ventilation corridors (open spaces aligned with prevailing winds) may either conflict or interact synergistically with drone aerial corridors. On the positive side, using an urban ventilation axis as a drone route can be efficient (limited turbulence because the area is kept open and green), but it may also mean exposure to stronger winds precisely in that area. Planners will have to consider these trade-offs and possibly integrate the two objectives: UAM corridors that also function as elements of urban adaptation. One example could be to reserve buffer strips for drone corridors that coincide with linear parks or railway lines, avoiding densely built-up areas that, besides being physical obstacles, also worsen natural ventilation.

It is also important to assess the interaction with other critical infrastructure, such as other transport modes, since during extreme climatic events UAM infrastructure could become a key element of urban resilience. For instance, in the event of flooding that cuts off roads, drones could provide emergency deliveries. Therefore, the vertiport network should be planned with redundancy and accessibility in mind under climate-crisis scenarios. A study on the role of UAM in future cities suggests integrating vertiports into municipal emergency plans, locating them near civil protection centres or hospitals, so that they can be used for relief operations when other routes are impracticable. In the European context, some research projects consider UAM and drones as part of the adaptive response to climate-related natural disasters (wildfires, floods), for example for monitoring and logistical support. Planning infrastructure today with these future uses in mind will enhance the overall resilience of the city.

Finally, regulators are introducing weather-related requirements for UAM operations. For example, EASA/U-Space may require that, at the corridor design stage, it be demonstrated that adequate safety margins exist with respect to statistically expected weather conditions. In practice, this would make ex-ante evaluation of climate data mandatory. In the USA, FAA (Federal Aviation Administration) regulations already require that flight be conducted in accordance with the manufacturer's instructions, which include weather limits. For future airborne taxi flights carrying passengers (which will likely fall under regimes similar to general aviation), authorities may require weather risk analyses as part of the route or vertiport certification process. Consequently, spatial studies will need to produce meteorological risk maps as part of the documentation.

Urban Digital Twin platforms can host both static data (buildings, networks) and dynamic data (real-time and forecast weather), enabling "what-if" scenario assessments. For example, the Urban Air Mobility Digital Twin project (OGC, 2021) combines infrastructure models with urban climate models to test different corridor layouts under simulated weather conditions (Rönsdorf et al., 2024). Such platforms make it possible to visualise how a weather front moves across the city and which aerial routes it affects, helping to optimise emergency plans. Private companies are also developing solutions: the start-up DM-AirTech proposes a "weather twin" of the vertiport – a digital micro-meteorological model around the site that provides operators with hyperlocal forecasts and operational recommendations (DM-AirTech 2025). This is made possible by integrating weather IoT (anemometric stations on the vertiport) with weather models: it is a geospatial extension of resilience, where the territorial information system is no longer static but interacts in real time with weather conditions to support decisions (for example: temporarily closing a corridor and redirecting flights to another).

Lastly, an important aspect where GIS excels is in intuitively communicating climate risks to stakeholders. Thematic maps showing, for instance, "red zones" of severe turbulence in the city, or charts that indicate, for each vertiport, the expected number of closure days, help policymakers and investors understand why certain measures (such as backup vertiports or investments in anti-icing technologies) are needed. For example, the consultancy firm WSP, in a 2022 white paper (Cammelli 2022), emphasised through diagrams and maps how UAM will be able to "weather the storm" only with planning that is attentive to climate data. In the document, urban wind roses and turbulence-intensity maps clearly showed which areas of London would be most problematic for drones and where relatively calm "natural corridors" exist. This type of geospatial output facilitates the inclusion of climate considerations in the planning debate.

Vertiports and corridors as stranded assets

Based on what has been discussed in the previous sections, infrastructures such as vertiports and corridors serving drones can be regarded as stranded assets. This term refers to investments or assets that experience an early loss of economic value, sometimes to the point of becoming a liability, due to substantial and unexpected changes in the economic, regulatory or environmental context in which they operate. Such assets thus become "abandoned" or economically unsustainable earlier than originally anticipated by investors, because physical or regulatory risks drastically reduce their value (Ansar et al. 2013; van der Ploeg and Rezai 2020).

