Aeolian Dust as a Transport Hazard

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Abstract

The effects of blowing dust on transport operations are often mentioned as one of the significant impacts of aeolian processes on human welfare. However, few studies have been presented to demonstrate this impact. This research examined official air traffic incident reports in Australia for inclusively 1969-2010 to characterize the hazard of blowing dust to aviation in the country, the first such study of its kind. For the 42 year record, 61 incidents were identified (mean 1.4 per annum), with the large majority occurring in the first half of the 1970s. Only 20% of incidents occurred from 1984 onwards. Australian dust activity has not decreased over time, and the reduction in incidents is partly explained by improvements in aviation technology. The centralisation of Air Traffic Control operations to major coastal cities may however have reduced pilot reporting of dust-induced aviation incidents. By type of dust activity, dust storms were associated with nearly half of the reported incidents and dust hazes produced around a quarter. Only 5% of incidents resulted in any physical damage to aircraft and only one case involving personal injury was reported. The majority of the adverse effects on aviation due to dust (nearly 60% of reported incidents) were related to difficulties for navigation and completion of scheduled journey. Since aircraft damage and bodily harm were rare, the impact of dust in Australia is mostly that of inconvenience and associated raised economic costs. From 1990, the temporal pattern of incidents does not show any significant increase despite several intensely dusty years associated with recent droughts. This suggests that Australian aviation safety may be relatively resistant to the adverse effects of atmospheric dust as a hazard.

Keywords: duststorm; sandstorm; air safety; aerosols; visibility; eolian

1. Introduction

When the wide ranging impacts of aeolian dust are discussed, the effect of suspended dust as a hazard for transport operations is commonly cited (e.g. Goudie, 2009; Okin et al., 2011). By reducing visibility, impairing mechanical function and even interfering with communication systems, dust has considerable potential to cause economic and strategic cost by disrupting the conveyance of both people and goods (Goudie and Middleton, 1992; Walker et al., 2009). The negative effect of these impacts is one of the well recognised ‘off-site’ costs associated with wind erosion and dust raising (Piper, 1989; Pimental et al., 1995; Williams and Young, 1999). Apart from a purely economic cost, transport accidents caused by blowing sand or dust storm events can also result in injury and death.

Despite the frequent mention of dust representing either a hazard, imposition or disrupter to different forms of travel, there appear to be relatively few studies that have reported relevant data or presented case examples. Information relating to road traffic incidents caused by dust seems to be the most common (e.g., Buritt and Hyers, 1981). Pauley et al. (1996), for instance, described the details a major accident in the San Joaquin Valley of California in 1991, where blowing fields adjacent to an interstate highway led to 164 vehicles colliding and 168 dead or injured. In the Lower Mojave Valley of California, Laity (2003) examined an area of locally enhanced aeolian activity, the blowing dust from which had caused fatalities on highways in the valley. Novlan et al. (2007) state that between one and two road traffic fatalities occur on average annually in the El Paso, Texas region due to dust storms. Nationwide for the United States, Ashley and Black (2008) included analysis of dust storms in their assessment of the deadliness of nonconvective wind events. Between 1980 and 2005 they report that 62 deaths were related to dust storms affecting road vehicles.

As well as disruption to road transport, air transport is also affected by dust. Airport closures and flight cancellations have been reported globally for locations within major mineral aerosol pathways such as the Canary Islands (Criado and Dorta, 2003), Riyadh, Saudi Arabia (Maghrabi et al., 2011), Abu Dhabi, UAE (de Villiers and van Heerden, 2007) and Sydney, Australia (Leys et al., 2011). For the latter, the intense dust storm activity of 23rd September 2009 that affected much of eastern Australia resulted in delays, which caused seven flights to break the 11 p.m. curfew for night operations in place at Sydney Airport (DIT, 2009). From other airline industry sources, Williams and Young (1999) estimated the costs of a 1994 diverted Boeing 747 landing at Melbourne instead of Adelaide due to a South Australia dust event as up to AUD 80,000. Elsewhere, Miller et al. (2006) have highlighted the significant effects of dust on military air operations in deserts. They detail the case of Operation Iraqi Freedom, and the support that dust-monitoring from satellite sensors provided operations from aircraft carriers in the southwest Asia theatre (also Walker et al., 2009). The operational problems encountered in the 1980 U.S. hostage rescue attempt in Iran, during which blowing dust dogged air operations and caused a collision between a helicopter and fixed-wing aircraft, were also linked to haboob events (Miller et al., 2008).

