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Systematic Review of Weather Observation and Forecast Resources Available to General Aviation Pilots

J W. Wallace

Nicoletta Fala

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J.W. Wallace
Oklahoma State University
Stillwater, OK

Nicoletta Fala
Oklahoma State University
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Weather continues to be a consistent hazard for pilots despite decades of progress in both pilot education and weather observation and forecasting technology. Much research has been done on the various facets of this problem, from pilot psychology to the weather information sources themselves. Weather-Intelligent Navigation Data and Models for Aviation Planning (WINDMAP) is a NASA University Leadership Initiative (ULI) that aims to use Unmanned Aerial Systems (UAS) to improve the accessibility and accuracy of weather information for General Aviation (GA) pilots and UAS operators. This paper aims to produce a systematic review of research on the topic using the Preferred Reporting Items for Systematic reviews and Meta Analyses (PRISMA) method that will then guide a further survey-based study of source utilization by GA pilots and UAS operators. Through the survey, we aim to evaluate satisfaction and need for improvements among weather products and education.

Weather continues to be a problem for pilots despite advances in both weather observation/forecasting technology and pilot education. According to the most recent complete Nall Report, of 42 weather related accidents in 2017, 32 proved fatal (AOPA Air Safety Institute, 2020). Despite making up only 4% of total accidents, the high fatality rate when compared to most other accident types makes weather accidents a problem worth investigating. Additionally, the growing Unmanned Aerial Systems (UAS) industry and budding development of Urban Air Mobility (UAM) will demand different or better weather observation and forecasting technology. To develop new and useful systems for pilots and UAS operators we must first review prior work and evaluate what products and information is available against the community's needs. The purpose of this review is to evaluate recent research in pilot education and weather observation and forecasting technology to better inform future work. Following the conclusions of this review, we will conduct a survey of both general aviation pilots and UAS operators to determine their respective aviation weather product awareness, use, and needs, as well as attempt to identify areas where new products could better serve UAS operators.

This research supports the WINDMAP NASA University Leadership Initiative (ULI), a four-year project which aims to address needs in real-time weather forecasting to improve the safety of low-altitude aircraft operations by integrating real-time observations from drones and other aircraft with weather prediction and flight management systems (Jacob, 2020). The literature review and survey introduced in this paper will provide customer requirements to inform system design and research within WINDMAP.

Methodology

The Preferred Reporting Items for Systematic reviews and Meta Analyses (PRISMA) method presents a systematic review method which allows us to simultaneously cast our literature net as wide as possible while also being able to narrow down to relevant literature in an efficient manner, as shown in Figure 1 (Moher, Liberati, Tetzlaff, & Altman, 2009). We included three search databases (Google Scholar, Scopus, and Microsoft Academic Graph) in the search. Each search used the same five sets of keywords: (1) 'aviation' or 'aircraft' or 'cockpit', (2) 'weather', (3) 'safety' or 'hazard' or 'risk' or 'decision making' or 'decision-making', (4) 'training' or 'education' or 'instruction' or 'information', and (5) 'pilot' or 'UAV' or 'drone'. Combining the items using Boolean operators yielded the following search criteria: "(aviation OR aircraft OR cockpit) AND weather AND (safety OR hazard OR risk OR 'decision making' OR 'decision-making') AND (training OR education OR instruction OR information) AND (pilot OR uav OR drone). Including 'UAV' or 'drone' proved to be more of a hindrance than a benefit as we ended up rejecting most of the papers with those keywords for failing to address the human UAS operators, instead focusing on the autonomous systems.

