TITLE:

Lost in Code: A critical analysis of using meteorological data for wind erosion monitoring.

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ABSTRACT:

Weather stations around the world record surface meteorological observations using the SYNOP coding system defined by the World Meteorological Organisation (WMO). These codes are used for a variety of meteorological studies, along with remote sensing and modelling studies of wind erosion and dust transport. Despite the widespread use of SYNOP codes in wind erosion research and monitoring in Australia and internationally, few studies, if any, have examined in detail the manner in which the codes are recorded and archived, and how this might affect the quality of the data and the outcomes of the research. In this study we investigate how different methods of recording and archiving SYNOP codes relating to wind erosion and dust transport can under-estimate the frequency and inaccurately record the timing of wind erosion events. We examine eight years of wind erosion data in the Lake Eyre Basin of central Australia (2000-2008) using more complete data from weather stations and compare them with the official archived dataset. On average, the number of dust days in the Lake Eyre Basin was under-estimated by 7% per year and the number of dust storm days (visibility < 1 km) by 15% per year. In addition, what appears to be a clear inverse relationship between rainfall and dust activity may in some cases be an artefact of dust codes having been lost in processing and archiving. We also found that thunderstorms are responsible for more dust storms than previously thought.

1.0. INTRODUCTION:

On September 23rd 2009 the entire east coast of Australia experienced one of the largest dust storms in approximately 70 years. The plume spanned nearly 2500 km for north to south and was several hundred kilometres wide, covering an area in excess of 800,000 km^2. This dust came as a result of two continuous days (21st – 22nd Sept.) of deflation in the Lake Eyre Basin. The town of Broken Hill in western NSW experienced dust storm conditions on both days and at approximately 16:00 AEST on the 22nd the town experienced near-total darkness with visibility no more than 10-20 meters with street lights on. The weather observers at the local Bureau of Meteorology (BoM) station recorded a moderate dust storm on the 21st and a Severe Dust Storm on the 22nd. However, according to the official BoM records, the only dust codes at Broken Hill on those dates were a dust whirl (dust devil) and locally raised dust. This paper examines why and how accurate records of this dust storm, and numerous other wind erosion events do not reach the public data archives used by scientists. We further contend that this problem is not just an Australian one, but could affect similar studies in all countries that use WMO-defined weather codes.

In the past 25 years, a number of studies into dust storm frequency and intensity have used coded weather observation records. In Australia, Bureau of Meteorology weather codes have been used to describe broadscale spatial and temporal patterns of dust activity (Buckley, 1987, McTainsh and Pitblado, 1987, McTainsh et al., 1989, McTainsh et al., 1990, Middleton, 1984). For some of these studies specialised datasets have been developed such as the Dust Event Database (DEDB) held at Griffith University, Brisbane, Australia. This dataset is a historic summary of the eleven types of WMO dust codes recorded by the Australian Bureau of Meteorology (Table 1) and provides data for the Dust Storm Index (DSI) (McTainsh, 1998) which has been widely used for wind erosion monitoring (e.g. McTainsh et al., 2007) (Equation 1). More recently, SYNOP dust weather codes were used by Lim and Chun (2006) to define thresholds of wind speed, temperature, vegetation cover and precipitation affecting dust entrainment in China. Fujiwara et al. (2007) used SYNOP dust codes from Chinese weather stations to explain the provenance of ^{137}Cs in dust over northwest Japan. Niang et al. (2008) used tallies of SYNOP dust storm codes as a measure of drought and land degradation in Mauritania. Mikami et al. (2009) integrated the SYNOP dust code records of China, Korea and Japan into the Japan Meteorological Agency's (JMA) dust forecasting model for validation purposes. In Australia, SYNOP dust codes have also been used in statistically-based studies of the long-term synoptic-scale weather patterns associated with dust storms (e.g. Ekström et al. 2004), and to identify suitable dust storms for atmospheric modelling case studies (e.g. Leslie and Speer, 2006). Bullard et al. 2008 also used these data, along with visibility records, for choosing satellite imagery in a geomorphological study of dust sources in the Lake Eyre Basin. More recently, Mitchell et al. (2009) compared dust storm frequency counts from SYNOP dust codes with nephelometer records in the Strzelecki Desert, Australia to evaluate the merits of ground-based instrumentation in remote locations.

McTainsh et al. (1987, 2007) outlined various limitations of SYNOP weather codes for measuring wind erosion in Australia. The main limitation identified relates to how weather observations are recorded in the field. Station-based observers have a choice of 100 of these codes (coded 0 to 99) to describe weather at up to 3 hourly intervals during the day. These records are usually entered in Electronic Field Books (EFB) or MetConsoles, however, observers are limited to just a few coded entries per observation. If more weather types are observed than there are entry slots available, the observer must prioritise the highest-coded weather types. As dust-related SYNOP codes are mostly between 6 and 35 on the 0-99 SYNOP scale, McTainsh and colleagues argued that dust codes could potentially be lost to higher codes (>35) due to the hierarchical nature of recording protocols. This hierarchical system of weather code recording is even more of a problem with the recording of 'Past Weather' codes; designed to identify all weather types since the last time the station made an observation, because intervals between observations can be between three and 18 hours.

This Past Weather problem was intended to be reduced in Australia when EFBs were introduced in the early 1990s, with the addition of a second Past Weather entry slot which allowed the recording of the highest and second-highest SYNOP code. Unfortunately, in the present context, due to limitations in data transmission capabilities and the perceived need to conform to WMO international format protocols, the second Past Weather code (along with many new features unique to the EFBs) were never processed, and instead were archived on computer tape which are not publicly available. Figure 1 is a conceptual model of this process.

In this paper, the original station data (1 code for Present Weather and 2 codes for Past Weather) are referred to as the 'Station' dataset, whereas the post-processing SYNOP-formatted version (1 Present Weather and 1 Past Weather) available to the public is referred to as the 'Public' dataset.

FIGURE 1 ABOUT HERE

This paper is based on a sample of the Station dataset and will primarily focus on re-analysing eight recent Dust Storm Years (DSY)[1] spanning 2000 to 2008 at 26 weather stations distributed throughout the largest dust source region in the Southern Hemisphere, the Lake Eyre Basin (LEB) of Central Australia (Tanaka and Chiba, 2006). The aim of this study is to investigate the consequences of having relied on WMO-formatted Public weather codes for the purpose of monitoring wind erosion, thereby providing an example of the potential limitations of using this (international) format of codes for scientific research.

A direct numerical comparison is drawn between dust-code tallies derived from both the Station and Public formats of the Australian weather codes database before examining the impact of these differences on the Dust Storm Index at the individual station scale and for the Lake Eyre Basin as a whole. Also included is a re-examination of the relationship between wind erosion derived from codes and rainfall as done by McTainsh (1989) who quantified the inverse-relationship between both phenomena. This re-examination is necessary because SYNOP codes >35; capable of superseding dust codes, are all related to precipitation.

2.0. Material and Methods

2.1. Stations and Timeline

This study relies on 26 stations with coded weather records in and around the Lake Eyre Basin (LEB) of Central Australia (Figure 2). These stations range from BoM-operated locations (3-hourly readings done by professionally trained observers) to cooperative sites (as few as two observations per day done by semi-trained volunteers).

FIGURE 2 ABOUT HERE

2.2. Dust codes dataset

The Station dataset was acquired courtesy of the Australian Bureau of Meteorology (BoM) for any calendar dates between July 1st 2000 and June 30th 2008 for which a dust code

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[1] Defined as the period from July 1st one year to June 30th the following year (McTainsh et al. 2004)

had been recorded in either the Present Weather slot or any of the two Past Weather slots. For comparison purposes, a simulated Public version of the dataset was created by including a supersession clause in the record as seen in Figure 1. The 11 SYNOP dust codes are outlined in Table 1.

TABLE 1 ABOUT HERE

2.3. Rainfall data

Monthly rainfall totals were acquired from Bureau of Meteorology rainfall archives and yearly totals were calculated to match the above-defined DSYs (i.e. July to June).

