Weather Risk Management Through a Systematic Approach to the Investigation of Weather Events

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Abstract

Pilots face many weather related dangers, enroute and in the airport environment, such as low level wind shear (LLWS), icing and turbulence. Despite technological advances in weather forecasting, dissemination and presentation of weather related data; weather continues to be identified, at all levels of the industry, as a contributing factor in aviation occurrences worldwide. Though accidents in the commercial aviation industry (i.e., transport and commuter categories) are rare, an April 2007 report by the International Air Transport Association indicated that 43% of accidents in 2006 occurred during operations in adverse weather (Malaysian National News Agency, 2007). In addition to accidents, weather has a massive impact on the air traffic system, an operator's bottom line, and is responsible for numerous injuries to flight crews and passengers every year. Just as humans will always make mistakes, weather will always be a contributing factor to aviation occurrences. The question is, to what extent? Can we minimise the number of weather related occurrences? Can we manage the risk and impact of weather on safety and operations? This paper will advocate the concept of a 'weather management system' (WMS) to manage the impact of weather in the operational environment. WMSs represent a more 'holistic' approach and are comprised of a series of 'weather risk control systems' (Wx-RCSs) designed to manage the impact of weather hazards (e.g., thunderstorms, turbulence, reduced visibility, LLWS) on safety and operations. Wx-RCSs are essentially 'mini' safety management systems (SMSs) with all the same components designed to manage weather risks, and enable the broader WMS to be integrated into an operator's overall safety management program (i.e., SMS) as well as influence fuel management policies. A keystone to supporting WMS, and safety improvement in general, is a systematic approach to weather investigations which produces knowledge derived from information and data gathered during the investigation. By using this knowledge and insight into meteorological conditions, human factors and organisational influences, and technical issues related to weather, investigators will be able to identify risks and vulnerabilities of systems which might cause future occurrences or contribute to their severity. By producing findings of risks and using an WMS framework, weather risks can be analysed and managed by using various Wx-RCSs in the form of equipment; decision aids; briefing strategies; training; awareness campaigns and materials; proactive forecasting systems; recovery procedures; and clear policies and operational procedures relating to weather and information exchange. Active management involvement, informed working groups, and effective monitoring of outcomes combined with multi-faceted approaches that incorporate recent scientific findings and developments in technology can assist the aviation industry reduce weather related occurrences, improve safety and productivity in flight operations and air traffic management, and reduce its environmental impact through improved fuel management.

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Introduction

Weather has a major impact on the safety, efficiency, and capacity of aviation operations. A 1995 study by the U.S. National Research Council showed 40-65% of delays experienced by U.S. domestic airlines were attributable to adverse weather, at an annual cost estimated at $4–5B per year (NRC, 1995). A more recent study showed weather accounted for 76% of all U.S. air traffic delays in 2004 (University Corporation for Atmospheric Research, 2005). Weather affects all phases of flight. On the ground, aircraft may have to be de-iced before departure, and runways have to be plowed. Lightning in the terminal area prevents ground handlers and fuelers from carrying out their work. Strong surface winds and wind gusts can cause ramp damage by blowing ground servicing equipment into aircraft. During periods of low ceilings and reduced visibilities departing and arriving aircraft are slowed by air traffic control (ATC) thus having a profound impact on runway acceptance rates; often lowered to 75-50% of normal (Qualley, 1997). These delays may necessitate the carriage of extra fuel – which in turn results in higher fuel burns due to increased weight. In regards to the enroute phase of flight, upper level winds (e.g., those associated with the jetstream) and temperatures have a significant impact on fuel burn and on-time performance. Turbulence is also a major concern to passenger carrying flights and military operations (i.e., re-fuelling), with icing, thunderstorms, and volcanic ash also impacting operations with closed air routes forcing costly re-routes (Qualley, 1997) and placing increased workload on controllers to manage the safety of aircraft and traffic flow through the airspace system.

Given recent technological advances in the cockpit, the ATC tower, and developments in weather forecasting, questions arise as to whether or not weather is "just the cost of doing business" (Dutcher, 2005; Regnier, 2008). Can the aviation community, along with others (e.g., power utilities, marine operations, vineyards, disaster and emergency management organisations), take advantage of these advancements to minimise the negative impact of weather on their operations and enhance their performance even further? These improvements have created the potential for the risk management and human factors communities to have a tremendous impact in distilling weather information into valuable tools to support and enhance decision making, leading to improvements in safety and operations. By combining meteorology with these seemingly vastly different sciences the greatest potential for impact in the future is in integrating weather forecasts into decision making, and coordinating activities through strategically directing resources using a risk based, systematic approach aimed at minimising the impact of weather on operations and safety. As a mechanism to support continuous improvements, a systematic approach to weather mishap investigation is needed. Such a comprehensive approach should be positioned not only to understand the meteorological phenomenon present at the time of the mishap, but also the decisions made in light of the surrounding situation. Armed with this improved understanding, findings of risk and practical recommendations can be made to correct safety deficiencies and further improve performance and support the development of tools and processes. Through integrating these systems into overall safety management programme and governing company management systems, improvements can be become part of everyday company operating philosophies and practices.