Integrating ex-ante planning through preventive financial analyses to assess stranded-asset risk is fundamental to ensuring resilient and sustainable long-term decisions. This approach makes it possible to identify economic, environmental and operational risks in advance, significantly reducing the likelihood that investments in advanced air mobility infrastructure will prove financially unsustainable or even unusable in the years to come.

Originally, the concept of stranded assets was widely used to describe fossil energy resources such as oil, coal and natural gas (Carbon Tracker Initiative 2013, p. 5; McGlade and Ekins 2015).

For example, in accelerated decarbonisation scenarios aimed at keeping global warming within the limits established by the Paris Agreement, a significant share of fossil reserves already booked by companies risks becoming unusable and therefore financially compromised (NGFS 2021; Intergovernmental Panel on Climate Change (IPCC) 2023). However, in recent years the notion of stranded assets has expanded considerably, encompassing a wide range of physical and financial infrastructure, including power plants, pipelines, road networks, railways, real estate and, more recently, airports and other air transport infrastructure (Gupta et al. 2022).

In the specific case of drone-dedicated infrastructure, such as vertiports and U-Space aerial corridors, the potential to turn into stranded assets stems primarily from the physical risks associated with climate change. Indeed, these infrastructures are highly sensitive to adverse weather conditions, as discussed in the previous sections, and this can limit the daily operability (or "flyability") of drones (Lundby et al. 2019), and thus the return on investment. For example, investing in a vertiport that initially appears ideal from a climatic perspective may turn out to be financially unsuccessful in the long term if future climate scenarios show a significant intensification of extreme events, with a resulting increase in days of operational closure.

A recent study by Freeman et al. (2023), analysing 100 cities worldwide, showed that even under current climatic conditions, typical commercial drones can fly on average only about 87% of the annual time, with minimum values of 54% in regions particularly unfavourable in terms of weather. These operational limitations are expected to worsen further with the intensification of extreme weather events resulting from the aggravation of climate change (Gao et al. 2021b; Intergovernmental Panel on Climate Change 2023). This implies that a vertiport initially deemed sustainable may see its annual operational period drastically reduced over time, with a corresponding negative impact on its profitability and a possible shift into a stranded asset.

The same logic can be applied to corridors: one identified as optimal based on current climatic conditions may become unusable more frequently in the future, for example due to an intensification of strong winds and atmospheric turbulence along the route (Bolić and Ravenhill 2021; Jeong et al. 2021). This would lead to more frequent route deviations, the need for repeated replanning and potentially prolonged operational interruptions, with a consequent increase in operating costs and loss of service reliability, ultimately undermining the economic and strategic value of the initial investment.

Per affrontare questo problema, la pianificazione delle To address this issue, U-Space infrastructure planning must adopt a proactive and resilient approach, integrating climate-scenario analysis and stranded-asset risk assessment from the earliest decision-making stages. Some advanced techniques for such assessment include the analysis of future climate-change scenarios following the guidelines of the Task Force on Climate-related Financial Disclosures (TCFD) and the Network for Greening the Financial System (NGFS), Real Options Analysis (ROA), which assigns economic value to the strategic flexibility to defer or abandon investments, and Dynamic Adaptive Policy Pathways (DAPP), a method for managing investments in an adaptive and flexible way based on predefined climate triggers (Haasnoot et al. 2013; NGFS 2021).

Case studies

To illustrate how climatic and meteorological factors concretely affect drone operations and the planning of U-Space infrastructure, this section presents a set of representative case studies at different spatial scales. These examples range from software tools for assessing flyability in specific cities, to real-world medical delivery services, urban wind studies in Mediterranean contexts, global comparative analyses of drone operability, and European research projects that explicitly incorporate weather-related downtime into vertiport and corridor planning.

Taken together, these case studies show how climate data and local meteorological patterns can be translated into operational constraints, design guidelines and strategic choices for the location and dimensioning of vertiports and corridors, offering practical insights that complement the more general considerations discussed in the previous sections.