2.4. Dust Storm Index

The Dust Storm Index (Equation 1) uses all dust entrainment codes (excluding dust haze [06] which measures dust transport) and prioritises Severe Dust Storms (codes 33 to 35) over Moderate Dust Storms (codes 30 to 32), which in turn are prioritised over Local Dust Events (codes 07, 08, 09 and 98). Due to the reliance on human subjective determination of dust storm intensity, dust codes are refined and corrected using visibility information from the stations. This corrective approach could only be applied to Present Weather codes for which visibility information is recorded. Past Weather codes do not have visibility information and were therefore left untouched.

$$\mathrm{DSI} = \sum_{i=1}^{n} \left[(5 \times \mathrm{SD}) + \mathrm{MD} + (0.05 \times \mathrm{LDE}) \right]_i \qquad [1]$$

Where:

DSI = Dust Storm Index at n stations where *i* is the ith value of *n* stations for i=1 to n. The number of stations (n) is the total number recording a dust event observation in the time period.

SD = Severe dust storm (daily maximum weather codes: 33, 34, 35)

MD = Moderate dust storm (daily maximum weather codes: 09, 30, 31, 32 and 98)

LDE = Local dust event (daily maximum weather codes: 07 and 08)

3.0. Results and Discussion

At an individual observation timescale, between July 1st 2000 and June 30th 2008 the 26 stations recorded 3925 dust codes in their Past Weather slots. A total of 204 (or 5.5%) of these were lost to supersession when processed for the public (Table 2). Dust codes 06 to 35 experienced losses of between 2% and 41.6%. Only Code 98 did not experience any loss over the eight years.

TABLE 2 ABOUT HERE

As supersession only occurs for Past Weather, it is important to understand how often dust codes get recorded in this category, compared to Present Weather where supersession is not a problem. By definition, the Present observation describes the weather *at* the time the recording is made, whereas the Past code covers several hours. These two types of observations were examined separately (Table 3). Dust codes 06 to 09 are relatively evenly distributed between Present and Past observations, with between 8% and 20% more events recorded in the Past. This relative balance in frequency changes significantly for the main dust storm codes (codes 30-35). Dust storms were recorded between 30% and 800% more often in the Past. This finding is important because; (a) the process of supersession described above is a Past Weather problem, and (b) the corrective approach of refining dust codes with visibility information is rendered somewhat limited because Past Weather, where most dust storm codes exist, does not have visibility information.

TABLE 3 ABOUT HERE

All these dust codes were lost due to supersession by higher codes describing various forms of precipitation; henceforth referred to as ‘wet’ codes. These range from various kinds of *local precipitation* (codes 14-16), *drizzle* (50-59), *rain* (60-69), *showers* (80-90) and *thunderstorms* (91-99). The latter accounted for close to 50% of all superseded dust storms (09, 30-35), the implication of which will be discussed below.

The 5.5% difference between the Station and Public versions of the dataset was not evenly distributed across the stations. At BoM-run stations for example, with observations made every three hours, the potential for supersession in the Past Weather entry was limited to the number of weather types seen during those three hours. However, at cooperative stations, Past Weather spans between six and up to 18 hours, often saddling two calendar dates between the last observation of one day and the first observation of the next day. Once observers run out of scheduled entries for the day – some make their last observation at 3 pm – all weather types observed will be in contention for the first Past Weather slot the next morning (usually at 9 am). These long periods of accumulating weather types increase the potential for losing dust codes to higher order codes. This is important if these codes are to be used to create indices such as the Dust Storm Index. For example, the loss of lower intensity events (07 and 08) would not be expected to have much impact on the DSI due to the weighting coefficient of 0.05 for such events. The loss of Dust Storms (Codes 09, 98, 30-35) with weighting coefficients of 1 or 5 would be expected to have a more pronounced impact on overall DSI totals. Furthermore, with a single observation describing the weather types of two calendar dates, there is a risk of recording the dust storms on the wrong calendar date.

These differences are based on the analysis of individual observations (many per day) but the Dust Storm Index presented in Equation 1 is derived from the yearly totals of *dust days* at stations. Each dust day is defined by the highest dust code recorded, either in the present or the past observation entry during that day. In effect, this means that although dust codes can be superseded at the scale of single observations, a ‘dust day’ can still be noted as having been dusty as long as at least one of the observations for that 24-hour period was not superseded. Also, at this dust day scale of analysis, BoM-run stations with up to eight observations per day are less likely to lose an entire day of dust to supersession compared to cooperative stations with only 2 to 4 observations per day.

3.1. Dust Storm Index

Individual stations are summarised (Table 4) in terms of (i) all new dust days identified over eight years, from which dust *storms* are extracted (middle columns), as these are the events that feature most in publications (e.g. Ekström et al., 2004, Leslie and Speer, 2006, Bullard et al., 2008, Mitchell et al., 2009); and (ii), the dust storm indices derived from both dataset variants are shown, along with the percentage difference between them (right-most columns).

TABLE 4 ABOUT HERE

The Station and Public datasets matched each other at only five of the 26 stations (Table 4). The remaining 21 stations recorded 127 days of dust that did not feature at all in the Public version of the dataset. As many of these events had been lost to supersession on the same calendar date across several stations, these 127 new Station dust days translate to 104 new LEB calendar days of dust (ave. 13 per year), equivalent to 7% of all dust days being lost per year for the basin.

As for dust *storms*, the Station and Public datasets matched each other at only seven of the 26 stations. The remaining 19 stations had between 1 and 13 more dust storms recorded than made public, with most stations characterised by a 2-3 dust storm difference. Overall, these stations lost 58 dust storms to supersession over 47 calendar days, equivalent to 15.2% of dust-storm days being lost on average every year in the LEB for the period studied. This resulted in a 14.3% lower DSI between the two variants of the dataset in eight years.

3.2. Issues of timing

As explained above, once a station runs out of scheduled observations for the day, all subsequent weather phenomena occurring up to midnight and into the next calendar day will be vying for the single Past Weather entry of the first observation that morning. This is significant for two reasons; a) datasets contain dust storms recorded on the wrong calendar date; and b) at a regional scale when multiple stations are used, dust storms can potentially be counted twice. For example, if a single large dust storm passes simultaneously over a 3-hourly BoM-run station and a neighbouring twice-daily (9 am, 3 pm) cooperative station at 5 pm, the former would record the event in the 6 pm Past Weather entry of *the same day* whereas the latter, having run out of scheduled observations, would have to wait until the next available Past Weather entry at 9 am *the following day*. In the case of multi-year multi-station studies where both BoM and cooperative stations are used, one dust storm has the potential of being counted twice *as well as* being recorded in the wrong calendar day.

To properly quantify this timing issue would require alternative parallel data sources such as instruments, satellite imagery or other BoM products for example, as well as an in-depth investigation into station practices. Although such a study is beyond the scope this paper, we did compare the Stations record to the BoM Phenomena Flags dataset. This dataset is also based on station-level observations. At 9 am every day, in addition to recording SYNOP codes, observers must report on the occurrence of specific weather phenomena if these were seen during the 24 hours from midnight to midnight *of the previous day.* Although such records require observers to remember what happened the previous day, the reporting system itself is simpler, with observers only required to enter Yes or No to a list of phenomena such as Dust Storm (visibility < 1000 m), Haze/Mist/Smoke, Strong/Gail Winds, Hail, Fog and Thunderstorms.

Based on available data we were able to compare the last six of the eight dust seasons covered by this study. We found 83 instances (over 65 LEB calendar days) in the Station record where dust storms were either:

- *Recorded on the wrong day*: this occurs when a dust storm begins after the last recording opportunity of the day and ends before midnight. The SYNOP code for that event is recorded as a Past Weather event the following calendar day.
- *Superfluous*: this occurs when a dust storm lasts all day (and is recorded appropriately) but is still active after the last recording of the day has been made. As above, the observer uses the first available Past Weather slot the next day to describe this, adding a superfluous day of dust to the previous *real* day of dust.
- *Missing from the record*: this occurs when a dust storm starts late in the day (when the observer has already run out of scheduled observations) and lasts overnight into the next day. Although the dust storm as an event is recorded *that next day,* its start date is missed because the observer had run out of recording opportunities.

