



Proceeding Paper

Classification of Unmanned Aerial Vehicles in Meteorology: A Survey[†]

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† Presented at the 16th International Conference on Meteorology, Climatology and Atmospheric Physics—COMECP 2023, Athens, Greece, 25–29 September 2023.

Abstract: Unmanned aerial vehicles (UAVs) are increasingly being used in meteorology research due to their ability to overcome challenges such as difficult access to hazardous locations and the need for high-resolution and real-time data. UAVs provide accurate and precise high-resolution data that allows scientists to study small-scale weather phenomena in unprecedented detail. This survey highlights the different types of UAVs used in meteorology, including fixed-wing, rotary-wing, and hybrid UAVs, as well as the various payload options available, such as sensors for temperature, humidity, pressure, wind, and precipitation. Overall choosing the appropriate UAV for meteorological applications relies on meeting specific mission requirements, including various factors.

Keywords: UAV; drones; meteorology; multirotor; fixed-wing; weather; sensors



Citation: Mourgelas, C.; Micha, E.; Chatzistavrakis, E.; Voyatzis, I. Classification of Unmanned Aerial Vehicles in Meteorology: A Survey. *Environ. Sci. Proc.* **2023**, *26*, 135.

<https://doi.org/10.3390/environsciproc2023026135>

Academic Editors: Konstantinos Moustiris and Panagiotis Nastos

Published: 31 August 2023



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1. Introduction

Meteorology research poses numerous challenges, such as accessing remote or hazardous locations and collecting real-time data during rapidly changing weather conditions. To address these challenges, unmanned aerial vehicles (UAVs) are increasingly utilized for gathering valuable atmospheric data. UAVs offer high-resolution and precise data, facilitating detailed investigations of small-scale weather phenomena. This survey explores the classification of UAVs in meteorology, encompassing diverse platforms and configurations such as fixed-wing, rotary-wing, and hybrid models. Fixed-wing UAVs provide extended flight time and endurance, while rotary-wing UAVs offer enhanced agility and lower altitude capabilities. Hybrid UAVs combine advantages from both types, rendering them versatile for various meteorological missions. The survey also emphasizes payload options, including sensors for temperature, humidity, pressure, wind, and precipitation. These payloads enable meteorological applications like weather forecasting, climate research, and atmospheric studies.

This paper presents a comprehensive survey on the classification of UAVs in meteorology, analyzing their types, applications, payloads, power sources, takeoff and landing techniques, and endurance. The aim is to establish an extensive understanding of the current state of the art in meteorological UAV technology.

This survey is organized as follows. Section 2 presents an overview of the publications included in the survey. Section 3 presents the methodology used for analysis and comparison of the publications. Section 4 presents a comprehensive assessment of UAVs' performance in meteorological research and applications. In conclusion, Section 5 presents the key findings and insights derived from the study.

2. Related Work

UAVs have proven to be valuable tools in wind measurement and meteorological observations. They have been used to detect Lagrangian Coherent Structures (LCSs) and

track hazardous agents after hurricanes [1], measure wind vector profiles using ultrasonic anemometers that are traditionally obtained through meteorological towers and radiosondes [2], provide precise airborne wind measurements in challenging terrains [3], overcome limitations with a dynamic model-based approach in wind measurement methods [4], and estimate turbulence regimes [5]. In addition, UAVs have been deployed to collect high-frequency wind measurements in hurricanes [6], study tornadoes [7] and access rear flank downdraft (RFD) inflows at higher altitudes [8]. Such studies can help advance our understanding of tornado formation, which is crucial for improving early warning systems and reducing damage and loss of life.

Meteorological measurements play a vital role in understanding and predicting weather patterns, and UAVs have been increasingly used for efficient and cost-effective data collection. UAVs gather meteorological measurements such as temperature, humidity, air pressure, wind data [9], atmospheric sampling, and boundary layer profiling [10]. Additionally, UAV applications expand to remote sensing of temperature and wind profiles with acoustic signatures and tomography [11], autonomous sensing and sampling in the lower atmosphere [12], flying weather stations [13], high-resolution measurements for Numerical Weather Prediction (NWP) [14], and near-surface environmental measurements [15].