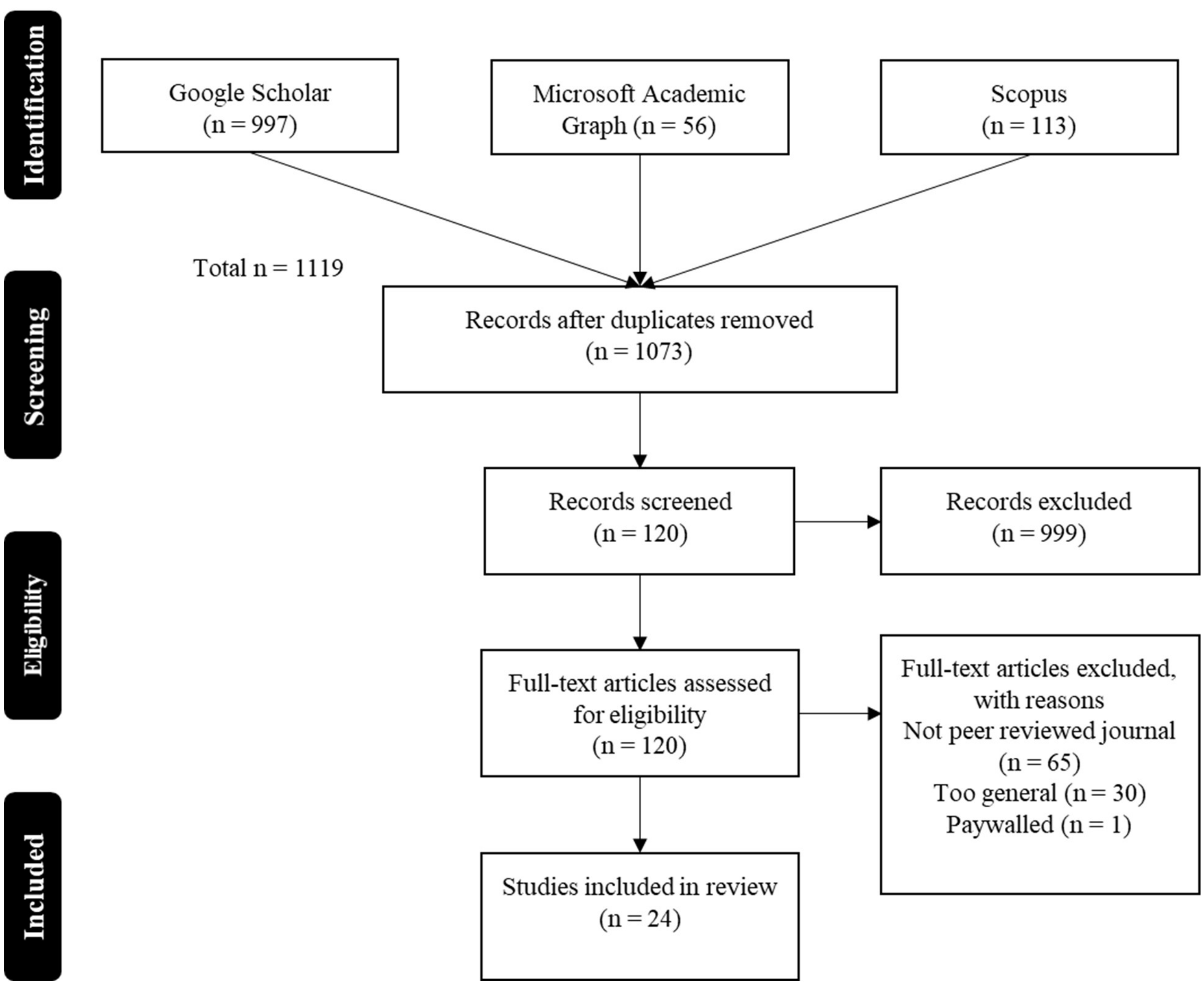

Figure 1. The systematic review discussed in this paper used the PRISMA method which consists of four steps that narrow down the identified papers based on relevance.