As for this problem being related to the number of observations made per day, no obvious patterns were found. All but seven stations were affected by these errors. In general, stations make more observations during the austral summer, late spring and early autumn months when daytime lasts longer (October to April). In winter, most stations drop one or two observations at either end of the day. These reductions did not however result in an increase in erroneously recorded dust storms as these decrease in number or cease altogether during the winter. Most superfluous, missing or wrongly recorded dust storm days were recorded between September through to January, at a time when the dust storm season is most active and station observations are most frequent. Stations with little or no timing problems were those such as the BoM-run Alice Spring station where; (i) observations are made every three hours, and more importantly, (ii) observations are still being made late in the day (i.e. 9 pm). No stations made timing errors at times when they had a 9 pm recording.

3.3. Station-Level Trends

The above-mentioned percentages may appear small in absolute terms, especially as they refer to the LEB as a whole. However, a common use of the DSI is for the inter-annual analysis of dust activity and its relationship with drought (McTainsh 1989, McTainsh et al., 1989), quite often for individual stations. It is at this scale of analysis that the differences between the Station and Public data can influence our understanding of wind erosion. By analysing each station individually, various trends in wind erosion (defined by the DSI), dust activity (dust-code frequency counts) and rainfall (responsible for 'wet' codes) were identified. We discuss these trends using three representative stations.

At Andamooka station (Figure 3), the Public-data DSI matched the Station-data DSI on only one of the eight DSYs studied. In total, this station lost 15 dust codes in eight years, 13 of which were Dust Storms (8 Severe, 5 Moderate). This result also exemplifies how the DSI can be sensitive to different types of dust events, with increases of between 14.3% (2006-07) and 203-fold (2000-01). These differences between the two datasets occurred despite the Andamooka region having less rainfall (fewer wet codes) than other stations. Although overall rainfall totals are low, supersession by wet codes was significant. The timing of the rain is therefore important and based on the analysis of wet codes, the short intensive thunderstorm events responsible for some of the identified dust storms are also responsible for the wet codes that supersede them. These events are known to be responsible for Moderate and Severe Dust Storms (Code 30-35), but are shown above to be associated with the highest-order codes (90s). In general, if the occurrence of dust coincides with a thunderstorm, an observer should record a code 98 (Thunderstorm with dust). However, as the rolling dust cloud (haboob) associated with a thunderstorm downdraft often precedes the onset of rain, an observer might not associate the two events; first noting a Code 34 for example (Severe Dust Storm), followed by a Code 95 or 97 (Thunderstorms with rain), with the former subsequently being lost to the latter due to the hierarchical nature of the WMO recording format. This station also exemplifies how one dust year (2003-04) can change its inter-annual DSI ranking; from being a relatively low DSY to being one of the highest.

Tibooburra in New South Wales (Fig. 4) is also one of many stations where the difference between the two datasets will affect its DSI profile. Although dust activity during 2006-07 was similar to previous years, the rainfall total for that year more than doubled, and with that the number of wet codes. These in turn contributed to the loss of dust codes and a halving of the DSI for that year in the Public archives. This station record also shows how the under-estimation of DSI for 2006-07 could lead to the incorrect conclusion that 2002-03 was the dominant wind erosion year of that time period.

Mount Isa (Fig. 5), on the northern fringe of the LEB, exemplifies stations where the rainfall is negatively related to dust activity, but also positively related to dust code suppression. This station also exemplifies how local dust events (not dust storms) can strongly influence the DSI profile of a station. In the highest DSI year (2007-08) Mount Isa had 111 local dust events (code 07) and no dust storms. The infrequency of high DSI-scoring dust storm codes is, however reflected in the lower overall annual DSI values compared to the southern LEB stations; Andamooka and Tibooburra which lie in the path of dust storm-producing frontal systems (Strong et al., 2010).

FIGURE 3 ABOUT HERE

FIGURE 4 ABOUT HERE

FIGURE 5 ABOUT HERE

To gain an overall understanding of the differences between the Station and Public variants of the SYNOP dataset for the LEB as a whole, the station tallies were combined (Fig. 6). Because nearly all stations lacked data for 2000-01 and the Jervois station lacked data for six of the eight years studied, the total cumulative tallies for the basin were derived for seven DSYs (2000-01 removed), from 25 of the 26 stations (Jervois removed).

FIGURE 6 ABOUT HERE

The years with the least difference between the datasets (≤ 6%) are those with high rainfall and low dust activity (i.e. 2001-02), and those with high dust activity and reduced rainfall (i.e. 2002-03, 2004-05 and 2007-08) (Fig. 6). For those years, either dust codes or wet codes dominated and therefore did not have to compete. However when both dust activity and rainfall occurred in the same DSY (i.e. 2003-04, 2005-06 and 2006-07), the difference between the two datasets was higher (from 22% to 34.4%) because of wet code supersession. Therefore for these DSYs as rainfall increases, so does the number of wet codes and in response the percentage difference between Station and Public datasets (Fig. 7).

FIGURE 7 ABOUT HERE

From a geomorphological perspective, the increase in error-inducing ‘wet’ codes with increased rainfall raises questions about the accuracy of past correlations between rainfall and dust activity using weather codes as the measure. Undoubtedly rainfall-induced soil moisture and vegetation responses play a major role in reducing dust entrainment at monthly timescales. The effects of short term increases in surface wetness following rainfall are, however less clear cut; depending upon soil type (e.g. sandy soil surfaces can dry out very quickly) and rainfall intensity. Therefore a complete cessation of dust activity following rainfall, as apparent from Public data, may on occasions be an artefact of the WMO recording protocols, whereby dust codes are superseded by wet codes.

From a meteorological perspective, the finding that nearly half of all superseded dust storms (09, 30-35) were superseded by *wet* thunderstorm codes is important, not simply because scientists end up conducting research with incomplete datasets, but because of the selective nature of dust storm code suppression. In many studies driven by the Public dataset (e.g. Ekström et al., 2004, Leslie and Speer, 2006), the mention of dust storms is predominantly linked to the passage of cold fronts, quite often dry spring-time cold fronts. With the selective exclusion of wet thunderstorm dust-storms from the Public dataset, it may not be surprising therefore that dry cold fronts are perceived as a major cause of dust storms. In reality there may be many more dust storms associated with thunderstorms than is currently recognised. In a recent examination of the roles of weather systems entraining dust in the southern LEB, Strong et al (2010) found that only 50% of dust events were associated with frontal systems. It is also particularly interesting in the present context, that this study supplemented the WMO weather code data with higher resolution observational data from a DustWatch station (Leys et al., 2008) which did not have the wet codes artefact in it.

These results also have implications for our understanding of the spatial distribution of dust storms across the continent. While it is widely acknowledged (from McTainsh and Pitblado, 1987 to Leys et al., 2008) that the low spatial density of BoM stations reduces the accuracy of such maps, until now there had been an implicit assumption that as large scale cold fronts are the primary generator of dust storm codes from Public data, the great distance between stations was less of a problem. The expected addition of new thunderstorm-related, and therefore more localised, dust storms will need to be taken into account in future wind erosion as the interpolative assumption that what happens at stations also happens between stations may not be as robust as currently thought.

From a climate modelling perspective, the finding that dust-storm days could be recorded on the wrong date or could be superfluous or missing and that the same dust event could potentially be recorded twice over two days at neighbouring stations has significant implications. Studies such as Ekström et al. (2004) relied on dust storm dates to statistically use climate model outputs with the view of identifying typical dust storm synoptic-scale weather patterns. If the timing of the recorded dust codes is important, for example, in understanding fast-moving cold fronts, the use of incorrectly dated events would reduce understanding of this important relationship. Furthermore, the assumption that large dust storms are primarily associated with the passage of fronts rather than thunderstorms may influence the design of dust-storm prediction models such as the U.S. Navy Aerosol Analysis and Prediction System (NAAPS) Global Aerosol Model (Westphal et al., 1987a, 1987b), or the 3D atmospheric composition GEOS-Chem model (Fairlie et al., 2007, Nam et al., 2009), as more attention may be given to dust entrainment under cold-front conditions at the expense of thunderstorms.