Furthermore, UAVs have the potential to enhance weather forecasting and atmospheric measurements [16] and provide accurate data on mixed-phase winter-weather events [17]. They have also been employed in specific applications such as cloud seeding [18], calculation of land surface temperatures [19], volcanic gas plume measurements [20], and cloud exploration [21]. These studies highlight the adaptability and versatility of UAVs in atmospheric and environmental research, demonstrating their potential in various scientific domains.

3. Methodology

The categories mentioned are essential for organizing and understanding the capabilities and limitations of UAVs used in meteorology. They provide a helpful framework for decision-making when choosing and utilizing UAVs for collecting meteorological data.

Figure 1 shows the tree structure with the proposed categories for comparison. Classification of UAVs in meteorology can be divided into five main categories based on various factors.

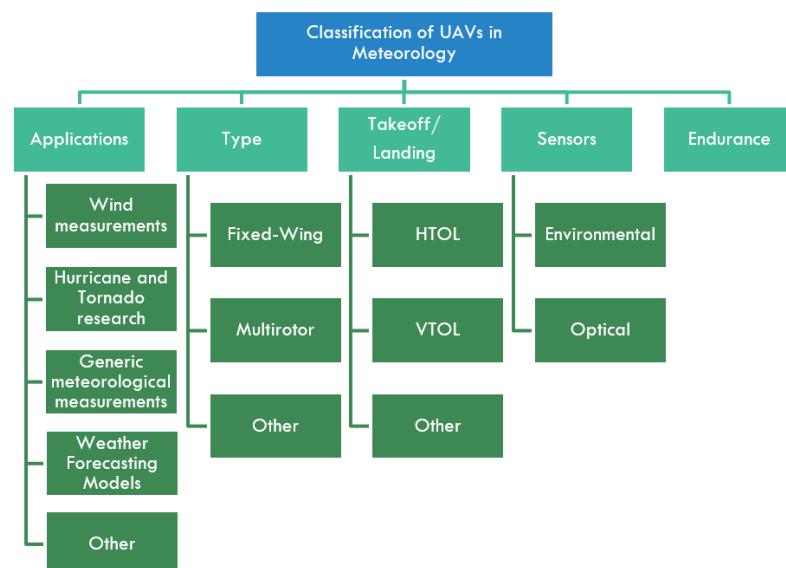


Figure 1. Categories featured in the methodology structure.

The first category is based on the applications that use drones to collect atmospheric data.

The second category is based on the type or shape of the UAV, which can be fixed-wing, rotary-wing, or other types like gliders. Fixed-wing UAVs have wings like traditional airplanes and can cover longer distances and stay in the air for longer periods of time. Rotary-wing UAVs have rotors and can hover and maneuver more easily in confined spaces. Other UAVs may combine the advantages of both fixed-wing and rotary-wing designs or can be used on specific applications.

The third category is based on the takeoff and landing of the UAV, which can be vertical, horizontal, or a combination of both. Vertical takeoff and landing (VTOL) UAVs can take off and land like helicopters, while horizontal takeoff and landing (HTOL) UAVs require a runway or catapult for takeoff and a net, runaway, or parachute for landing. Some UAVs use a combination of both VTOL and HTOL, allowing for greater flexibility in operations.

The fourth category is based on the endurance of the UAV, which refers to how long the UAV can remain in the air before needing to land and recharge or refuel. Endurance can vary greatly depending on the size, weight, and design of the UAV.

The fifth category is based on the sensors used in the UAV for environmental measurements, which can include anemometers-pressure-temperature-humidity (TPU), wind, UV, and particle concentration sensors. In addition, optical sensors such as cameras allow the UAV to collect data on weather patterns and other environmental factors.