Background

Weather Hazards

Pilots face many weather related dangers such as low level wind shear (LLWS), icing, thunderstorms, and turbulence in the enroute and airport environment. Despite technological advances in weather forecasting, dissemination and presentation of weather related data, weather continues to be identified as a contributing factor in aviation occurrences worldwide; at all levels of the industry. In the U.S., historically, about two-thirds of all general aviation (GA) accidents that occur in instrument meteorological conditions (IMC) are fatal. Moreover, though weather-related accidents are not frequent, they account for a large number of aviation fatalities - only 6% of GA accidents are weather-related but they account for more than one in four fatalities that occur in GA annually (National Transportation Safety Board [NTSB], 2005). In the commercial airline industry, a 2007 study by the International Air Travel Association (IATA) showed that the 2006 global average hull-loss rate was 0.48 accidents per million flights, or one accident for every two million flights for IATA's member airlines. Though accidents in the commercial aviation industry (i.e., transport and commuter categories) are rare, IATA indicated that 43% of accidents in 2006 occurred during operations in adverse weather (Malaysian National News Agency, 2007).

In addition to accidents, there are numerous injuries to flight crews and passengers due to weather related mishaps each year. For instance, of all weather-related commercial aircraft incidents in the U.S., 65% can be attributed to turbulence encounters (Sharman, Tebaldi, Wiener, & Wolff, 2006). Further, research at NASA estimates that airlines encounter severe turbulence nine times a month, resulting in an average of 24 injuries per month (Adams, 2001), with major U.S. based carriers estimating they receive hundreds of injury claims and pay out "tens of millions" per year (Sharman, et al., 2006). Encounters with turbulence can also be costly in operational and financial terms. An encounter with severe turbulence may result in significant damage to the aircraft requiring expensive inspections and repairs. Flight deviations, meals and hotels, and passenger inconvenience, not to mention bad publicity are all ruboff factors to be factored into the real cost of an encounter. Considering these factors, along with litigation, NASA's Aviation Safety program estimates the cost to the airlines from encounters with turbulence runs more than US$100 million a year (Adams, 2001), with one airline estimating that each encounter of severe turbulence costs an average of US$750,000 (Collaborative Decision Making, n.d.).

Besides turbulence, weather events such as the London Heathrow fog event, and the crippling winter storms in Canada and the U.S. in December 2006, to name a few events, have vividly exposed the enormous impact of weather on operations. These types of events can have a swift and grave impact on both an air operator's and an airport's bottom line.

Technological Improvements

Given accidents and disruptions in air traffic caused by hazardous weather are magnified by the lack of understanding of weather information (to be discussed later) and an intrinsic uncertainty of weather forecasts a great deal of research and development work, worldwide, has been directed at increasing the accuracy, precision and reliability of aviation weather forecasts in efforts to improve safety and air traffic management. Many of the improvements in aviation weather forecasting have come from the introduction of complex and advanced technologies (including increased levels of automation) into the weather office. These improvements have been relatively rapid in the weather forecasting domain - particularly over the last 20 years. These changes have come in the form of such technologies as high resolution satellite imagery, Doppler radar, Automated Weather Observing Systems (AWOS), and improved atmospheric computer modelling (i.e., numerical weather prediction (NWP) models).

In addition to the improvements in technology in the weather office, improvements in the observation, analysis, and dissemination of weather related information has allowed for improvements in aviation safety and performance. Improvements in aircraft radar, the development of the Low Level Wind Shear Alert System (LLWAS), and other technology for the observation of weather can be used to support decision making and evade hazardous weather. Technologies in the U.S. like the Integrated Terminal Weather System (ITWS) to observe and forecast local thunderstorms using Doppler radar data out to one hour in advance, and the Collaborative Convective Forecast Product (CCFP) to forecast thunderstorms 2/4/6 hours in advance, have been used to improve safety and air traffic flow management. Similarly, improvements in the dissemination and display of weather information will also continue to improve safety. Many national weather services provide a great deal of aviation weather data for pilots and other users via the Internet with more and more pilots using it as their primary, however some their only, source of weather data for flight planning. Aircraft weather radar, the Aircraft Communications Addressing and Reporting System (ACARS) provide crews with weather data on the flightdeck. With technologies such as Electronic Flight Bag (EFB), and NASA's Aviation Weather Information (AWIN) Graphical Weather Information System (GWIS) transmitting graphical weather products to the cockpit will further improve safety and efficacy of operations.

Pilot Weather Training

The most common factor contributing to weather-related accidents is pilot error which can be directly coupled to the lack of pilot understanding of the details of their flying environment (Sand & Biter, 1997). A 2002 NASA study (Burian, 2002) involving over a thousand pilots, from students to airline pilots to instructors, revealed a number of alarming findings in relation to pilot's comprehension of weather. The participants, who had an average of 2140 total flight hours logged (median = 650 hours), were asked to complete a short weather knowledge test. Analysis of results showed participants, in general, performed quite poorly on the weather test. Many pilots apparently lacked operationally relevant weather knowledge and/or had difficulty recalling what was once learned. The study also found that many pilots did not have an accurate perception of their level of weather knowledge, with many rating their mastery of weather better than their actual performance. Pilots at all levels of formal training, but particularly those who were certificated to fly only in visual meteorological conditions (VMC), also generally had difficulty in integrating weather knowledge from across different weather categories (e.g., weather hazards, weather services, weather interpretation, and weather-related decision making). All participants, visual flight rules (VFR) only pilots in particular, also had difficulty in demonstrating an understanding of the implications weather information has for real flight operations. In addition, pilots at all levels of formal training also had difficulty on items that required them to ‘decode’ information in various weather products (i.e., forecasts and observations) or to read various weather charts. The study also found that all pilots, including many instructors, were unable to select correct answers for VFR weather regulations questions. Only 44.7% of all pilots were able to correctly identify Marginal VFR visibility and ceiling levels and 45.9% of all pilots actually incorrectly identified IFR visibility and ceiling levels as those that constitute Marginal VFR.