From a remote sensing perspective, both the missing dust codes and erroneous calendar dates can influence the selection of imagery for analysis and any subsequent result based on that imagery. Although problems related to the timing of dust codes can be overcome with a visual check of imagery on or around the date of the dust code, the problem of missing dust codes remains. Bullard et al. (2008), for example used MODIS imagery to quantify dust-source types in the Lake Eyre Basin from a set number of dust-storm days identified from the Public dust-code record. It is acknowledged and widely known that such study would have preferentially identified active sources from imagery containing little or no cloud cover (i.e. dry weather systems), to the detriment of dust events, and therefore active sources, under cloud cover. It is less well known that the loss of data on days of rainfall-inducing (wet-code) cloud cover may be greater than currently assumed. Sources in drier less cloud-covered regions of the LEB, such as the dunes of Simpson Desert in the Northern Territory, might be identified as more active than sources further south in the basin, such as dry lakebeds, because of a higher instance of cloud cover associated with passing cold-fronts anchored to low pressure cells in the Great Australian Bight (Southern Ocean).

Anticipating the potential limitations of using SYNOP codes as their only guide to selecting imagery, Bullard et al., (2008) also used visibility data, thereby identifying additional potential dust events. As explained above, visibility is also used to re-code incorrectly coded dust events by BoM observers according to the criteria outlined in Table 1 (McTainsh et al., 2004), but as explained above (Table 3), because visibility records are only available for Present Weather observations, these corrections cannot be applied to the more numerous Past Weather dust storms. Ideally, in both cases (remote sensing and corrective coding), an independent source of continuous visibility information would be available and easily synchronised with observations.

Losing high-order dust codes to wet codes also has significance for our understanding of long distance dust transport, because assuming that an entrainment event can be superseded in the driest part of Australia – where wet codes are less common – then dust plumes coded as dust haze (code 06) further downwind have a greater chance of being superseded by wet codes while passing over wetter coastal regions (Fig. 8). An implication of this in Australia is that our understanding of the operation of the Southeast and Northwest dust paths out of Australia (Bowler, 1976, McTainsh 1989), although improved (e.g. McGowan et al., 2009), is less complete than it could have been. The implication of wet code supersession for our understanding of global dust paths exiting, for example the Sahara and China internationally is also potentially significant. Although nowadays the movement of dust can be tracked and quantified around the globe using satellites and surface instruments, such technological advances are relatively recent, therefore WMO weather station data still has an important role. Furthermore, the high cost of deploying and maintaining surface instruments makes weather stations the only realistic monitoring option for developing and/or sparsely populated countries (e.g. Africa, China, Australia). Wherever such instruments can be set up there are advantages to be gained by correlating their data with WMO observational data.

A comparison of dust activity data in the Strzelecki Desert of Central Australia from both instruments and neighbouring weather stations by Mitchell et al. (2009) identified many dust storms recorded by the instrument that did not feature in the station records, and vice versa. Although the distance between the various sites could explain some of these discrepancies - especially if the dust event was a local thunderstorm, it is also very likely that the suppression of dust storm codes in the weather records contributed to the identified mismatch.

FIGURE 8 ABOUT HERE

The decision made by the BoM to add a second Past Weather ‘button’ to Australian Electronic Field Books and MetConsoles during the 1990s and early 2000s was potentially fortuitous for wind erosion and dust transport research, but as it has never been made Public, this potential has yet to realised. The questions arise as to, how other WMO affiliated meteorological agencies around the world have handled their weather phenomena data, and if they altered their recording protocols in a similar manner to the BoM? As this type of information is seldom published widely it is not surprising that there is little information in the international scientific literature to draw upon. In the absence of such information it is reasonable to assume that most countries report one Past Weather observation based on WMO reporting protocol. A compounding factor to the loss of (dust) codes to supersession is that due to financial restrictions, many WMO stations around the world are either reducing the number of observations they make per day or observers are being replaced by Automatic Weather Stations (AWS). These changes are occurring in Australia, as during this eight-year study nearly all 26 stations experienced a decrease in the number of observations they made per day, thereby further lengthening the number of hours – and the number of weather types – to be covered by the Past Weather entry.

4.0. Conclusions and Recommendations

Many studies make use of the WMO SYNOP weather codes but very few question the manner in which these codes are recorded, and therefore are aware of how this might impact their research. The aim of this study was to critically evaluate the use of weather codes for monitoring dust activity and wind erosion in Australia. We have shown that; (i) the WMO hierarchical coding protocols contributed to an underestimation of 7% of all dust days and 15.2% of dust storm days per year in the Lake Eyre Basin. Although these are not large percentages we found that; (ii) by examining individual stations the relationship between dust activity and rainfall may not be as reliably established as previously thought by using weather codes. This is based on the finding that at many stations the apparent suppression of dust activity by rainfall may in part be an artefact of dust codes being superseded by the higher-order *wet* weather codes associated with the rain. Rainfall supersession was identified here at two time scales: when *wet* codes occurred (near) simultaneously with the dust codes, and by correlating annual totals of rainfall, the number of wet code days and the gap between the Station and Public DSI totals (Fig. 7). The positive relationship between annual rainfall, number of wet codes and their inverse relationship with gap between the Station and Public DSI totals means that the timing of rainfall, and not just total amounts, is important. This leads to finding (iii); that a significant number of severe dust storms associated with thunderstorms had been superseded. This highlights the problem that even if a relatively small number of wet codes supersede thunderstorm dust-storms this can significantly influence the DSI profile of a station. This underestimation raises questions about some of the conclusions of past studies using SYNOP codes to query, verify or validate climate models or select satellite imagery to pinpoint dust sources. Our understanding of inter-annual wind erosion regimes could also be compromised. These problems are compounded by the fact that dust storms can be recorded on the wrong day and that single-day dust storms can be recorded over two days and vice versa. As SYNOP codes are used in Australia to map wind erosion for environmental auditing purposes, and to provide government policy makers with information, it is in the interests of the Australian government (and other governments in a similar situation) to maximise the quality of data available for such environmental audits. In Australia the government is in a very good position to make this happen, because it also funds the BoM therefore has the capacity to finance the retrieval of these lost codes.

Returning to the example we started with; of the massive dust storm that hit Broken Hill on the 22nd September 2009. The reason that there is no Public record of the moderate dust storm (code 32) on the 21st and Severe Dust Storm (code 35) on the 22nd is that these Past Weather observations were superseded (according to the WMO-defined hierarchy protocol) by the ‘light rain showers’ (code 80) that also occurred at the time. Therefore the dust whirl (08) and raised dust (07) codes that were reported as Present Weather phenomena became the defining descriptors of one of the largest and most memorable dust storms in recent history for Broken Hill and Australia.

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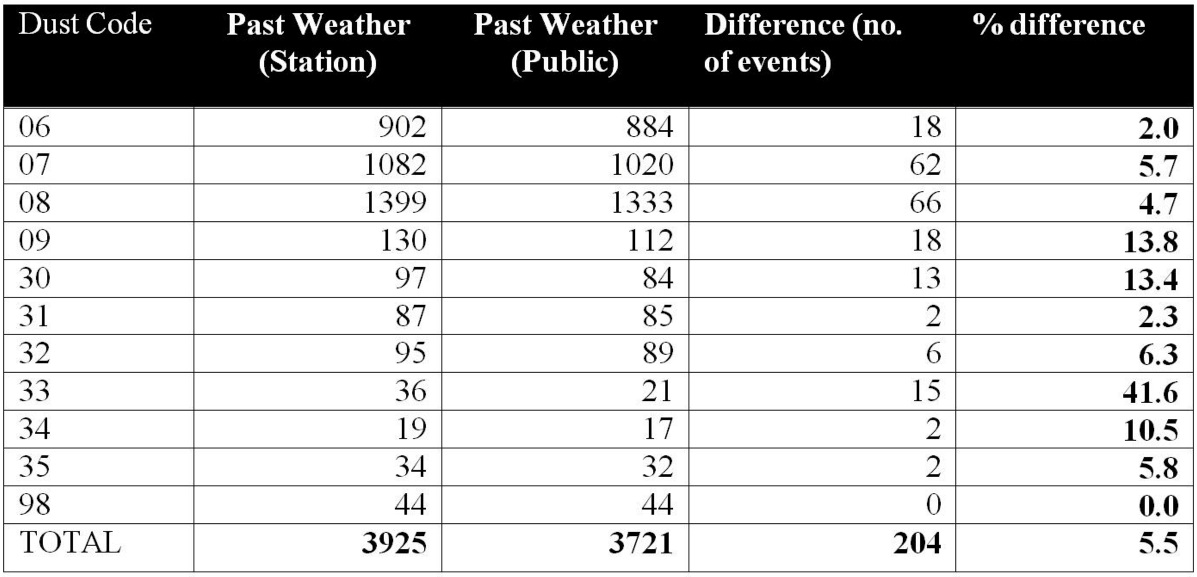
Tables

Table 1: Dust-related codes as part of the 100 SYNOP internationally recognised (WMO) weather codes (adapted from pp. 24-25 of the Australian Bureau of Meteorology ‘Recording and Encoding Weather Observations’).