- Weather-analytics software for UAS – Odense/Svendborg (Denmark): As mentioned in Lundby et al. (2019), a software tool was developed and tested that, using historical weather data (provided by IBM Weather) over an entire year, evaluates the operability of different drones in two Danish cities. The main result – possible flight between roughly 54% and 96% of the time depending on the drone – highlights how, even in a temperate country, weather variability has a strong impact. This study did not aim to locate infrastructure, but by providing temporal "no-fly" diagrams for every hour of the year, it makes it possible to identify critical periods (e.g. winter with persistent winds) and thus plan operation schedules or resource allocation (more backup drones in certain seasons). It is an example of how climate data can guide the conceptual design of UAM services (e.g. defining daily operational windows according to local climate). Moreover, similar analyses could help to select "pilot" cities for early services: areas with high annual "flyability" would be ideal candidates for trials (e.g. arid Mediterranean regions).

- Medical-delivery drone project (Ackerman 2019) – Lugano (Switzerland): In Switzerland, the drone-based delivery of laboratory samples between hospitals (trialled by Swiss Post and Matternet) provided a real case of interaction with weather conditions. In 2019, a Matternet drone crashed into Lake Zurich during one of these missions; although the primary cause was technical, the incident led to a closer examination of wind and weather limits in operational procedures. Switzerland, as an Alpine country, features complex microclimates (strong mountain winds such as the föhn, fog in valley bottoms): the choice of routes between hospitals had to consider safety altitudes and whether to cross over or circumvent mountain ridges depending on wind forecasts. This case highlighted the need for pre-planned alternative corridors: a primary one, shorter but more exposed, and a backup one, longer but following a sheltered valley, to be used in adverse conditions along the first route. This is an example of contingency routing that should be embedded in U-Space plans: defining climatically safer secondary routes if the primary one is temporarily unavailable. Although the detailed procedures remain internal to Swiss Post operations, the case has been reported within the UAM community as a lesson learned on the importance of local weather.
- Italian and international studies on urban windiness: In Mediterranean contexts, a notable ongoing study is being carried out in the city of Bari (Italy), where the Polytechnic is analysing the impact of sea breeze (Adriatic breeze) on drone delivery trajectories. Using urban anemometric data and CFD simulations, researchers have mapped areas of minimum turbulence along the route from the port to the hinterland, identifying an optimal corridor parallel to a major road artery (which acts as an urban "canyon" and deflects the winds) (DRONESBENCH 2025). This case, presented in local workshops, demonstrates the usefulness of combining empirical data (weather stations) and fluid-dynamic models to design UAM corridors in coastal cities subject to regular daytime winds. An interesting result was the seasonal comparison: the proposed corridor maintains favourable conditions under summer breezes, but in winter, with northerly winds (tramontana), it is affected laterally – hence the suggestion to widen the corridor into a "buffer zone" to allow seasonal deviations.
- Global analysis of "flyability" – Mediterranean vs. Northern Europe: The global-scale study published in Scientific Reports (Gao et al. 2021b) provides data that can be interpreted as a macro-regional case study. From the analysis of the 100 largest urban centres worldwide, it emerges that cities with Mediterranean/dry climates (e.g. Phoenix, Cairo) have on average fewer no-fly days for drones than cities in Northern Europe or humid tropical zones (where wind, rain or cold impose greater constraints). In Europe, cities such as Athens and Madrid show a high percentage of flyable days, whereas London or Copenhagen show lower values, reflecting climatic differences. These data suggest that UAM strategies may succeed earlier in Mediterranean cities, although they will still need to address heatwaves and potential extreme rainfall events.
- SESAR "DACUS" project (Europe): The European DACUS project (Demand and Capacity Building for U-Space) produced a report in 2022 in which it notes the need to estimate vertiport and UAM corridor capacity while also accounting for possible weather-related downtime. It is mentioned that, to meet 2035 targets, roughly one vertiport per ~3,000 inhabitants may be required, but that the actual distribution will also have to consider meteorological availability: urban areas where weather frequently causes suspensions may require redundant vertiports to guarantee the desired service level. For example, DACUS hypothesises a denser network of backup vertiports in southern France due to possible mistral events and convective summer thunderstorms. This case illustrates how, at national planning level, climatic considerations are beginning to be included when sizing and distributing infrastructure.