This lack of pilot understanding is not surprising when considering the state of weather training. Most civilian primary ground schools in America include a mere nine hours of weather instruction. U.S. Air Force pilot training consists of 15 hours of formal weather instruction, as compared to 50 or 60 hours in the past, whilst U.S. Army aviator weather training consists of about 30 hours. (Lankford, 2000). Student aviators and Naval Flight Officers in the U.S. Navy receive a little over two weeks of meteorology training in their first year of flying, followed by about half an hour of training each year during instrument refresher (Cantu, 2001). Lankford (2000) argues regulations perpetuate this trend. In most countries, regulations only required pilots, from student to commercial pilots, to obtain and use weather reports and forecasts, recognise critical weather situations, and estimate ground and flight visibility. For the most part, only the airline transport pilot certificate requires the applicant to have any serious meteorological knowledge (Lankford, 2000).

In addition to deficiencies in basic meteorology training, despite the many advances in the use of NWP, Doppler radar, and satellite imagery over the last 15 years training in these areas, even at the highest levels and in the most progressive company, is largely absent; though practical and operations orientated training with these tools would greatly improve safety and efficacy with improved flight planning and decision making. Similarly, a recent study by Honeywell (Goold, 2008) uncovered deficiencies in weather radar training and understanding, and revealed almost 70% of pilots were dissatisfied with weather radar training. Pointing out that current radars are concerned primarily with weather analysis and avoidance, the study highlighted that proper interpretation depends on a pilots’ adequate understanding of weather radar and meteorology. That said, the researchers concluded most operators do not provide initial or recurrent weather-radar training. It was found that most available training takes place on the job with many pilots describing a ‘trial-and-error experience’ and learning from information obtained from other pilots. Such practices may lead to improper radar operating procedures and techniques and further perpetuate a poor understanding of fundamental weather radar concepts, including its limitations. Once again, regulations seem to perpetuate this trend, with the study also revealing there is little incentive for operators to provide such training since regulators do not require it. This is also true of the advances in NWP and other technologies available.

Weather-related Pilot Decision Making

Decision making is a complex process of gathering and processing information in working memory and formulating and implementing a plan of action. Decision making is fundamental to all aspects of flying operations, including weather. Most research examining weather-related decision making has focussed particularly on understanding why VFR pilots risk flying into deteriorating weather.

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One key reason why pilots may decide to continue a VFR flight into adverse weather is that they make errors when assessing the situation. That is, pilots are seen to engage in VFR flight into IMC because they do not accurately assess the hazard (i.e., the deteriorating weather conditions). A study by Goh and Wiegmann (2001) indicated that pilots with more experience were generally more confident of their ability to recognise problems and to generate and implement solutions. However, contrary to previous research on expertise, results suggested that pilots with more experience did not necessarily feel more confident in their ability to diagnose flight-related problems. The researchers argued that this may be the result of pilots not being trained as thoroughly in diagnostic decision making processes as are experts in other domains. Yes, pilots are generally trained to detect problems, such as engine failures, but to then rely on checklists and documented emergency procedures to diagnose and resolve the problems. In addition, some checklist procedures even bypass the diagnostic stage altogether and simply require an emergency landing. Goh and Wiegmann (2001) point out that though the necessity to perform diagnostic procedures may be reduced or even eliminated for some in-flight problems, other problems such as changes in weather are still important. Therefore, recognising that the weather has changed does not imply a pilot will generate the most optimal plan to deal with it. Being able to diagnose how serious this weather change is and the options available given the constraints of the situation (e.g., the weather change precludes the option of returning to the origin), are highly important. Consequently, in the event that a pilot encounters situations that are not easily defined in emergency procedures (e.g., inadvertently encountering adverse weather), the pilot will need to rely on his or her own abilities to diagnose the problem quickly and accurately. Results of the research indicated that even experienced pilots did not have an overwhelming confidence in their abilities to accomplish this task as it related to weather (Goh and Wiegmann, 2001). A 2002 study by NASA lends support to this showing that pilots at all levels of formal training, but particularly those who were certificated to fly only in VMC, generally had difficulty in integrating weather knowledge from across different weather categories (e.g., weather hazards, weather services, weather interpretation, and weather-related decision making) (Burian, 2002). Give the discussion of pilot’s training in meteorology this is not surprising, especially in light that though diagnostic skills are essential they are largely not taught besides the mechanical reading (decoding) of forecasts and observations.

With respects to technology, Wiggins (2005) argues that despite the significant advances in the technology related to the prediction and reporting of weather conditions, the safety and efficiency of a flight remains dependent upon the pilot making an accurate and expeditious decision concerning the impact of the conditions reported. Moreover, in addition to weather reports and forecasts, the pilots of advanced technology aircraft now have available, weather radar systems that display a vast array of weather-related information in real-time. It is assumed that the provision of this information has the potential to improve weather-related decision making by enabling pilots to recognise changes in the weather conditions at a relatively early stage of the flight and thereby take appropriate action. However, as discussed, pilots may lack the confidence and skills to accurately diagnose and assess weather features and make sound and timely decisions. Couple this with the often lack of adequate training in many of these new technologies and the true value of all the money and effort spent on developing these technologies aimed at supporting decision making becomes clearer.