SYNOP Code	Weather Description
06	Dust Haze
07	Raised dust or sand
08	Well developed Dust Whirls (dust devils)
09	Distant or Past dust storm (distant at time of obs or past station in past hour)
30	DECREASED Slight or Moderate sand or dust storm with visibility <1000 m but >200m
31	STABLE Slight or Moderate sand or dust storm with visibility <1000 m but >200m
32	BEGUN or INCREASING Slight or Moderate sand or dust storm with visibility <1000 m but >200m
33	DECREASED Severe dust storm with visibility <200 m
34	STABLE Severe dust storm with visibility <200 m
35	BEGUN or INCREASING Severe dust storm with visibility <200 m
98	Thunderstorm with dust or sand storm

Table 2: Summary of dust observations in the Station and Public datasets based on 26 stations in the Lake Eyre Basin between 2000 and 2008.

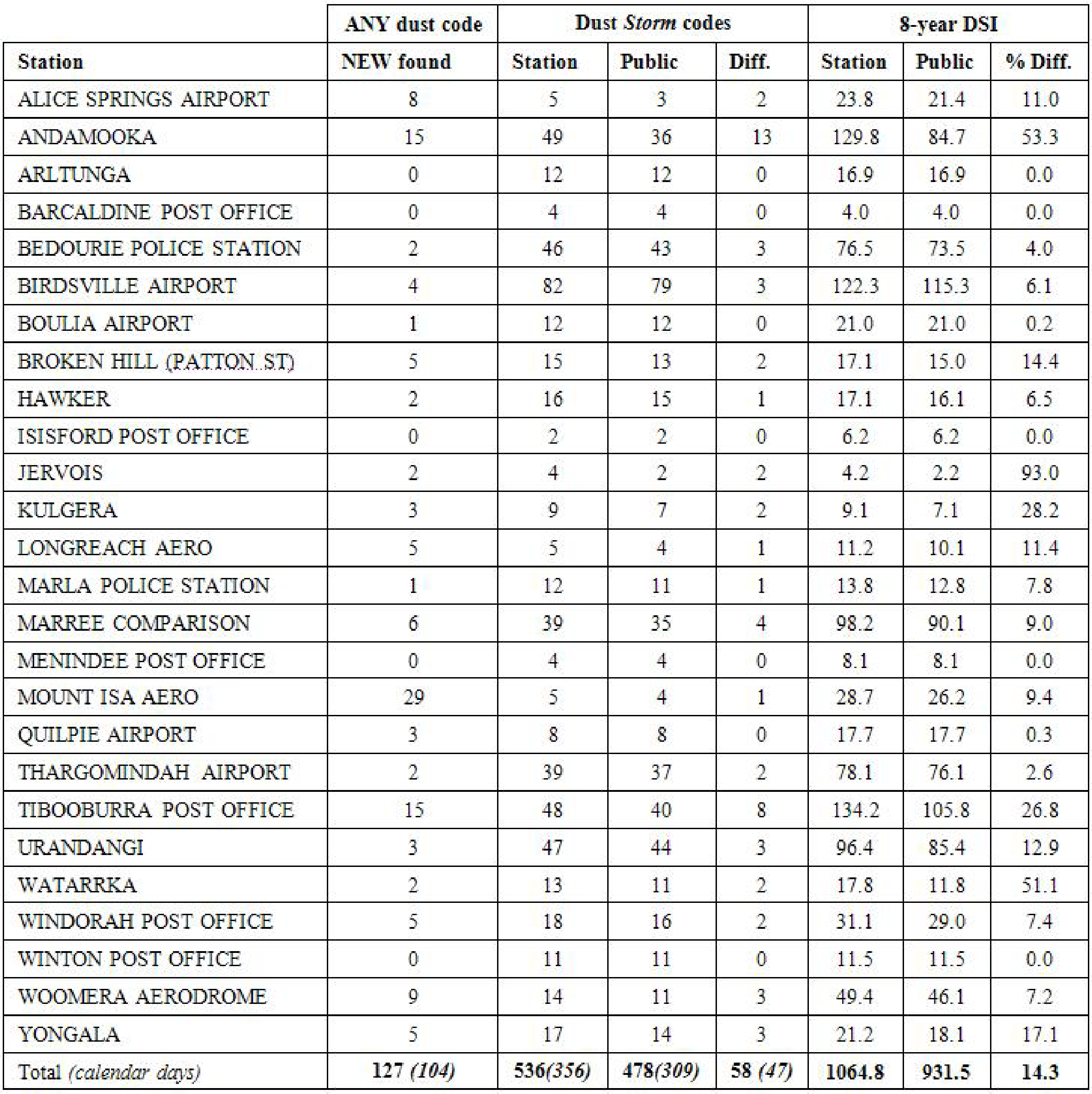


Dust Code	Past Weather (Station)	Past Weather (Public)	Difference (no. of events)	% difference
06	902	884	18	**2.0**
07	1082	1020	62	**5.7**
08	1399	1333	66	**4.7**
09	130	112	18	**13.8**
30	97	84	13	**13.4**
31	87	85	2	**2.3**
32	95	89	6	**6.3**
33	36	21	15	**41.6**
34	19	17	2	**10.5**
35	34	32	2	**5.8**
98	44	44	0	**0.0**
TOTAL	**3925**	**3721**	**204**	**5.5**

Table 3: Frequency of dust codes as recorded into Present and Past Weather observations based on 26 stations in the Lake Eyre Basin between 2000 and 2008.

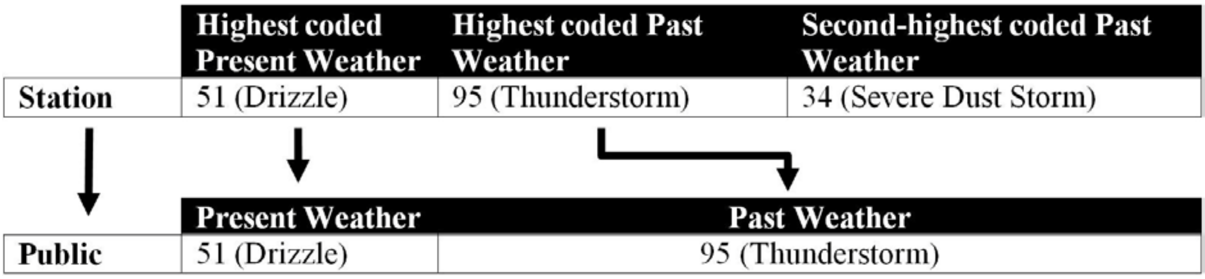
Dust Code	In Present Weather	In Past Weather	% diff.
06	799	902	12.89
07	900	1082	20.22
08	1167	1399	19.88
09	120	130	8.33
30	42	97	130.95
31	67	87	29.85
32	61	95	55.74
33	4	36	800.00
34	10	19	90.00
35	15	34	126.67
98	4	44	1000.00

Table 4: Summary of the 26 stations showing the total number of new dust codes found, the difference in the number of dust *storms* (09, 30-35, 98 only) between the Station and Public datasets the resulting eight-year DSI.