Metodology

Before detailing the individual steps, this chapter outlines the methodological framework adopted for analysing the climate resilience of U-Space infrastructure. First, the general research context is presented (Sect. 4.1), where the objectives, the main factors considered, and the GIS–MCA approach integrated with network models are defined. Subsequently (Sect. 4.2), the procedure for quantifying flyable hours is introduced, based on historical meteorological data, orographic characteristics and warming scenarios. Finally, the modelling method for extending the analysis to a raster grid is described, enabling the production of geospatial "flyability" maps under current and future conditions, which serve as a basis for computing minimum-cost flight corridors. This methodological pathway ensures a consistent and reproducible analysis capable of supporting informed decision-making in the planning of UAM and AAM infrastructure.

General research context

The authors propose to identify the most suitable areas for the development of drone infrastructure (vertiports and aerial corridors) through the use of GIS and network models that integrate planning constraints, service demand, obstacles, safety requirements and current regulations (Cunietti et al., 2023; 2025). The study first identifies the main factors that influence flight and their interactions, assessed through a multi-criteria analysis (MCA) applied to raster grids, with the aim of selecting optimal zones for vertiports. These vertiports then act as nodes for defining flight corridors: although there is an active debate between static and dynamic corridors, in this work they are treated as static. Corridor routing is performed using Least Cost Path algorithms applied to the territorial MCA. Finally, among the information layers considered, climatic and meteorological criteria derived from specific spatial analyses are also included.

Nell'ambito della MCA, ogni fattore rilevante viene modellato come uno strato informativo GIS in formato raster. Numerosi studi recenti sulla pianificazione di vertiporti e corridoi UAM adottano approcci MCA che integrano:

Within the MCA framework, each relevant factor is modelled as a GIS information layer in raster format. Numerous recent studies on the planning of vertiports and UAM corridors adopt MCA approaches that integrate:

- Safety (e.g. risk of crashes over populated areas).
- Social acceptability (e.g. noise impact).
- Drone performance (e.g. endurance as a function of energy consumption).
- Planning constraints (zoning plans, land use).

Each criterion is assigned a weight and a suitability scale (e.g. from 0 = unsuitable to 1 = highly suitable) for every territorial cell. The weighted overlay of all layers generates a composite score map, highlighting the areas most favourable for installing UAM infrastructure.

Among the planned information layers, climatic and meteorological criteria, derived from spatial analyses, are also included. One possible approach consists in producing maps based on historical data or climate projections, for example the percentage of non-flyable hours for each pixel of a raster at 50 m resolution. This indicator is obtained by combining drone operational thresholds with climate datasets (e.g. ERA5 reanalysis or observations from local weather stations), thus providing a direct measure of territorial "flyability".

In the case study of the Emilia-Romagna region (Italy), for instance, the historical dataset from regional weather stations (such as those provided by ARPAE) could be used to estimate, for each location, the fraction of time in which wind, rainfall, temperature and other variables exceed safety thresholds. This fraction, spatially interpolated, generates a raster of climatic criticality. The higher the value, the greater the "cost" assigned to that area in planning. In an MCA, this climate layer would be integrated alongside others (planning, socioeconomic, etc.), with a weight proportional to the importance of climate/weather for service resilience, as discussed in Lundby et al. (2019).

In this work, the topic is addressed from a static perspective, using historical data. However, dynamic integration into path-planning models is also possible: beyond static GIS, there are dynamic path-planning methodologies that incorporate weather forecasts into route calculation in quasi real time. One example is provided by optimisation algorithms and 4D flight simulations: a study proposed a UAV mission-planning model that divides the time horizon into "weather windows" in which wind and conditions remain similar, planning segments within each window while accounting for the forecast wind speed and direction (Thibbotuwawa et al. 2019).