4. Evaluation

Based on the analysis of [1–4], Table 1 indicates that multirotor UAVs are the preferred choice for wind measurement applications. This preference is due to the ease of use provided by their vertical takeoff and landing capabilities compared to fixed-wing UAVs [5], which require a larger area for horizontal takeoff and landing. It is worth noting that all UAVs utilized in these applications are powered by batteries. However, [5] demonstrates better endurance, making it suitable for longer flight durations and extended measurement periods. The sensors employed in these applications predominantly comprise wind sensors, complemented by humidity, temperature, and infrared sensors.

In the context of hurricane and tornado research, papers [6–8] highlight the preference for fixed-wing UAVs. These UAVs are equipped with standard atmospheric pressure, temperature, and humidity sensors, providing essential data for these challenging missions. All the UAVs in this category are powered by batteries, ensuring their autonomous operation, although there are variations in the takeoff and landing techniques. Notably, in [6], the UAV is deployed by being dropped from an airplane, with the important distinction that it is not recovered after its mission. The UAV in [7] employs a catapult for takeoff, while the UAV in [8] is hand casted into the air and subsequently retrieved using a parachute. One common characteristic among these UAVs is their extended flight time, which can be attributed to the aerodynamic nature of fixed-wing designs. The ability to sustain longer flights enables these UAVs to cover greater distances and gather more data, making them valuable tools in hurricane and tornado research.

After an extensive review of studies [10–15], it has been established that multirotor UAVs are the optimal choice for generic meteorological measurements due to their enhanced maneuverability, providing greater control during takeoff, landing, and hovering. Multirotor UAVs are also more suitable for close-range and low-altitude applications, as they are capable of vertical takeoff and landing. Their compact size allows for quick and efficient deployment in the field, where they can collect various measurements using sensors such as PTU, wind, UV index, and camera modules. All multirotor UAVs in this category are battery powered, making them easy to deploy at any time.

In contrast, the fixed-wing UAV in [9] utilizes an internal combustion engine, achieving up to 5 h of flight time and carry heavier payloads over long distances. However, its complexity in maintenance, difficulty in quick deployment and recovery, and high cost make it less feasible for generic meteorological measurements.

Table 1. Applications and characteristics of UAVs.

Paper	Type	Application	Sensors	Power	Takeoff/Landing	Endurance
[1,2] [3,4]	Multirotor	Wind measurements	Wind	Battery	VTOL ¹	15–30 m
[5]	Fixed-wing	Wind measurements	Wind, PTU ² , Infrared	Battery	HTOL ³	2 h
[6]	Fixed-wing	Hurricane and Tornado research	PTU, Infrared	Battery	Dropped by airplane/Do not recover	1 h
[7,8]	Fixed-wing	Hurricane and Tornado research	PTU	Battery	HTOL	2–3 h
[9]	Fixed-wing	Generic meteorological measurements	PTU	ICE ⁴	HTOL	10 h
[10,15]	Multirotor	Generic meteorological measurements	PTU, Wind, Particle concentration	Battery	VTOL	-
[11]	Multirotor	Generic meteorological measurements	PTU	Battery	VTOL	28 m
[12,14]	Multirotor	Generic meteorological measurements	PTU, Wind	Battery	VTOL	18.5 m
[13]	Multirotor	Generic meteorological measurements	PTU, UV index, Camera	Battery	VTOL	-
[16]	Glider	Weather Forecasting Models	PTU	Gliding	HTOL	Up to 5 h
[17]	Multirotor	Weather Forecasting Models	PTU	Battery	VTOL	18–20 m
[18]	Tiltrotor	Cloud seeding	Calcium chloride flares	ICE	VTOL	5 h
[19]	Multirotor	Calculation of land surface temperatures	Thermal infrared camera	Battery	VTOL	38 m
[20]	Multirotor	Volcanic gas plume measurements	MultiGAS	Battery	VTOL	30 min
[21]	Fixed-Wing	Cloud exploration	PTU, Wind, Droplet extinction	Battery	HTOL	1 h

¹ Vertical takeoff and landing. ² Barometric pressure, temperature, and relative humidity. ³ Horizontal takeoff and landing. ⁴ Internal combustion engine.