With a considerable portion of its area lying in semi-arid or arid climatic conditions, and with often large-scale dust raising events a common occurrence (McTainsh et al., 2005; Strong et al., 2010; Leys et al., 2011), transport operations in Australia are strongly subject to hampering by dust. The existence of population centres in or on the margin of dust yielding areas, the large distances between settlements and the prevalence of light aircraft for servicing remote stations, especially in the drier centre, ensures aviation operations are especially vulnerable to dust in Australia. The long distance transport of sediment during major dust events also means that aerosols suspended into the atmosphere can affect Australian airspace well away from source areas (Bowler, 1976; Sprigg, 1982; McGowan and Clark, 2008a). Here, we analyse official air traffic incident records to characterise the nature of aeolian dust as a hazard to air transport across Australia for 1969-2010.

2. Methods

2.1 Data sources

The Australian Transport Safety Bureau (ATSB) is the Federal government agency with the remit to investigate and catalogue air safety issues for the Commonwealth. A search of all air incident records held by the ATSB was conducted to extract those officially catalogued incident occurrences that included either the terms “dust”, “sand” or “willy willy” within the description of the incident. Sand was selected to identify those dust events possibly described by aviation staff as sandstorms. Willy willy is the Australian name for dust devil or dust whirl. This term was initially used as a search trigger because it was also anticipated that such meteorological phenomena could likely feature air traffic incidents involving dust raising. The search process was helped by the fact that those incidents in which wind-raised dust or sand was a dominant factor typically came under the ATSB event type classifier “Environmental-Weather-Other”. Each event report contained a suite of standard information such as date, location, aircraft model and manufacturer, plus a text summary of the known incident details. The degree of information included in reports was typically of relatively good detail and provided considerable data to assist in the interpretation of each incident.

Careful inspection of the returned records ensured that the final list for analysis contained only those incidents with a mention of aeolian dust as a causative factor in some way. This check eliminated cases where dust was reported only as a consequence of the incident (e.g. reports mentioning dust and gravel kicked up by an aircraft overshooting a runway), or, where the dust involved was of volcanic origin. From this quality control of the data, it was seen that none of the incidents identified by willy willy occurrence contained any explicit mention of dust being present. Rather, all willy willies were related to adverse effects of turbulence and wind-shear on aircraft operation, not the effects of aeolian entrainment or suspension of sediment. As a result, the willy willy reports were not included in the final analysis of the data.

To aid assessment of the dust-related air incidents, the incident reports were interpreted alongside the Dust Event Database (DEDB) held at Griffith University. The DEDB is a temporally extensive inventory (> 1960) of daily dust activity throughout Australia and is based on weather codes and data collected by the Bureau of Meteorology.

In using the ATSB dataset to assess the impact of dust on aviation, there is one important caveat. In September 2009, large portions of eastern Australia experienced severe dust storms (Leys et al., 2011). This period of highly intense dust activity had a major impact on air travel, from flight groundings to airport closures, but no official reports of dust-related incidents were returned from the ATSB at all for this period. A follow-up data extraction and inspection of all ATSB records (regardless of specific dust mention) for the most intensely dust affected week of 19-26th September verified that none of the reports could be attributed to dust. The lack of incidents for this period highlights that the ATSB record relates strictly to dust as a hazard to active flights, and does not reflect the full impact of dust on air operations, such as delays or cancellations.

2.2 Classification of incidents

After those records related to blowing dust had been gathered, the incident description, the officially classified incident type, as well as damage and injury information was analysed to allocate each incident into different groups for summary results. The type of dust activity associated with incidents was also determined. Descriptions of the dust event within the air report were augmented by reference to the DEDB to classify the nature of aeolian activity for each incident. DEDB records enabled a nationwide assessment of the extent, intensity and duration of dust activity for those days when air incidents occurred.

3. Results and Discussion

3.1 Type of adverse effect

During the period 1969 to 2010 inclusively for Australia, a total of 61 officially reported air incidents were found to be attributable in some way to the effect of blown dust. (A further nine incidents were attributable to the impact of willy willies, but as stated, these are not included in the subsequent analysis.) Relatively few of the cases reported any damage being caused to aircraft or equipment (4.9%) and only a single incident resulted in physical harm to personnel, whereupon the reported level of injury was rated as slight (Table 1).

>> TABLE 1

The dominant impact caused by dust on Australian aviation through the study period relates to adverse effects on navigation. Incidents that involved a return to the initial take off location (16.4%), diversion to and landing at some alternative to the original destination (27.9%), pilot reported uncertainty of position (8.2%) or an inability to even locate the final destination (4.9%) were all related to enhanced difficulties in navigation due to atmospheric dust (57.4% overall). Occasionally, dust was reported specifically as preventing flight Visual Meteorological Conditions (VMC) from being maintained. The breakdown of such conditions, where flight is guided by visual contact with the ground and the avoidance of other aircraft is through visual sighting, all necessitated some kind of deviation from the originally intended route or destination in order to maintain VMC.