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Can We Manage the Weather?

It can be seen that various initiatives exist to improve aviation safety and air traffic management through the development of technology for the display and dissemination of weather related information, improvements in observations and the accuracy of weather forecasts, and such projects as the CCFP and ITWS in America. Besides advancements in technology, there is a growing amount of research looking at pilot weather-related decision making and ways to improve it – though studying VFR flight into IMC appears to dominate these research activities. Also relevant to the 'weather problem' is the number of developments in other areas like cognitive engineering, expertise, instructional techniques, and safety management.

However, despite these improvements are we actually doing anything? The answer is yes, but a more pertinent question might be "are we doing enough"? Sure these advances have made significant improvements to aviation, but are we getting the most from them? Are we just 'spinning our wheels' if we are designing technology to improve efficiency and safety, but not training people adequately, in some cases at all, on how to use it? We are still landing and taking off aircraft when the terminal area is blanketed with thunderstorms. There are still numerous injuries due to turbulence every month. There are major weaknesses in pilot's understanding of key concepts in meteorology. There are major weaknesses, at all levels, in pilot weather analysis and diagnostic skills, as well as in assessing the impact of weather on their flight. It seems we have reduced the weather problem down to a number of components or silos, but in some respects it appears this reductionism has made us half-blind. It is time to step back from the puzzle and see the whole picture - from 35,000 feet. The systems view. By looking at the bigger picture we can see potential for overlap. Through identifying the strengths and weaknesses of work in each silo and the potential interplay between them we can develop a common thread. This common thread will allow for a unified, concerted effort instead of having silos working in isolation. The status quo will have only limited results. The greatest potential for improvement in safety, air traffic management, aircraft operations, and fuel management is in a more unified effort for managing weather.

Another advantage of a systems view is the ability to see how different systems interact. Like human behaviour we cannot control 'Mother Nature.' But through studying human behaviour and the relationships between humans, tasks, environment, technology, tools, etc we have been able to realise significant reductions in accident rates. Borrowing from Reason (2000), we cannot change weather; however we can change how we interact with it and making our organisations and operations more 'weather tolerant.' By looking at the relationships between weather, technology, human factors, and operations we can design our interaction for better results. Different system outcomes can be had by building different relationships, sometimes using the very same or similar parts, because small changes to the parts can make a tremendous difference (Vincente, 2003). By applying this same philosophy, to weather, we can design relationships with technology, operations, human factors, etc that will lead to harmony, not tension – good fits, not bad.

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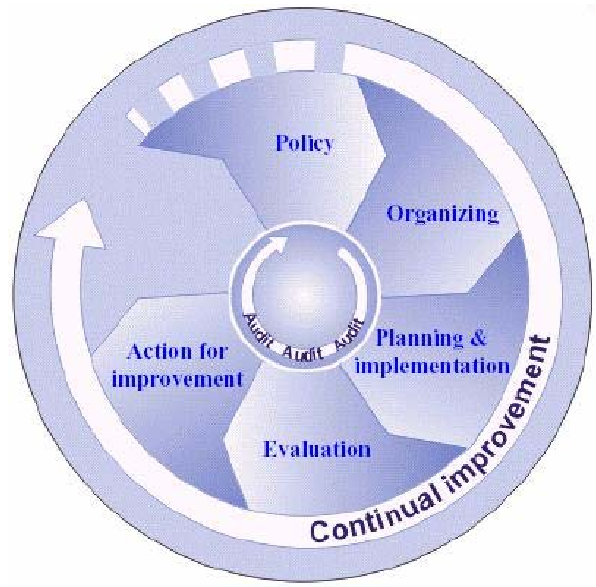
Weather Management System

The systems view is useful for identifying components of a large system of activity and for seeing the interplay between them. Though this will allow for improvements in products, procedures, and technology whilst having affinity with humans and operations, a mechanism to direct these activities is needed. Staying within the realm of systems-thinking, we must develop a mechanism to strategically direct management strategies to manage weather. From a different view we can further break the weather problem down into system components and examine the interplay between them. Using a risk-based approach we can identify deficiencies and areas of risk and then direct activities to manage these risks by prescribing help from the various products and programmes developed as a result of a greater cooperation between silos (e.g., weather displays that are built upon governing principles of human-computer interaction - HCI). By using a risk-based approach these systems can be integrated into other management activities (e.g., company management, safety management, air traffic management, fuel management) as well as allow for everyday use and industry implementation using a common framework. Borrowing from occupational health and safety management systems (OHSMS) theory (International Labour Office [ILO], 2001) and recognising that like fatigue, ramp damage, maintenance error, etc weather is a source of risk which also needs to be managed using a 'weather management system' (WMS) which focuses activities to maximise results. In essence, coordinating and focussing activities using a WMS is working at the intersection of meteorology and the science of risk management to improve relationships and consequently safety and performance.