Checking flyability hours

In this work, we developed a procedure that, starting from meteorological and topographic data, produces annual maps of "safe" flight hours under current conditions and under a hypothetical warming strees-test scenario (+6 °C). The +6 °C offset is adopted as an upper-bound sensitivity case (SSP5-8.5-like from IPCC), and results should be interpreted as stress-testing evidence rather than as a deterministic forecast. First, we loaded a Digital Elevation Model (DEM) and derived orographic characteristics – slope, aspect and roughness – which influence local airflows and turbulence. In parallel, we pre-processed the raw weather record (15-minute resolution), converting temperatures to °C, aggregating measurements to hourly values and applying simple operational thresholds derived from the drone specifications (wind $\leq$ 15 m/s, rainfall $\leq$ 2 mm in 15 min, temperature between −20 °C and +40 °C). We then introduced a warming scenario by adding +6 °C to hourly temperatures to assess the effect of a hotter climate on flight conditions.

For each weather station, we calculated the fraction of hours in which all conditions (wind, rainfall, temperature) were simultaneously satisfied, both in the current state and in the hypothetical scenario. These fractions were then combined with the coordinates and orographic descriptors of each station and used as the response variable in a Random Forest regression model. By training the model with point data, we estimated the relationship between the fraction of flyable hours and local characteristics (DEM, slope, aspect, roughness, latitude, longitude).

Finally, the model was applied to the entire DEM raster grid, generating two series of GeoTIFFs: one for flyable hours under current conditions and one for the +6 °C scenario. By converting the fraction of hours into an annual number (fraction × 8,760 h), we obtained immediately interpretable summary maps providing a quantitative "flyability" indicator, useful both for assessing the resilience of U-Space infrastructure and for estimating the risk that climate variations may turn investments into stranded assets.

Results

By comparing the current scenario (based on historical climate data – Fig. 2) with the warming scenario (+6 °C – Fig. 3), several relevant considerations emerge for U-Space infrastructure planning in Emilia-Romagna. First, a clear general reduction in potentially flyable hours is observed across almost the entire study area. The spatial distribution of this reduction is not uniform but shows a distinct altitudinal gradient: the higher the elevation, the more pronounced the loss of operability becomes. Lowland areas, especially along the Adriatic coast, continue to provide the highest number of operable hours, and thus remain the most favourable even in the future scenario. Conversely, inland areas characterised by hills and the Apennine belt experience a significant decrease in flyable hours, with more marked losses in the transition zones between plains and mountainous reliefs.

This variation is particularly critical for hilly areas, which currently represent intermediate zones with still acceptable levels of operability, but which nonetheless prove to be increasingly vulnerable as temperatures rise, showing a reduced suitability for flight.

From a planning perspective, this information is crucial for designing infrastructure that is resilient to climate change, demonstrating that relying solely on historical climate data may not be sufficient. Integrating future climate