	ANY dust code	**Dust *Storm* codes**			**8-year DSI**		
Station	**NEW found**	**Station**	**Public**	**Diff.**	**Station**	**Public**	**% Diff.**
ALICE SPRINGS AIRPORT	8	5	3	2	23.8	21.4	11.0
ANDAMOOKA	15	49	36	13	129.8	84.7	53.3
ARLTUNGA	0	12	12	0	16.9	16.9	0.0
BARCALDINE POST OFFICE	0	4	4	0	4.0	4.0	0.0
BEDOURIE POLICE STATION	2	46	43	3	76.5	73.5	4.0
BIRDSVILLE AIRPORT	4	82	79	3	122.3	115.3	6.1
BOULIA AIRPORT	1	12	12	0	21.0	21.0	0.2
BROKEN HILL (PATTON ST)	5	15	13	2	17.1	15.0	14.4
HAWKER	2	16	15	1	17.1	16.1	6.5
ISISFORD POST OFFICE	0	2	2	0	6.2	6.2	0.0
JERVOIS	2	4	2	2	4.2	2.2	93.0
KULGERA	3	9	7	2	9.1	7.1	28.2
LONGREACH AERO	5	5	4	1	11.2	10.1	11.4
MARLA POLICE STATION	1	12	11	1	13.8	12.8	7.8
MARREE COMPARISON	6	39	35	4	98.2	90.1	9.0
MENINDEE POST OFFICE	0	4	4	0	8.1	8.1	0.0
MOUNT ISA AERO	29	5	4	1	28.7	26.2	9.4
QUILPIE AIRPORT	3	8	8	0	17.7	17.7	0.3
THARGOMINDAH AIRPORT	2	39	37	2	78.1	76.1	2.6
TIBOOBURRA POST OFFICE	15	48	40	8	134.2	105.8	26.8
URANDANGI	3	47	44	3	96.4	85.4	12.9
WATARRKA	2	13	11	2	17.8	11.8	51.1
WINDORAH POST OFFICE	5	18	16	2	31.1	29.0	7.4
WINTON POST OFFICE	0	11	11	0	11.5	11.5	0.0
WOOMERA AERODROME	9	14	11	3	49.4	46.1	7.2
YONGALA	5	17	14	3	21.2	18.1	17.1
Total *(calendar days)*	**127 *(104)***	**536*(356)***	**478*(309)***	**58 *(47)***	**1064.8**	**931.5**	**14.3**

List of Captions



	Highest coded Present Weather	Highest coded Past Weather	Second-highest coded Past Weather
Station	51 (Drizzle)	95 (Thunderstorm)	34 (Severe Dust Storm)

	Present Weather	Past Weather
Public	51 (Drizzle)	95 (Thunderstorm)

Figure 1: Simplified conceptual sequence of how weather codes are recorded and subsequently made public. In the Public format of the dataset, the lower of the two Past Weather codes is deleted in favour of the highest Past Weather code.

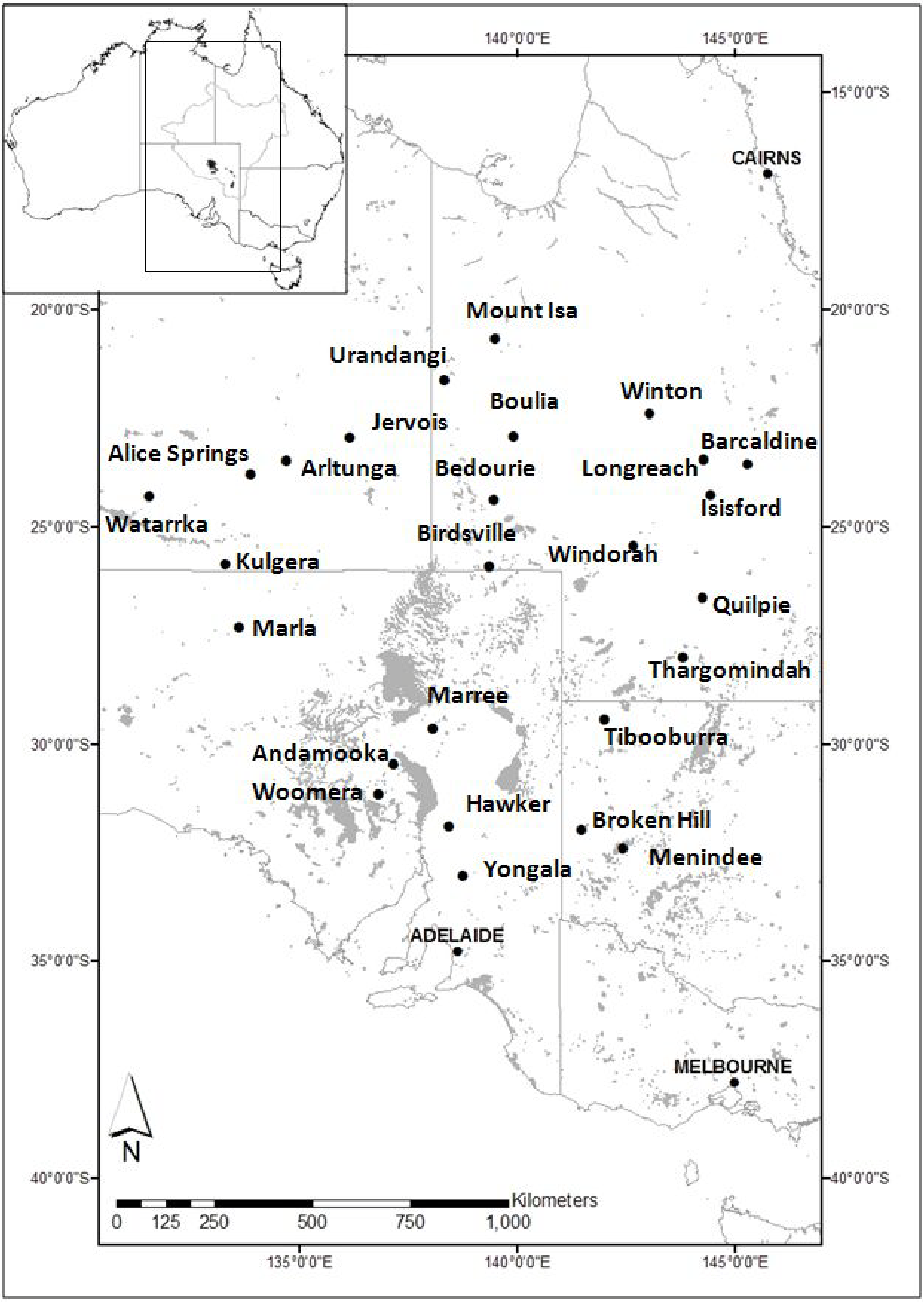


Figure 2: Map of Central Australia showing the 26 stations used in this study.

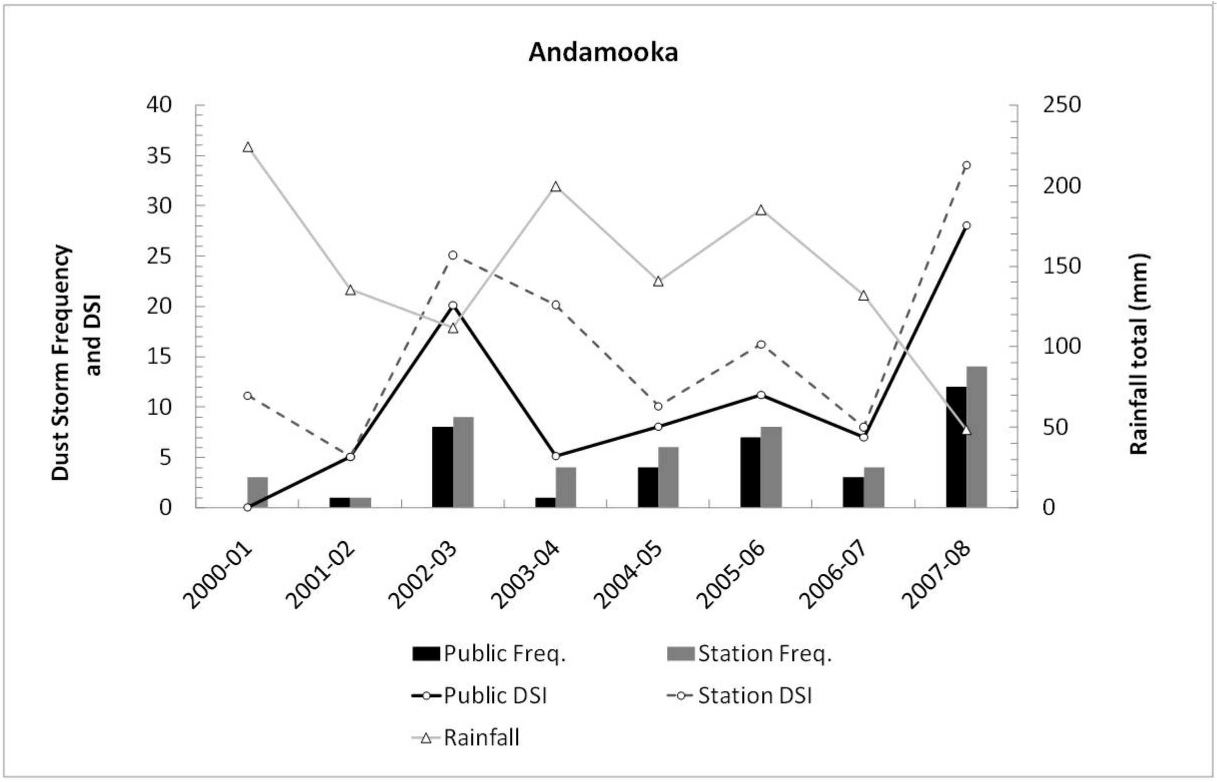


Figure: 3: Andamooka Dust Storm frequency, Dust Storm Index and rainfall.