A WMS, like an OHSMS and safety management system (SMS), is a systematic approach to managing weather. It applies techniques used to manage other aspects of business performance such as quality and safety. This approach is based in General Systems Theory (input, process, output and feedback). Unlike a prescriptive program (e.g., federal regulations on pilot training, VFR and IFR flight minimums), a WMS does not focus solely on compliance with regulations; it takes a broader perspective and aims for continuous improvement. A WMS is a risk-based approach aimed at managing risks effectively through systematically identifying hazards (e.g., winter weather, LLWS, thunderstorms, fog), assessing and controlling risks (i.e., disruption to operations, fuel wastage, death, injuries), evaluating and reviewing risk control measures to ensure that they are effectively implemented and maintained. A WMS strives for continuous improvement, which can be achieved by monitoring system effectiveness and taking action to improve the system where required. This active monitoring means that organisations can address weather issues and system failures even before an accident occurs.



<u>Figure 1.</u> Main Elements of a Weather Management System

Borrowing again from guidance on OHSMS by the ILO (2001), a WMS has five main elements (see Figure 1) which follow Deming's (1986) internationally accepted Plan-Do-Check-Act (PDCA) cycle. These five elements are namely: Policy, Organizing, Planning and implementation, Evaluation, and Action for improvement. 'Policy' contains the elements of 'weather policy' and employee participation. It is the basis of the WMS as it sets the direction for the organisation to follow. 'Organizing' contains the elements of responsibility and accountability, competence and training, documentation and communication. It makes sure that the management structure is in place, as well as the necessary responsibilities allocated for delivering the weather policy. 'Planning and implementation' contains the elements of initial review, system planning, development and implementation, weather-related objectives and hazard prevention. Through the initial review, it shows where the organisation stands concerning weather, and uses this as the baseline to implement the weather policy. 'Evaluation' contains the elements of performance monitoring and measurement, investigation of injuries, damage to aircraft, and disruption of services as a result of weather, audit and management review. A WMS shows how the larger management system functions and identifies any weaknesses that need improvement. It includes the very important element of auditing, which should be undertaken for each stage. 'Action for improvement' includes the elements of preventive and corrective action and continual improvement. It implements the necessary preventive and corrective actions identified by the evaluation and audits carried out. It also emphasises the need for continual improvement of weather-related performance through the constant development of policies, systems and techniques to prevent and control weather-related occurrences, injuries, and negative impact on the efficacy of operations.

Weather Risk Control Systems

The broader WMS contains a number of smaller 'weather risk control systems' (Wx-RCSs) designed to manage the impact of a weather hazard (e.g., thunderstorms, turbulence, reduced visibility, LLWS) on safety and operations (Dutcher, 2005). A Wx-RCS is essentially a “mini” SMS with all the same components designed to manage weather risks, and enable the broader WMS to be integrated into an operator’s overall safety management program (i.e., SMS) as well as influence other areas connected to weather like fuel management policies and air traffic management.

Part of the output of a Wx-RCS is risk controls or types of defences that prevents a hazard from creating harm (i.e., preventive controls) or mitigates the harm once an event has occurred (i.e., recovery controls). Defences can be categorised into three different types, namely:

- *Engineering defences*. Physically prevent a hazard from causing harm such as de-icing fluid, or other ‘engineering fixes’ like outfitting aircraft with weather radar.

- *System defences*. Control hazards by specifying procedures to be followed, such as a company policy regarding operations near thunderstorms, LLWS recovery procedures.

- *Human defences*. Are the actions, competence and expertise required by individuals to prevent hazards from being realised in the first place. For example, a pilot’s ability to recognise and diagnosis echoes on weather radar is a human defence that prevents planes from flying into thunderstorms.

As part of prescribing risk controls it is important to identify risk controls that can be put in place to prevent or reduce the likelihood of an undesirable event occurring (that is, preventive controls), and risk controls that can be put in place to minimise the consequences of the undesirable event (that is, recovery controls) (Walker & Bills, 2008). Given both types of controls are important for maximising safety a useful tool for this type of analysis is the ‘Bow-tie model’ (see Figure 2) (Reason, 1997).

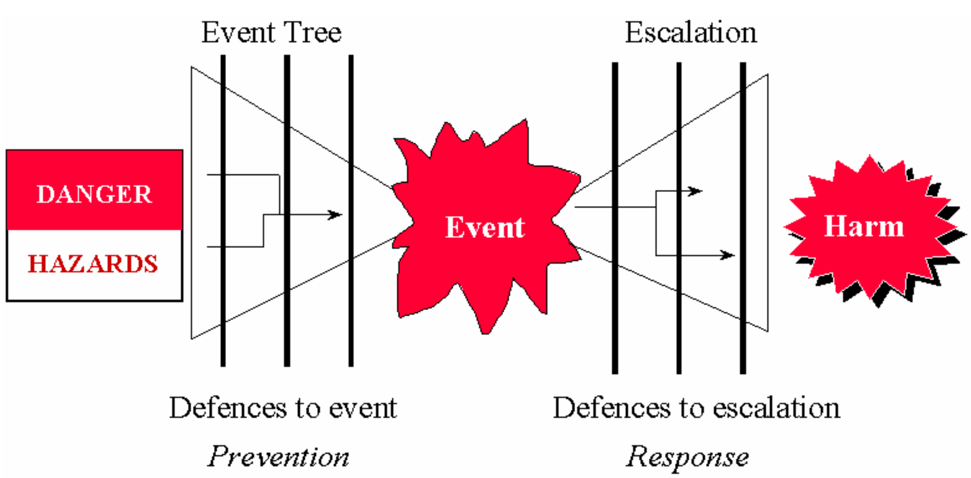


Figure 2. Bow-tie Model

'Defences-in-depth'

The terms 'defences-in-depth' or 'lines of defence' are used to refer to the notion that there are generally a number of risk controls providing layers of protection in a transport operation. Each layer of risk controls provides assurance against the possible breakdown in the preceding layer. Reason (1997) noted that deficiencies in defences or risk controls can occur due to individual actions or to systemic problems (for example, being poorly designed in the first place). At any particular time in any safety system, there will be weaknesses in some risk controls, and these weaknesses will change over time. These holes or weaknesses can occasionally align, leading to serious consequences (Walker & Bills, 2008). Like humans, defences are not perfect, thereby necessitating several layers of defences. If one defence fails the hazard still may not cause harm because other defences are in place. The number of defences in place will depend on the level of risk posed by a specific hazard. High hazard activities (e.g., landing in bad weather) require multiple redundant systems, for example weather radar, instrument landing system (ILS) and ILS procedures to reduce the risk of an accident.