For 9.8% of all incidents, a reduction in communications performance due to the presence of dust was the primary issue prompting the report. Dust storms are known to create static and atmospheric attenuation of signals, which can interfere with radio communications (e.g., Edwards and Brock, 1945; Goudie and Middleton, 1992). The degradation of communications was also occasionally mentioned in some incidents where a different adverse effect took precedence in the classification. For example, where radio problems were cited in conjunction with positional uncertainty. In total, communication difficulties attributed to dust were mentioned across 13.1% of all incidents.

While the impact of decreased visibility was implicit in many of the adverse effects (e.g. the failure to locate an intended destination from the air), the impact of reduced visibility was stated as the primary effect of dust in 23.0% of the incidents. Frequently these cases involved flight activities in visibilities that contravened Australian flying regulations and thereby triggered an incident report. The ‘Miscellaneous’ category in Table 1 contains those incidents (4.9%) where dust affected flying operations in a manner that could not be conveniently classified into the other categories, for example, dust-related effects on aircraft handling.

A notable aspect of the reports is that 13.1% featured some mention of inadequate weather forecasting playing a part in the incident. Predominantly, these mentions were criticisms of pre-flight forecasts not predicting the presence of dust en route, and its eventual presence causing the flight to be altered in some way. By law in Australia, an official pre-flight forecast which indicates that visibility is likely to be reduced below certain specified values due to the likely presence of dust, either en route or affecting the destination, requires pilots to carry extra fuel before departure. Correct forecasting of dust therefore is an important requirement for successful, efficient air passage, and erroneous or inaccurate forecasts can prompt interruptions to operations such as fuel-forced diversions or returns to aerodrome of origin.

3.2 Types of aeolian activity

Of the 61 incidents identified, 47.5% were related to the effects of dust storms (Table 2). The events placed into this group were those where reports contained sufficient information on the nature of the dust (e.g. pilot or air traffic control description), together with cross checking of the DEDB, to infer that the incident was related to conditions of active dust raising. An air incident in the context of a large dust storm event is shown in Figure 1. Instances of dust haze, where the suspended sediment had been uplifted by a previously occurring dust storm, or was located far removed from sources of emission, accounted for 23.0% of incidents. A further 8.2% of the reports mentioned dust associated with the occurrence of thunderstorms. Events in this category were determined from the incident report descriptions only. Dust raised by thunderstorm downdraughts can often be relatively local in extent, thus if such an event affects a flight, it may well go undetected by any observer site and therefore not feature in the DEDB. Relatively few of the reports (6.6%) were interpreted as being cases involving local, small-scale instances of aeolian entrainment. Such small-scale instances of blowing activity were associated only with aircraft operations on the ground, for example on dirt runways (Table 2). For the final 14.8% of reports, confident classification of the aeolian activity responsible for the incident was not possible from either the report information or DEDB resources.

>>TABLE 2

>>FIGURE 1

3.3 Phase of flight and type of air operation affected

Table 2 also reveals that the large majority (68.9%) of dust-related air incidents occurred during the ‘in flight’ phase of aircraft operation. Given that the greatest part of any journey is the portion spent in flight, and this involves change in location by the aircraft over time, cruising is the phase where the potential for encountering dusty conditions is greatest. While pre-flight weather forecasting attempts to reduce the level of hazard for this flight phase, the changeable atmospheric conditions of dust events makes the cruising phase especially susceptible to those adverse effects grouped as navigation-related (e.g., forced returns, positional uncertainty).

While accidents resulting in damage were rare overall, their highest frequency was during the takeoff phase, where both a dust storm and local entrainment were associated with incidents serious enough to damage machinery (Table 2). On the final approach and descent into the final destination, diversions can be required or positional uncertainty develop at this late stage of the flight. Such problems can arise during descent due to a worsening of visibility and flying conditions when the altitude decrease during landing brings the aircraft into higher concentrations of dust nearer the surface. Dust ceilings during major dust storms are commonly <2500 m. For instance, McGowan and Clark (2008b) estimated the ceiling for one western Queensland dust event to be 1000 m, while in a very large dust storm in 2002, the ceiling was estimated from aircraft to be 1500-2500 m (McTainsh et al., 2005). During the landing phase itself, only 4.9% of incidents occurred, all of which were related to impairments of visibility.

Both the role of the aircraft and the transport operation it was conducting are also included within the official ATSB incident reports. This information allowed assessment of which type of conveyance dust represented the biggest hazard. Table 3 shows that fixed-wing aircraft were by far the main form of aircraft affected, not surprising given their dominance of flight operations. Only two incidents involved helicopters, but one of these resulted in one of the relatively few instances of serious damage. Table 3 also reveals that passenger transport was the main form of operation affected by dust. All the incidents where damage was reported (three events, Table 1) were associated with charter operations.