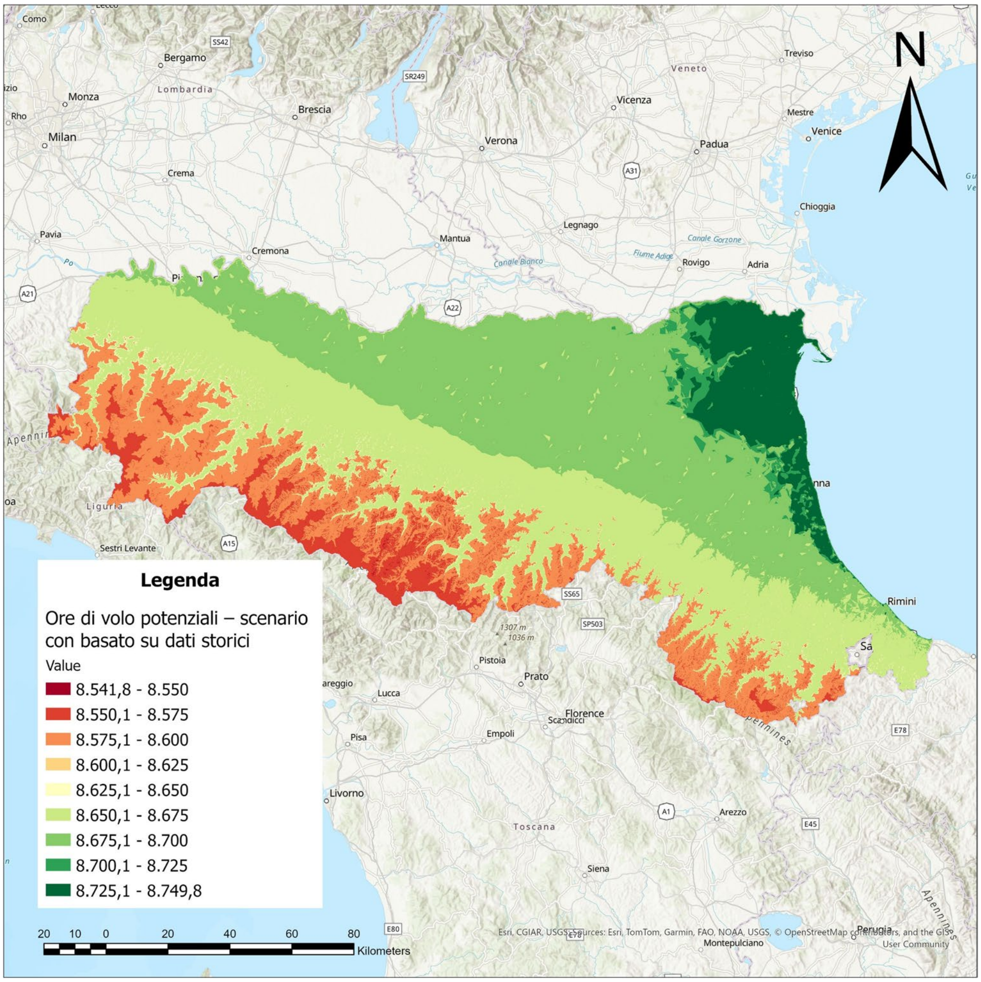

Fig. 2 Potential flight hours - scenario based on historical data

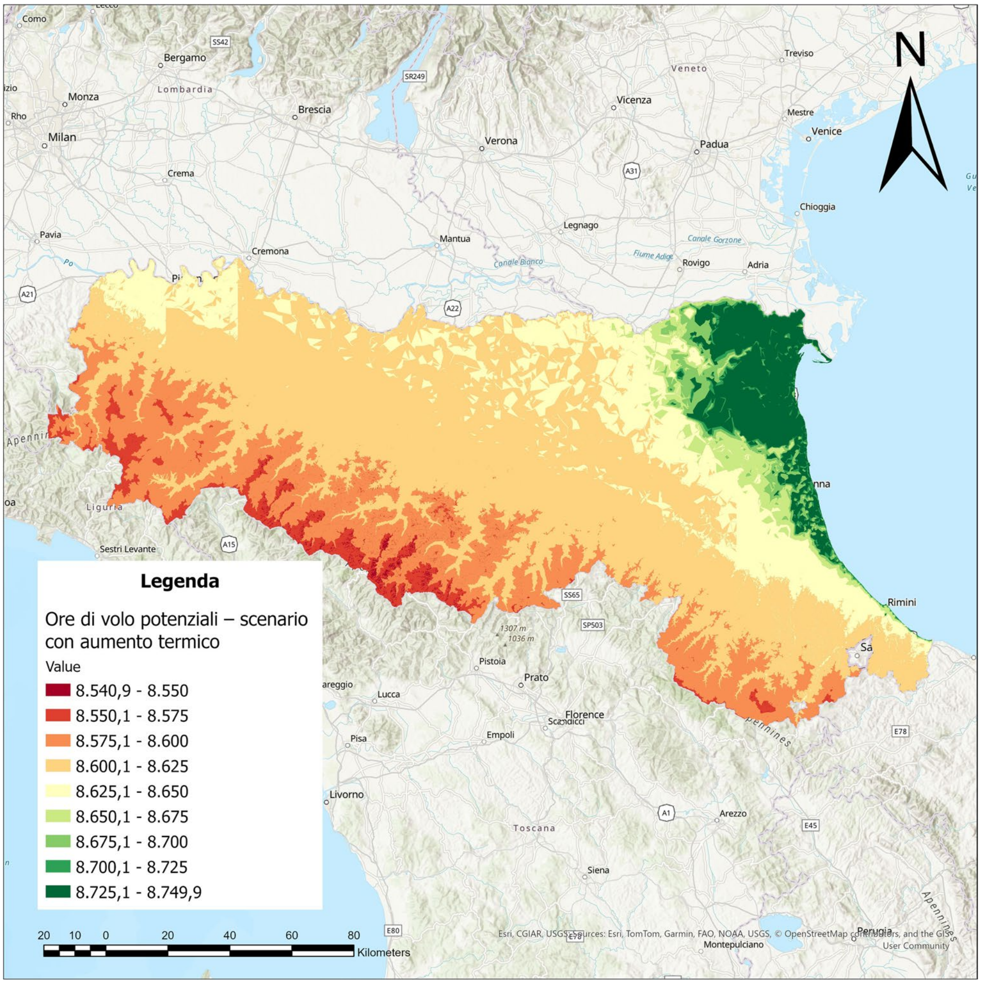

Fig. 3 Potential flight hours - scenario with thermal increase

scenarios into territorial analyses makes it possible to identify potentially critical areas in advance, and thus to direct investments and the siting of vertiports and aerial corridors towards areas that will maintain a high level of operability even under significant environmental change. Therefore, although the absolute percentage reduction may appear limited, the spatial reshaping of "flyability" represents a key element in defining advanced air mobility (UAM/AAM) infrastructure, with direct implications for its long-term operational continuity and economic effectiveness.

Conclusions

Although the historical and future flyability maps show only a marginal reduction in total flight hours, they clearly highlight that climate warming has an impact. This effect is spatially uneven, and this picture leads to two main considerations for U-Space infrastructure planning. First, the siting of vertiports and aerial corridors should be prioritised in areas where flyability remains high even in the future, by integrating dynamic climate maps into decision-making processes. Second, in inland and foothill areas – where the service risks becoming intermittent – it is necessary to develop adaptation strategies: alternative routes, satellite vertiports in valleys, energy storage systems to compensate for operational blackouts, and real-time weather monitoring. Only through "climate-aware" design, which accounts for the spatial variability and future degradation of atmospheric conditions, will it be possible to ensure the long-term safety, continuity and reliability of drone services.