Removing duplicates resulted in a list of 1073 papers. Two reviewers (JW and NF) scanned titles and abstracts to determine eligibility and exclude papers which were not relevant to the subject. The two reviewers classified papers as *include*, *exclude*, and *maybe include*, and advanced any papers that belonged in the *include* and *maybe* categories to the full-text eligibility assessment. JW's review advanced 120 papers for full-access eligibility and NF's 130, with a conflict of 65 papers (5.6%). However, the conflict percentage includes disagreements where one reviewer classified a paper as *include* and the other as *maybe include*. Advancing both categories to full-text assessment eligibility decreased the conflict. We used the Rayyan web app to do this review (Ouzzani, Hammady, & Elmagarmid, 2016). At the full-text assessment stage, we evaluated papers for eligibility using two inclusion criteria: the papers had to be published in a peer-reviewed journal and have an adequate focus on pilot-weather interactions.

Results

We selected 24 articles that meet the inclusion criteria. Articles selected covered a range of topics from methods for educating pilots about new weather products to the development and implementation of the weather products themselves. While three selected papers do not directly address pilot-weather product interactions, they contain relevant information for design and technology implementations. We identified three themes in the reviewed literature. The accuracy and interpretation of weather products by pilots was the primary focus of most of the papers reviewed, some focusing more on the weather products and others more on the pilots. Papers focusing on the products themselves frequently addressed the symbology used by the product to convey weather information, while those focusing on pilots examined the use, effects, and education considerations for different weather products. A third theme emerged focusing on the pilots' biases and experiences with poor weather. This section describes the prior research in the literature in the context of the three themes.

Theme 1: Weather Products

Weather products are a central theme in ten of the papers reviewed. Within this theme there emerged two subthemes: symbology, and non-graphical modes of communicating information.

While papers on symbology were not definitive in their recommendations with respect to display symbology, they indicated that the graphical language used impacted pilot interpretability. Weather display symbology impacted pilot behavior and decision making in both VMC and IMC simulated flights (Ahlstrom, 2015). However, rather than recommending specific symbology for weather displays, Ahlstrom recommended that the development and assessment of a cockpit application which would automatically track and alert the pilot to weather conflicts or changes.

Papers with design as a central theme researched additional modes of conveying information. Pilot aids, in the form of either general digital copilots or more specialized tools, were featured in two papers. A digital copilot decreased head-down time in all tasks except determining the weather communication frequency (Wilkins, 2018). While the tasks assessed do not relate to pilot interpretation of weather information in the cockpit, the technology shows promise. A Risk Situation Awareness Tool (RSAT) also shows promise as an additional input source for pilots making decisions about how to best route around thunderstorms and other hazardous weather (Parmar & Thomas, 2020). The study presented pilots with NEXRAD loops with flight paths overlaid with and without the RSAT calculated risk and asked them to determine if the path was safe, or to determine which of two paths was safest. The study found that pilots who used RSAT were more likely to choose safer flight paths than the control group.

NEXRAD has been in use in GA for some time, but the topic of its reliability is not settled, with some researchers arguing that the current NEXRAD cannot reliably enable safe flight around heavy weather (Knecht, 2016). Knecht developed a study using a storm model to generate a looping NEXRAD-type simulation, and found that weather movement greatly degraded safety while weather depth had no effect. Knecht recommends adding future predicted weather and a range ring to NEXRAD to improve safety.

Theme 2: Education

Education played a large role across the literature reviewed. With many new technologies becoming available, research needs to evaluate 1) whether (or how much) education is required on how to use these new technologies and 2) if education is needed, integration of new technology education into existing training for new pilots.

A two-hour course on NEXRAD for GA pilots improved the subjects' knowledge scores and ability to apply concepts in paper-based scenarios (Blickensderfer, et al., 2015). However, the study did not employ a simulation or flight evaluation of pilot knowledge. This study affirms findings by a similar study on NEXRAD education, where a short course provided similar benefits to pilots (Cobbett et al, 2014).