>>TABLE 3

3.4 Spatial distribution of incidents

Mapping incident locations reveals the majority occurred in and around the Lake Eyre Basin (LEB) (Figure 2), the main dust emitting region on the continent (Prospero et al., 2002; Bullard et al., 2008; Strong et al., 2010). The regional city airports at Broken Hill, Mount Isa and Alice Springs are on the fringe of the LEB, lying in known pathways from the basin (e.g., Sprigg, 1982), and were all associated with multiple dust-related incidents (Figure 2). The flight route between Mount Isa and

Alice Springs was also particularly subject to interruption by dust. Four reports were located at or near Mildura, which is located both within the main southwest pathway of dust from the LEB as well as within a local, predominantly agricultural dust source region, the Mallee (McTainsh et al., 1990). A small cluster of incidents was also found in southern Western Australia, a secondary dust source region of Australia (McTainsh and Pitblado, 1987).

>> FIGURE 2

The number of events seen at coastal or humid tropical northern locations (>500 mm rainfall, Figure 2) is of some interest because these incidents occurred well away from the dominant dust source areas. These incidents mainly involved either small scale, localised dust raising, which was typically restricted to the aerodrome or immediate area of incident, or conversely, were related to very large scale events involving the advection of dust along pathways to the continental margins and beyond. A total of 14 (around a quarter) of incidents occurred outside the dry zone of the 500 mm isohyet. Three of these involved highly point sourced local entrainment events, two were associated with major dust storms breaking out of the dry interior and four were due to hazes experienced in coastal areas. As an example of the latter, the DEDB identified that there was significant wind erosion occurring in western Queensland on both the 1st and 2nd January 1970 with dust raising reported around Charleville and Longreach. A day later, much of the entrained dust had been transported to the east along the south-east dust path (McTainsh, 1998) and had formed the reported dust haze that rendered the destination Heron Island undetectable for one flight (Figure 2; Table 2).

3.4 Temporal distribution of incidents

Figure 3 shows that the vast majority of reported incidents were from the earliest part of the record, with 54.1% in the first half of the 1970s. After this peak, incidents became fewer in number but showed a relatively consistent frequency up until 1983. Much fewer cases have been reported in the last 20 years of the record. Given the complexity of the factors that determine the number of dust-related incident reports arising for any given year, any correlation between frequency of incident reports and measures of annual dust activity would not be expected to be particularly strong.

Despite this, it is still informative to examine the time series of incidents next to a record of annual dustiness.

The Dust Storm Index (DSI) is a metric that has been successfully used to express long term (>50 years) trends in dust activity for Australia (for a detailed review see O'Loingsigh et al., submitted). The DSI value for a location is derived from the daily records of dust weather codes reported annually at that observer station, with variable weightings for the different dust codes (e.g. local dust events are weighted less than severe dust storms) in the form:

$$DSI = \sum_{i=1}^{n} [(5 \times SDS) + MDS + (0.05 \times LDE)]$$

where *DSI* is annual Dust Storm Index from *n* stations and *i* is the *i*th value of *n* stations for *i* = 1 to *n*. The number of stations (*n*) is the total number of stations recording a dust event observation in the year. *SDS* is Severe Dust Storm (maximum daily dust code: 33, 34, 35), *MDS* is Moderate Dust Storm (maximum daily dust codes: 30, 31, 32 and 98), *LDE* is Local Dust Event (maximum daily dust codes: 07, 08 and 09). The development and explanation of the DSI is beyond the scope of this paper, and is fully explained by McTainsh and Tews (2007). For this study, a national annual DSI value was calculated from 180 (*n*) long term measuring locations throughout Australia. The DSI is used here to provide a general context of nationwide dustiness with which to interpret the annual variability of air incidents (Figure 3).

>>FIGURE 3

Variability in rainfall is a characteristic of the Australian climate, and droughts are well known to enhance both the frequency and magnitude of dust emission on the continent (McTainsh et al., 1989; McTainsh et al., 2005). While there were small increases in the frequency of air incidents for dry years showing relative dust peaks in 1983 and 1994, the major annual peaks of dustiness were 2002 and 2009 (DSI = 2.68 and 3.17, respectively). The beginning of the 21st century was associated with a period of prolonged drier conditions referred to as the Millennium Drought that severely affected eastern Australia. Significantly, however, the Millennium Drought and the attendant increase in wind erosion did not have any increased impact on aviation (Figure 3). It seems therefore that contemporary air transport in Australia, at least in terms of officially catalogued reports, is little affected by periods of enhanced dust activity.