Researchers in [16,17] contribute to the advancement of weather forecasting models through the use of different drone types. Study [16] employs a glider drone that operates without motors, relying on natural lift sources such as thermals, ridge lift, and wave lift for sustained flight. The glider's battery powers only the sensors, resulting in a silent operation. However, gliders have inherent limitations, including a restricted range and landing area and reliance on favorable weather conditions for lift generation, as well as an airplane to tow it during take-off and when ascending. Conversely [17], utilizes a custom-made multi-rotor drone powered by batteries, capable of VTOL. This feature allows the drone to operate in confined spaces and hover in specific locations. However, the multi-rotor drone has a shorter endurance of 18–20 min compared to the glider, necessitating more frequent battery changes or recharging. Notably, both UAVs are equipped with PTU sensors and are tailor-made to suit their respective research objectives.

Paper [18] focuses on the utilization of a tilt-rotor unmanned aerial vehicle (UAV) specifically designed for cloud seeding purposes. Tilt rotors offer a unique combination of VTOL capability and airplane-like efficiency, allowing them to achieve higher speeds and cover longer distances. They provide greater flexibility in terms of operating in confined spaces compared to fixed-wing UAVs, as they do not require a dedicated runway. However,

tilt rotors tend to have higher weight, maintenance requirements, and costs due to their complex design and rotating nacelles. The UAV in [18] incorporates calcium chloride flares as sensors. It is powered by an internal combustion engine (ICE) and possesses a VTOL capability. The notable advantages of this UAV include its impressive endurance of up to 5 h, enabling it to effectively carry out cloud seeding operations. However, it is important to consider that the use of an ICE for power generation may introduce emissions and contribute to noise pollution, which are potential drawbacks to be addressed.

In [19], a multi-rotor UAV is employed for the calculation of land surface temperatures. This UAV is equipped with a thermal infrared camera and is commercially available. It operates using a battery power system and possesses VTOL capability. The key advantages of this UAV include its adaptability in capturing thermal data within densely populated urban areas and its relatively extended endurance of 38 min. For the purpose of volcanic gas plume measurements [20], employs a multi-rotor UAV equipped with the MultiGAS sensor platform, which has been developed specifically by the researchers. It operates using a battery power system with VTOL capability. Although it offers the advantage of flexibility in maneuvering around volcanic areas and collecting valuable gas data, its endurance is limited to 30 min.

Lastly [21], utilizes a battery-powered fixed-wing UAV for cloud exploration. This drone is equipped with PTU sensors, wind sensors, and droplet extinction measurement capability. It operates using a battery-powered system and offers multiple options for takeoff and landing, including hand casting or a catapult launch, as well as a horizontal or parachute landing. It is important to note that the Skywalker X6, being a fixed-wing UAV, requires a suitable runway or launching area for takeoff and landing, which may limit its usability in certain environments compared to drones with (VTOL) capabilities.

5. Conclusions

In conclusion, the survey on the classification of unmanned aerial vehicles in meteorology highlights that the choice of UAV type depends on the specific requirements of the mission. Multirotor UAVs are the preferred choice for wind measurement and generic meteorological applications due to their ease of use, maneuverability, and ability to operate in confined spaces. On the other hand, fixed-wing UAVs are preferred for hurricane and tornado research due to their extended flight time and ability to cover greater distances. Glider drones are a suitable option for eco-friendly research, but they have inherent limitations. Tilt-rotor UAVs offer a unique combination of vertical takeoff and landing capabilities and airplane-like efficiency, making them ideal for cloud seeding operations. Overall, the selection of a UAV for meteorological applications depends on the specific needs of the mission, such as endurance, payload capacity for sensors, and operational flexibility.

Author Contributions: Conceptualization, C.M., E.M., E.C. and I.V.; Data curation, C.M., E.M., E.C. and I.V.; Methodology, C.M., E.M., E.C. and I.V.; Writing—original draft preparation, C.M., E.M., E.C. and I.V.; Writing—review and editing, C.M., E.M., E.C. and I.V. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Ethical review and approval were waived for this study as it did not contain sensitive and confidential information.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare that they have no conflict of interest to report regarding the present study.

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