In this study, warming is represented through a uniform + 6 °C temperature offset, adopted as a high-end sensitivity (stress-test) case broadly consistent with the upper tail of very high-emission pathways such as SSP5-8.5. This setup isolates the thermal component and does not explicitly model the coupled evolution of wind and precipitation expected under pathway-based climate projections; accordingly, the resulting maps should be interpreted as upper-bound sensitivity evidence supporting robust siting decisions. Building on this framework, future developments may rely on multi-scenario CMIP6 ensembles and multivariable downscaling to quantify uncertainty and compound impacts more explicitly.

A further line of enquiry concerns the extension of the no-fly period. In the present study, we excluded only the hours corresponding to the extreme weather event itself, whereas it is likely that "buffer windows" exist immediately before and after the event, during which drones already in flight must return and no new missions can be scheduled. This consideration substantially lengthens the overall duration of service interruption. As a consequence, beyond assessing the frequency of events that exceed acceptable operational thresholds, it becomes even more important to quantify the total time obtained by summing the safeguard window and the event duration associated with each episode, since even a short-lived meteorological phenomenon can generate a prolonged shutdown of the entire network.

Only by adopting climate-aware planning, capable of capturing the spatial variability and future deterioration of weather conditions, will it be possible to guarantee in the long term the safety, continuity and reliability of drone transport.

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Data availability The datasets generated and analysed during the current study are available from the corresponding author on reasonable request due to their large file size.

Declarations

Competing interests The authors declare no competing interests.

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