It is interesting to note that although the 1970s was the period of time when dust-related incidents were most common, there were no aircraft reports for the years 1974-75. Pronounced La Niña conditions held sway over Australia in 1974, which made it a very wet year in which dust activity was significantly suppressed (Figure 3). Moomba for instance (location in Figure 2) had an annual rainfall in 1974 of 869 mm, an amount around four times its long term average. Inundation by floodwaters, growth of surface-protecting vegetation in response to the rains and residual soil moisture levels persisting throughout the country's dryland regions meant 1975 was a reduced dust year too, and no incident reports were catalogued for that year either.

After 1983 the number of reports lessened considerably with only 20% of the events occurring in the latter 27 years of the study. Through this period however, a general increase in aerosol levels was observed between 1997-2007 for Australia (Mitchell et al., 2010), and the DSI also shows an overall upward trend for this period (Figure 3). The decrease in reports of dust-associated air incidents cannot therefore be attributed to any significant reduction in dust activity throughout the continent. Furthermore, there has been no consistent decrease in air travel, which could be another possible explanation for the reduced number of dust-related reports over time (Figure 4).

>>FIGURE 4

As there is no evidence of decreased dustiness concurrent with the reduction in number of air incident reports, one possible explanation is that advancements in technology have helped reduce the impact of dust on aviation. For instance, the increasing prevalence of Global Positioning System (GPS) units in aircraft from the early 1990s has significantly reduced positional uncertainty in conditions of reduced visibility. Also, improved communications due to the progressive replacement of High Frequency (HF) radio by the introduction of now almost universal Very High Frequency (VHF) radio coverage for air traffic control purposes renders communication much less susceptible to degradation due to static in dust storm conditions. As evidence, the last instance of a report citing communication difficulties from dust was May 1979.

Reduced reporting by pilots may also be a possible explanation for the reduced number or reports through the study period. In the early years covered by the study, areas of regional Australia that were outside the coverage of Air Traffic Control radar were served by regional reporting stations known as “Flight Service Units” (FSU). These were, in effect, radio stations manned by local airport Flight Service Officers with whom pilots filed flight plans and passed position progress reports via HF or VHF radio. Whilst the procedures were not mandatory, the extant culture was such that the significant majority of pilots used the service. These units were dis-established progressively from the early 1980s and effectively disappeared within about 10 years. Whilst centralised Air Traffic Control took on procedural control for instrument flights, a culture developed where pilots flying in visual conditions rarely used the new service. Hence, many of the track deviations and diversions that occurred outside of controlled airspace were not apparent to air traffic controllers and hence were less likely to be reported by pilots. It is possible therefore that much of the reduction in aviation incidents attributable to dust is more apparent than real.

4. Conclusion

Between 1969 and 2010 inclusively for Australia, there was a total of 61 (and an annual average of 1.4) officially reported air incidents where blowing dust was identified as a factor. The vast majority of these reports occurred in the early 1970s, but two very wet years in this period (1974 and 1975) saw no incidents. Across all incidents there were no fatalities and very few occurrences of injury or damage-causing accidents attributable to atmospheric dust. The fact that almost three quarters of the incidents resulted in navigational or visibility-based problems means dust impacts upon aviation can be described largely in terms of economic cost and inconvenience.

An attempt to fully quantify the economic cost of navigational difficulties caused by dust would need consequences such as flight diversions to be valued, and these assessments would be hard to perform. From their study in South Australia, Williams and Young (1999) valued the detour of a single large passenger jet in 1994, but found the general opinion of private aviators was that blowing dust was not responsible for significant increases in flying costs, based on the 20 years before 1999. Many other aspects of increased expense, such as the greater maintenance costs necessary for aircraft operating in commonly dusty environments are also not taken into account in this study. Furthermore, the data used here relate to the reported impact of dust on active flights, thereby representing the active hazard that dust represents. The data therefore cannot be used to assess major financial costs for air transport which result from dust activity such as flight cancellations and re-scheduling.

One issue obfuscating the drawing of air safety conclusions from the ATSB record is the known change in incident reporting protocol following the demise of Flight Service Units in Australia. While it seems highly probable that technological advancements have helped reduce the frequency of dust-related navigational and communication incidents, the extent to which the decline in reports over time reflects a changing degree of the dust hazard, or reflects reduced reporting of dust-induced aviation incidents by pilots, is uncertain. Despite this uncertainty, it is clear that the reduced frequency of incidents cannot be accounted for simply by an overall decrease in atmospheric dust loading. While there has been an upward trend in dustiness, the number of air incidents has not increased. Furthermore, from around 1990, periods of highly elevated dustiness (typically associated with drought periods) have not seen jumps in the number of safety incidents, especially in terms of damage or injury. This leads to the inference that contemporary Australian aviation safety demonstrates considerable resistance to the hazard of blowing dust.