The introduction of Electronic Flight Bags (EFB) improved preflight skill development and aeronautical decision making in student and private pilots with under 100 total flight hours (Misra & Halleran, 2019). In this study, participants not given EFBs were less likely to detect weather-related hazards. However, while EFBs proved useful, it is important for ab-initio pilots' interpretation, analysis, and decision making skills to be able to make accurate decisions without the assistance of an EFB (Misra & Halleran, 2019). An analysis of instrument approach accidents between 2002 and 2012, found that instrument approach accidents peak around 120 days after the last Instrument Proficiency Check (IPC) (Fanjoy & Keller, 2013). However more accidents occurred closer to the IPC date than further out. Current FAA IPC regulations do not mandate what training is required for IPCs, only giving a recommendation instead (Fanjoy & Keller, 2013). A more recent FAA Advisory Circular provides additional information on how to conduct an IPC, including guidelines for an IPC conducted in an approved simulator, but Advisory Circulars are not regulatory (Federal Aviation Administration, 2018). Evaluating the effectiveness of the newest updates to IPC guideline could have research potential.

Evaluating thunderstorm-related accidents from the NTSB database from 1996 to 2014 determined that the majority of flights resulting in accidents violated FAA-recommended separation distance from extreme convection (Boyd, 2017). Boyd argues for additional emphasis on thunderstorm hazards and safe practices during ab-initio and recurrent pilot training.

Theme 3: Pilot attitudes, biases, and experiences

To design effective weather products for pilots we need to know how pilots behave as humans. Papers that address pilot attitudes with respect to hazardous weather as well as cognitive biases in the general aviation pilot population help investigate how pilots think and make decisions and the research has applications in weather decision making. Developing tactics to combat risk-prone attitudes and de-bias pilots may prove helpful in reducing weather related fatalities in general aviation.

Common cognitive heuristics such as anchoring and adjustment, confirmation, and outcome bias, can lead to cognitive biases with adverse effects in three different studies of weather-related decision making (Walmsley & Gilbey, 2016). Weather reports obtained pre-flight affect pilots' interpretation of weather in-flight, evidence of anchoring bias. In one of the reported studies, pilots interpreted the decisions of pilots who flew into deteriorating weather more favorably when the outcome was positive than when it was negative, evidence of outcome bias. Another study found no evidence that pilots favored disconfirmatory evidence over confirmatory evidence when deciding which environmental cues were most useful in deciding whether to continue a flight. Using the "considering the alternative" technique to reduce the effect of the two negative biases identified in previous studies and de-bias weather-related decision making was ineffective at countering both biases (Walmsely & Gilbey, 2017).

Research on pilot attitudes may also point to differences between pilots who avoid adverse weather and those who do not (O'Hare, Hunter, Martinussen, & Wiggins, 2011). Pilots with more recent flight time may be more likely to be involved in adverse weather encounters, and pilots who are risk intolerant less likely. Experienced pilots with instrument ratings and high levels of instrument flight time were more likely to have not flown "VFR into IMC," though they have encountered weather conditions of significant concern during flight. Flight training hours nor number of flight safety seminars attended in the past year were not helpful in discriminating the three groups of pilots, casting doubt on the efficacy of flight safety seminars and flight instruction. Given enough exposure nearly all pilots will encounter weather conditions, some will emerge emboldened and optimistic about their skills while others will emerge more cautious and unwilling to encounter such conditions again (O'Hare, Hunter, Martinussen, & Wiggins, 2011).

Conclusion and Future Work

General aviation weather products, training, and pilots represent a complex system which spans many disciplines and industries. In this paper, we did a systematic review of the literature on weather information and products and how pilots use them. The review did not identify any research on what information UAS operators require or how they use it. WINDMAP aims to use drones to add to our weather observation, forecasting, and reporting capabilities for all low-level flying operations. While the literature review did not result in UAS weather decision making requirements, our future work includes developing and disseminating a survey to General Aviation pilots and UAS operators to identify their weather information needs. The needs identification from this literature review and upcoming survey will help WINDMAP develop new and improved weather products.

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