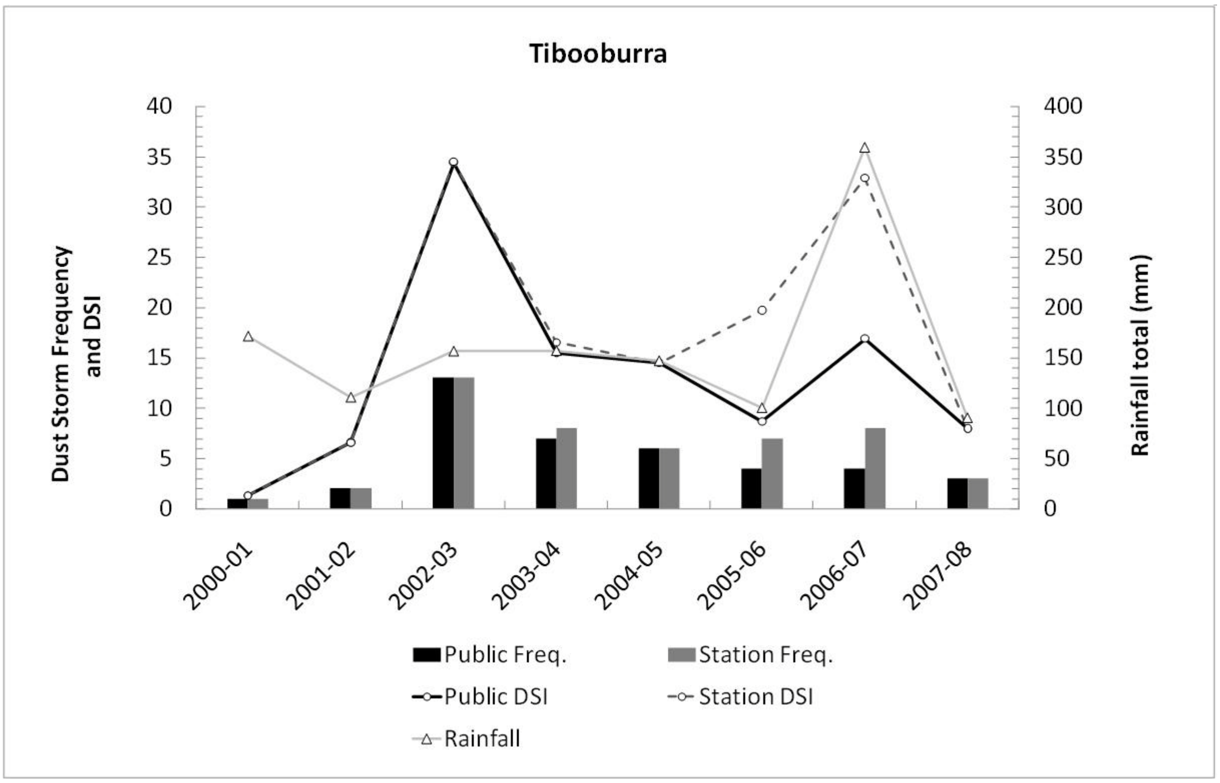


Figure: 4: Tibooburra Post Office Dust Storm frequency, Dust Storm Index and rainfall.

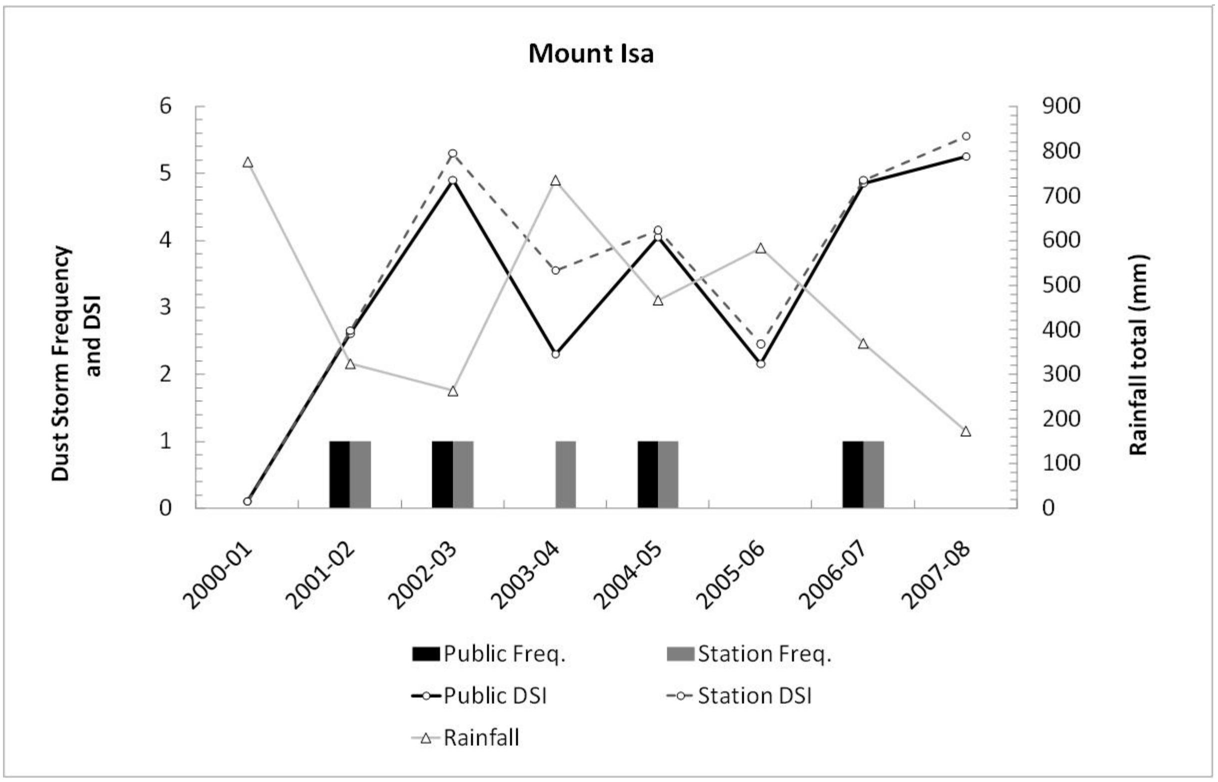


Figure: 5: Mount Isa Aerodrome Dust Storm frequency, Dust Storm Index and rainfall.