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Table 1: Nature of the adverse effect to aviation caused by dust

Broad category of effect	Specific disruption	% of incidents (n)
Navigation (57.4%)	*Diversion*: scheduled trip could not be completed and diversion to unplanned landing was required	27.9 (17)
	Return: aircraft required to return to its take-off location	16.4 (10)
	Destination: unable to locate intended destination	4.9 (3)
	Position: reported uncertainty in aircraft location	8.2 (5)
Communication (9.8%)	Communications reported as impaired	9.8 (6)
Damage (4.9%)	Resulted in aircraft damage	3.3 (2)
	Resulted in aircraft damage & injury	1.6 (1)
Visibility (23.0%)	Impairment of visibility was the primary reported effect of dust	23.0 (14)
Miscellaneous (4.9%)	Report of miscellaneous, non-optimal flying operations caused by dust	4.9 (3)

Table 2: Adverse effect of dust to aviation by type of dust activity and the phase of flight impacted

Phase of flight	Adverse effect	Type of dust activity					Total
		Dust storm	Haze	Thunderstorm related	Local entrainment	Undetermined	
Taxiing or takeoff (14.8%)	Damage	1			1		2
	Diversion	1					1
	Visibility	1	1		2		4
	Miscellaneous		1		1		2
In flight (68.9%)	Damage					1	1
	Diversion	9	2	1			12
	Position		3	1			4
	Destination		3				3
	Return	5	1	1		3	10
	Visibility	4				2	6
	Communications		1	2		3	6
Approach or descent (11.5%)	Diversion	4					4
	Position		1				1
	Visibility	1					1
	Miscellaneous	1					1
Landing (4.9%)	Visibility	2	1				3
		29 (47.5%)	14 (23.0%)	5 (8.2%)	4 (6.6%)	9 (14.8%)	

Table 3: Dust-related incidents by type of aircraft involved and nature of air operation

Type of aircraft	% (n)
Fixed wing	96.7 (59)
Helicopter	3.3 (2)

Type of air operation		
Passenger	Charter	46.0 (28)
	Low capacity	1.6 (1)
	High capacity	42.6 (26)
Freight		1.6 (1)
Unknown		8.2 (5)

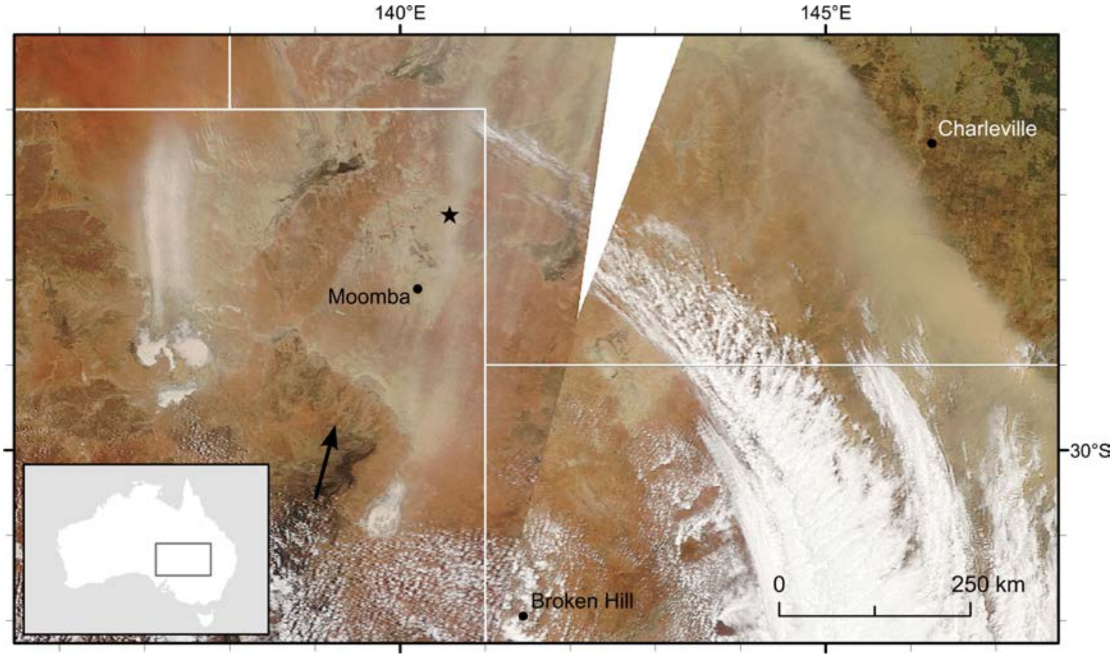

Figure 1: ‘True colour’ Moderate Resolution Imaging Spectroradiometer (MODIS) imagery showing wide scale dust storm conditions and location (star) of the incident reported at 10:30 CSuT, 2nd February 2005. With insufficient fuel for diversion, the small aircraft was forced to emergency land due to decreasing visibility in the dust storm. Arrow marks general wind direction. Satellite image was captured 1 hour 30 minutes after time of the incident report. More detailed remote sensing analysis of this dust event is available in Baddock et al. (2009). Image source: NASA MODIS Rapidfire.