Investigation of Weather-related Occurrences

To allow for lessons learned, occurrences must be comprehensively investigated to determine if weather was a contributing factor to the occurrence. Investigations must include gathering and plotting atmospheric data to establish the state of the atmosphere at the time of the occurrence, as well as identify weather hazards (e.g., icing, LLWS, lightning, turbulence) which may have played a role in the occurrence. Though it is important to understand what meteorological conditions and phenomena influenced the aircraft, it is also important to understand decisions made by pilots, controllers, dispatchers in relation to the weather. Such an analysis may highlight issues with pilot or dispatcher incorrect and/or incomplete knowledge due to training deficiencies, and/or poor dissemination of weather data, or incomplete weather data due to reporting limitations.

That said, to simply say a pilot flew into bad weather does little to explain why. A key question is "Why did it make sense at the time?" Through 'reverse engineering' investigators can gain an understanding of the systemic connections between human behaviour and features of the tasks and tools that the people worked with, and of the operational and organisational environment in which they carried out their work. Therefore by gaining a comprehensive understanding of the evolving situation in which people's behaviour took place, investigators will be better suited to understand the behaviour (Dekker, 2002). To facilitate this, a systematic approach to weather investigations must look at the mishap from, obviously, a meteorological perspective identifying the weather conditions and phenomena that may have played a contributing role in the mishap but also from a technical and human factors and organisational perspective. Understanding the context in which humans err is fundamental to understanding the unsafe conditions that may have affected their behaviour and decision-making. These unsafe conditions may be indicative of systemic risks posing significant accident potential.

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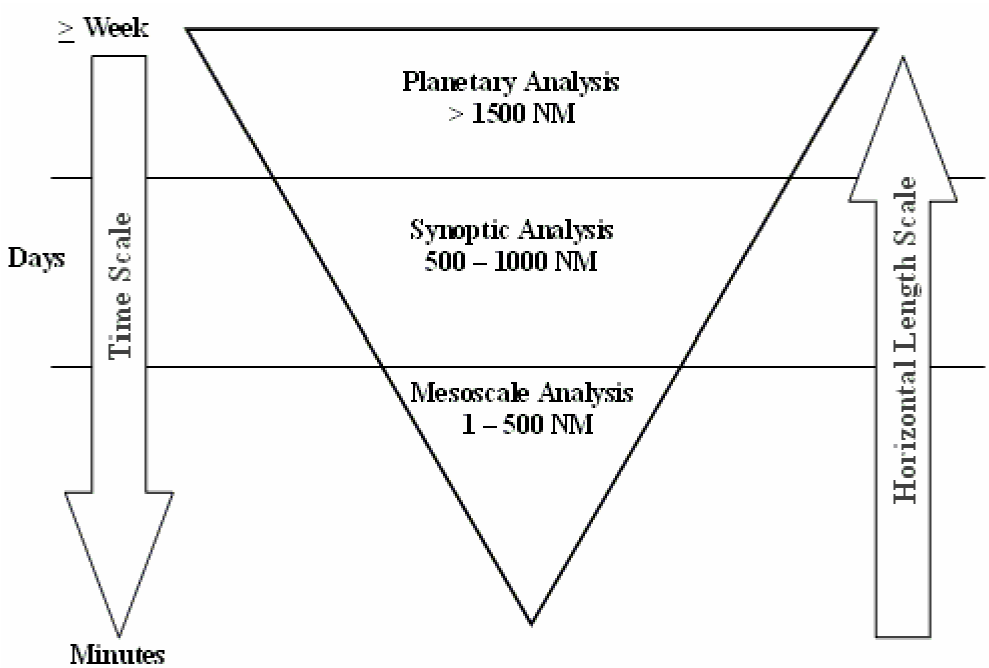
Meteorological Perspective

To allow for a comprehensive examination of weather data, the investigator must utilise a methodological approach, allowing examination of data in the vertical (i.e., surface, 850/700/500/250 millibar levels) and the horizontal (discussion to follow).