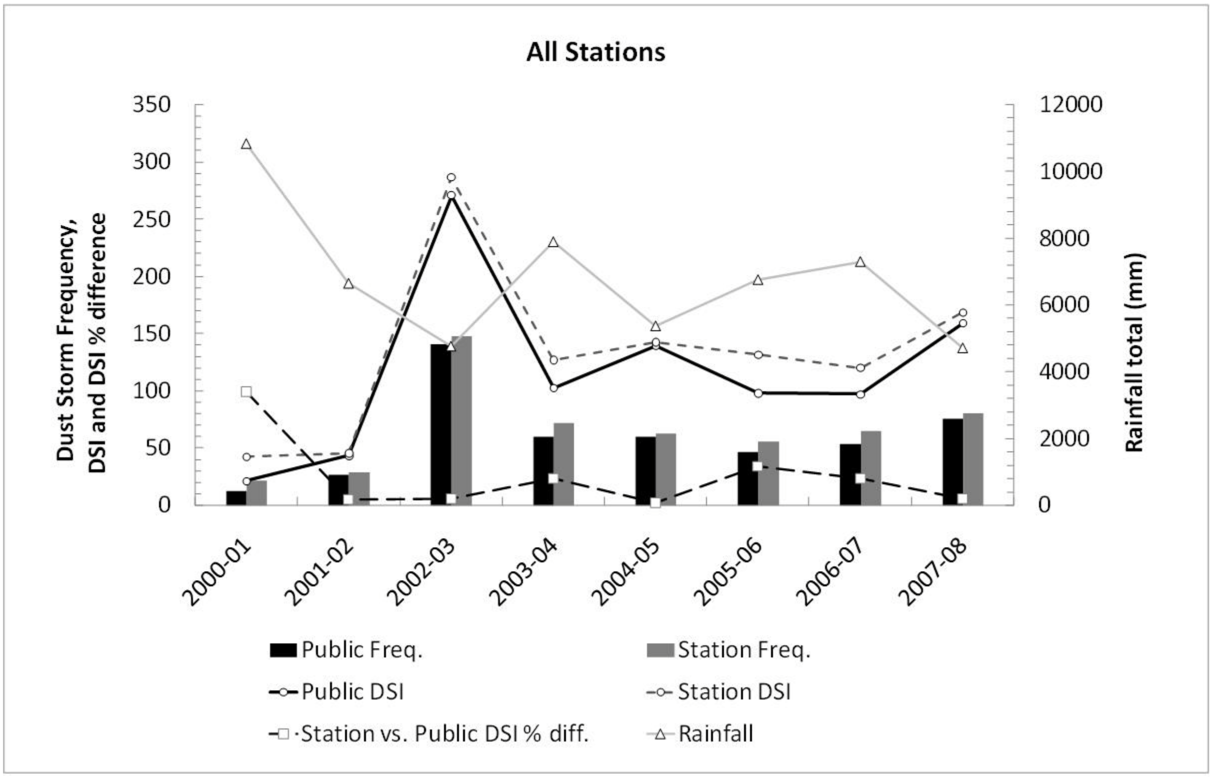


Figure 6: 25-station cumulative totals for Dust Storms, DSI and Rainfall with additional information on the percentage difference between the Station and Public data DSIs, with: 2001-02 +5.2%, 2002-03 +5.8%, 2003-04 +23.9%, 2004-05 +2.4%, 2005-06 +34.4%, 2006-07 +22%, 2007-08 +6%.

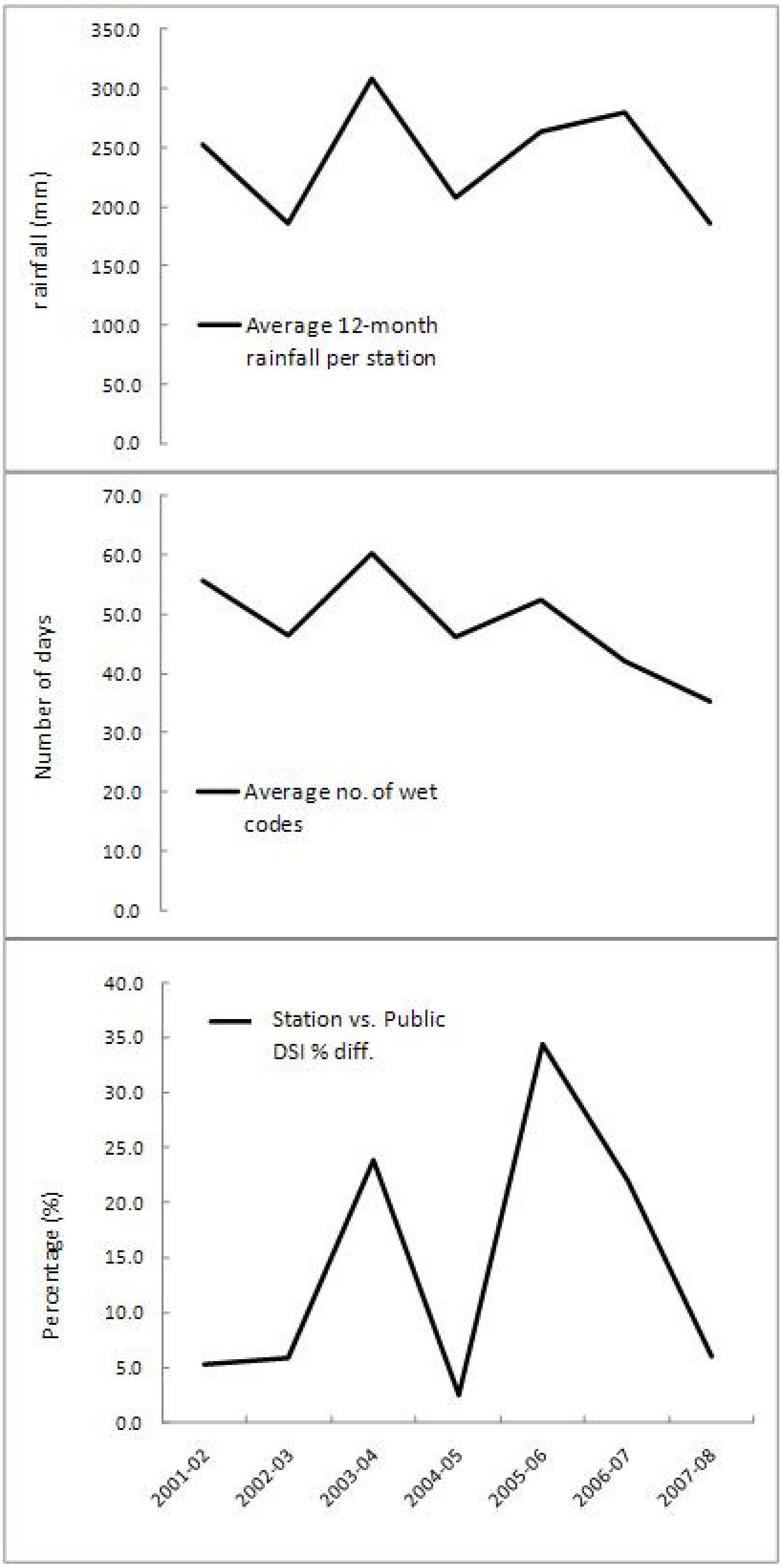


Figure 7: Overall trend shift over time of the percentage difference between Station and Public codes, rainfall, and the number of ‘wet’ codes.

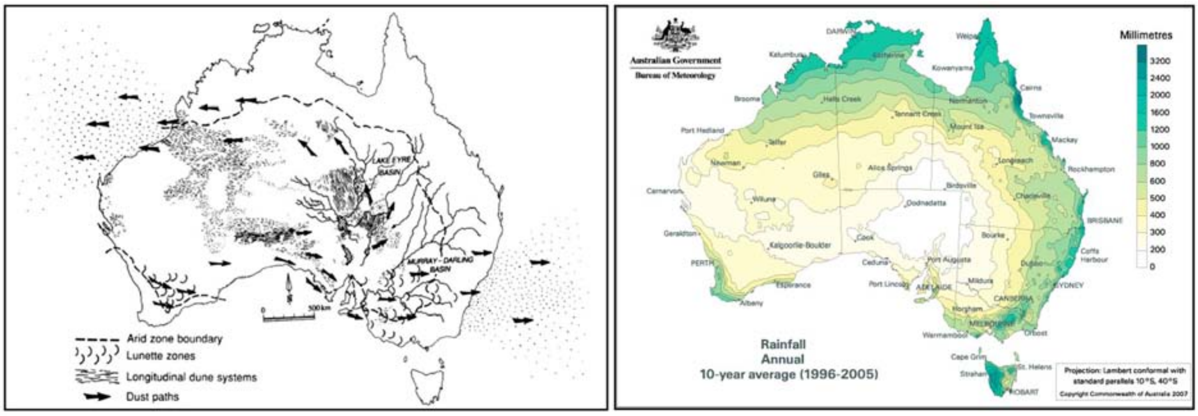


Figure 8: Left: Southeast and Northwest Australian dust paths (modified from Bowler, 1976 as seen in Hesse & McTainsh, 2003) and Right: 1996-2005 decadal rainfall map of Australia (Courtesy of the Australian Bureau of Meteorology).