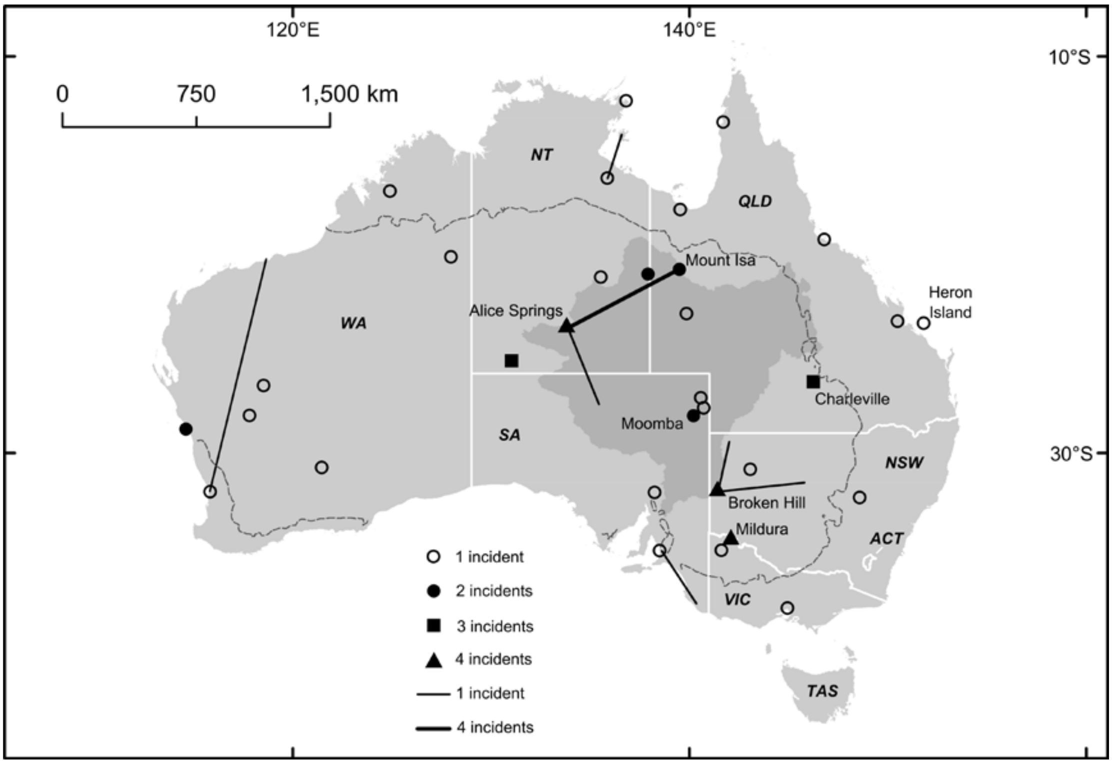

Figure 2: Spatial distribution of reported incidents (two incidents not included due to insufficient location information). Points represent either a specific location when provided in the report, or, the named location where a report mentioned the incident occurring within a certain area. Lines represent routes when the best spatial information for an incident was along a flight path. Lake Eyre Basin extent is indicated in darker grey. Dashed line is 500 mm isohyet.