<u>Analysis Funnel</u>

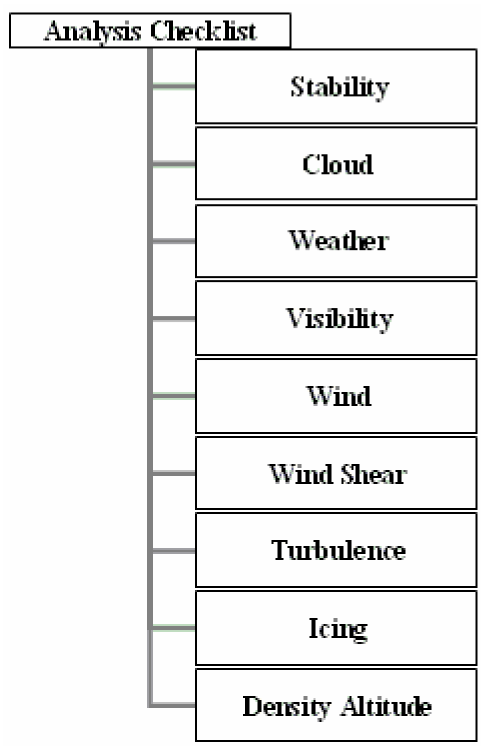
The 'analysis funnel' is built upon Orlanski's (1975) notion of scaling which is essential to establishing the importance of various processes in the atmosphere. Primarily, for the purpose of weather investigation, there are three size scales (largest to smallest): planetary (or hemispheric), synoptic, and mesoscale (see Figure 3). Given most energy transfer in the atmosphere is downscale from the planetary scale analysis should begin there, gradually working downscale and inward towards the smallest scale. This framework essentially forms an analysis funnel providing an investigator with a comprehensive understanding of the state of the atmosphere and interrelation of scales (Dutcher, 2004). In other words, this will provide an understanding of why the weather did what it did at the local level as a result of the interplay between local factors (i.e., topography, bodies of water, local stability, water and air temperatures) and the larger scale dynamics (i.e., highs, lows, frontal systems, jetstreams, upper level troughs, ridges, and vorticity, thermal advection). Essentially, this provides the "why" of the weather.



<u>Figure 3.</u> Analysis Funnel

Weather Analysis Checklist

From analysis of research and various aircraft accidents and events Dutcher (2003; 2004) developed the 'weather analysis checklist' (WAC) to provide a sound analytical framework to assist in identifying flight conditions and possible weather hazards present (see Figure 4). The WAC is structured to allow a logical flow for analysis, moving downward from stability; since stability determines virtually every subsequent factor. Moreover, many of the items in the checklist are influenced by the proceeding item. For instance, an unstable atmosphere will allow for the formation of towering cumulus and cumulonimbus clouds resulting in thunderstorms and rain and consequently reduced visibility. Additionally, the unstable conditions can cause surface winds to become variable and gusty. With thunderstorms comes the presents of wind shear associated with downbursts (e.g., microburst) as well as turbulence. The strong vertical currents inside the towering cumulus and cumulonimbus clouds combined allows for the rapid growth of large water droplets representing a significant icing threat above the freezing level. Warm temperatures can create high density altitude conditions which can have a major impact on aircraft performance. In addition, thunderstorms can also cause erroneous altimeter readings.



<u>Figure 4.</u> Weather Analysis Checklist

In addition to a structured framework for analysis, the WAC is also useful as a tool to provide for a clear summary of conditions at each scale, allowing others to follow the logic of the investigator. Following the comprehensive analysis of all scales (as per the Analysis Funnel) with regards to the weather analysis checklist, the four-dimensional understanding of the atmosphere must be related to each phase of flight to determine if, and what, weather hazards were present during: (a) taxi, takeoff to top of climb; (b) enroute; and (c) top of descent, approach, landing, and taxi.

By combining the Analysis Funnel with the WAC an investigator can systematically identify weather hazards at every phase of flight and be able to explain ‘meteorologically’ why the weather behaved in such a manner. In other words, this identifies the “what”, “where”, “when”, “how”, and “why” of the weather.

Technical Factors

In addition to examining the weather-related occurrence from a meteorological perspective, investigators must also consider technical factors which may have restricted the accuracy and comprehensiveness of meteorological data provided to aircrews, ATC, and operators. In some cases investigators may breakdown and test meteorological instrumentation if the accuracy of weather data is suspect. In cold climates, during winter, ice can form on meteorological instrumentation and is thus a possible consideration during an investigation. For instance, during periods of freezing precipitation ice accretion may reduce the efficiency or cause complete failure of anemometers, restricting the validity of wind data. These same considerations may be applied to aircraft instrumentation as well as the affect of temperature and density changes on altimeters. Technology for gathering and displaying weather information must also be examined to understand the capabilities and limitations of such tools (i.e., radar technology, high-resolution zoom satellite imagery). Consideration must also be given to possible limitations of technology as a result of atmospheric phenomena. For instance, aircrews flying into thunderstorms, and areas of hail, as a result of false radar returns caused by radar attenuation due to absorption.

Human Factors and Organisational Issues

Comparison of forecast conditions, aircrew actions, and the investigator’s identification of possible hazards may suggest possible issues with aircrew judgement. However, simply stating that the pilots flew into adverse weather conditions does little to explain why. Investigators must endeavour to identify why the aircrew’s decisions made sense to them at the time. Were there human factors related barriers to effective aircrew weather decision making? For instance, lack of knowledge due to inadequate training or poor provision of weather data, and operating norms.

The overall process of occurrence investigation within the human factors field is similar across many methodologies. However, differences arise in their particular emphasis of the techniques. Whilst some focus on management and organisational oversights and omissions, others consider human performance/error problems (on the frontline) in more depth (Livingston, Jackson, & Priestley, 2001). With that said, both levels must be examined to gain a comprehensive understanding of how such things as organisational norms and policies impacted decisions and behaviours, and how organisational structures influenced the communication of weather information and consequently decisions.

Adequacy of Service

Emphasis should be placed upon determining whether the crew was adequately informed regarding hazardous weather conditions. The observing, forecasting and briefing facilities involved and the services provided should be examined with a view to determining whether such things as: whether pertinent regulations and procedures were satisfactory, available, and adhered to; that forecasts and briefings were accurate and made effective use of all known and relevant information; and communication of information to the relevant aeronautical personnel was accomplished without delay and in accordance with prescribed procedures.

Adequacy of Flight Documentation and Messages

In some countries, frequently observed local weather effects at an aerodrome may be listed in fight supplements data as a warning to aircraft. These flight supplements are often used for flight in VMC. However, these same warnings may be silent in documents relating to flight in IMC for the same aerodrome. Therefore, comparison of such documents should be made so as to highlight possible disparities. As an example, a flight supplement for an aerodrome surrounded by rough terrain with frequently strong winds, may warn of possible mechanical turbulence given certain conditions (i.e., wind direction and speed). However, this warning may be silent in approach plates used in IMC. In addition, investigators must also consider the possibility that frequent use of these particular aerodromes, may breed complacency and thus non-use of such documents even in VMC.

Aside from flight documentation, consideration to messages in flight must also be given, for instance significant meteorological information (SIGMET) messages. Such data should be examined for clarity and brevity and whether they facilitated understanding and use of messages given conditions of flight. This may also include the ‘cognitive ergonomics’ of weather displays and messages (e.g., HCI considerations). In addition, the possible limitations of reports such as with pilot reports (PIREPs) must also be considered. These limitations are particularly relevant to reports of icing and turbulence given their interpretation is subjective (e.g., Bass, Kvam, & Campbell, 2002).

Operating Norms and Policies

Norms, whether organisational, group or individual may significantly influence behaviour and operations. In relation to weather, an investigator must analyse the various organisations, groups and norms of the aircrew (if possible). Particular attention should be paid to norms and policies relating to the dissemination of information, and analysis of data. For instance, a possible norm of pilots failing to read dispatch reports in their entirety due to their considerable length. This norm of seeking only certain data may have restricted the comprehensiveness of weather briefings provided. In addition, federal regulations and operator’s operational policies regarding flight in hazardous weather conditions and the operational reality should be analysed for disparity. Such analysis may also be applied to industry norms, e.g., penetration of thunderstorms in terminal areas (Rhoda & Pawlak, 1999).

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Individual Proficiency

Investigators must also give consideration to the proficiency of individuals (i.e., pilots, dispatchers, controllers). Borrowing from Rasmussen (1982), there may be issues with academic and operational knowledge of meteorology and perhaps the limitations of the aircraft and technology. In addition, there may be deficiencies in skill of personnel in interpretation of products and application of data. In addition to identifying deficiencies, it is equally important to uncover why they exist. In other words, are these deficiencies the result of inadequate training and dated knowledge? Furthermore, an investigator should also consider the possible influences of workload and pressure (either real or perceived) on errors and decision making of individuals and crews.

The Role of Systems Theory in Accident Interpretation

The most important question in an investigation is "why?" Occurrences are seldom the result of a single cause. Although individual factors when viewed in isolation may seem insignificant, in combination they can result in a sequence of events and conditions that result in an accident. Systems theory is the study of the interaction of people, their tools, equipment, materials, facilities, procedures, software, and work environment and how they work to accomplish a common goal. Using a systematic approach to investigating a weather occurrence from a meteorological, technical and human factors perspective allows an investigator to identify various conditions and factors that played a role in the event. However, it offers little about the dynamic interplay between the various factors and the conditions that allowed events to transpire. In order to gain this understanding we must again step back to see the bigger picture and make sense of it using various models of systems thinking like Reason's 'Swiss Cheese' model (1990) and the SHEL model (Edwards, 1972; Hawkins, 1987). Having assessed the interplay between factors, an investigator can identified deficiencies and systems failures and produce findings of risk and make recommendations as to how to manage these risks (i.e., risk controls). Therefore, the results of a weather investigation can be used as input into a WMS to allow for continuous improvement.

Conclusion

Weather has a significant impact on safety, air traffic management, fuel burn, and on-time performance. In response to calls for improvement, several initiatives now exist to improve aviation safety and air traffic management through the development of technology for the display and dissemination of weather related information, improvements in observations and the accuracy of weather forecasts and specialised forecast products. Besides technological advancements, research continues to grow into pilot weather-related decision making, cognitive engineering, expertise, instructional techniques, and safety management. However, despite these improvements, weather continues to be a contributing factor in many accidents. In some instances we are designing technology to improve efficiency and safety, but not training people adequately, in some cases at all, on how to use it. We are still landing and taking off aircraft when the terminal area is blanketed with thunderstorms. There are still numerous injuries due to turbulence every month. And there are major weaknesses in pilot's understanding of meteorology and training. It appears a unified, concerted effort to focussing efforts is needed as the status quo will have only limited results. The greatest potential for improvement in safety, air traffic

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management, aircraft operations, and fuel management is in a more unified effort for managing weather using a systems view. By using a WMS we can strategically direct management strategies to manage the risk and impact of weather hazards (e.g., thunderstorms, turbulence, reduced visibility, LLWS) on safety and operations.

It can be seen that though we cannot control or change weather we can actually do something about it. Weather is *not* "just the cost of doing business." By studying the relationships between weather, technology, human factors, and operations we can change how we interact with weather thus improving safety and performance and making our organisations and operations more weather tolerant.

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