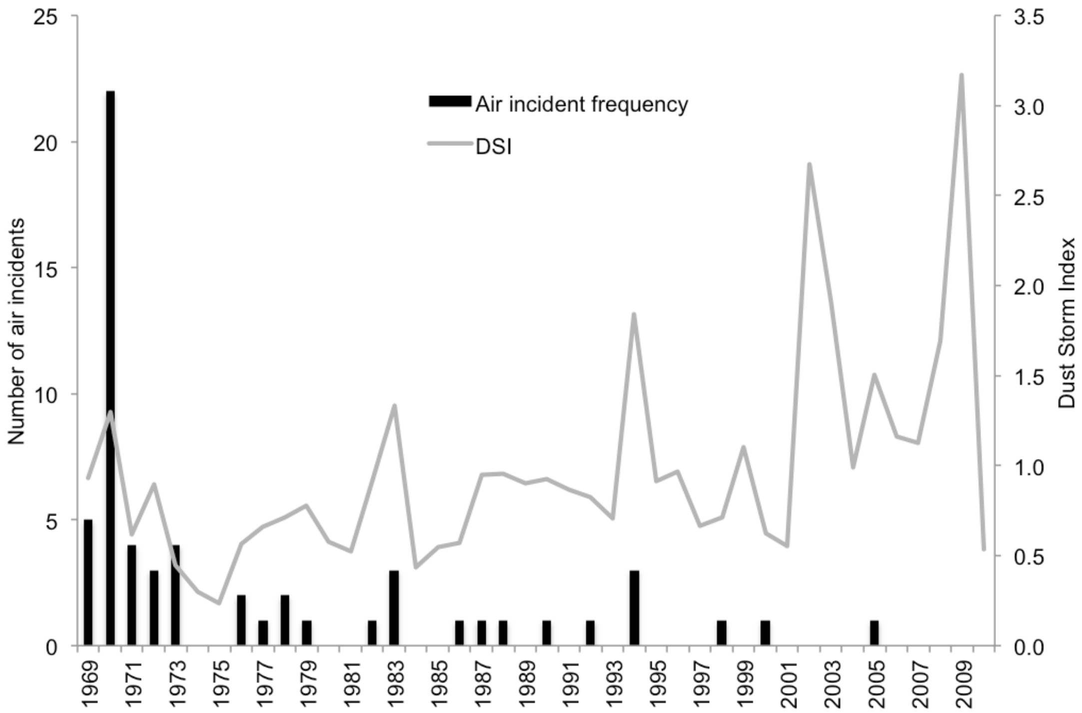

Figure 3: Annual Dust Storm Index (DSI) and frequency of aviation incident reports. See explanation of DSI in the text.

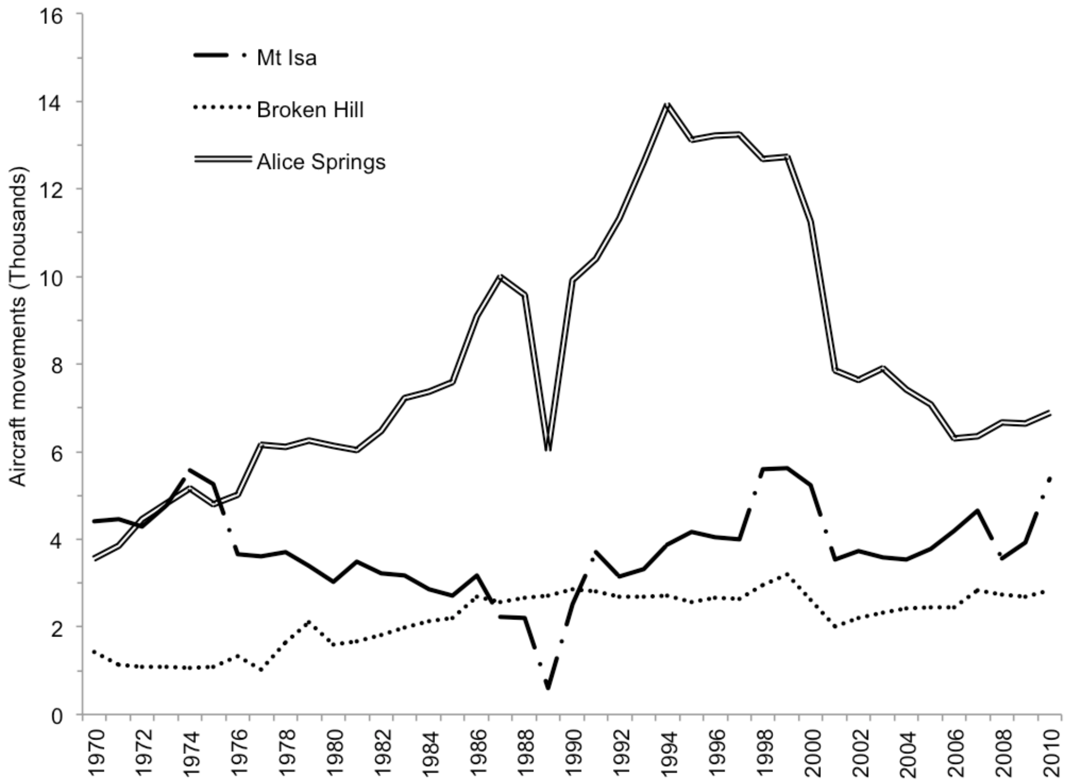

Figure 4: Annual aircraft movements for three regional Australian airports bordering the Lake Eyre Basin (locations in Figure 2). Movements are inbound and outbound flights, and relate to regular public transport schedules only. Data are for financial years, and official accompanying notes state that for Mount Isa the apparent decline 1987-90 is due to non-reporting by an airline for this period. Data from BITRE (2011).