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PM10 CONCENTRATIONS AND MASS TRANSPORT DURING “RED DAWN” - SYDNEY 23 SEPTEMBER 2009

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Abstract

The “Red Dawn” dust storm on 22 and 23 September 2009, called “Red Dawn”, was the largest to pass over Sydney in term of reduced visibility (400 m) since reliable records began in 1940. The maximum hourly PM_{10} concentration measured near Sydney was 15,366 µg/m^3 at Bringelly and is the highest ever recorded for Sydney and possibly any Australian capital city. The Australian air quality standard of 50 µg/m^3 per 24 hours was massively exceeded at Randwick (1,734 µg/m^3) and Newcastle (2,426 µg/m^3). Red Dawn was caused by drought and the extreme wind conditions caused by a low pressure trough and cold front associated with a deep cut-off low pressure system. The source of the dust was the red sandplains of western New South Wales, the sandplains, riverine channels and lakes of the lower Lake Eyre Basin and Channel Country of Queensland. Between 22 September 2009 at 1400 to 23 September 2009, 0.3 Mt of PM_{10} dust was transported off the coast between Albion Park and Newcastle (182 km length) near Sydney. The maximum hourly rate of PM_{10} dust lost off the coast near Sydney was 71,015 t/h on 22 September at 2100. Calculating the total suspended particulate sediment lost off the Australian coast for the 3000 km long Red Dawn dust storm gives an estimate of 2.54 Mt for a plume height of 2500m. This is the first and largest off-continent loss of soil ever reported using measured, as apposed to modelled, dust concentrations for Australia.

1. Introduction

On 23 September 2009 the worst dust storm to hit Sydney since reliable records began in 1940 enveloped the city with choking dust for nine hours and reducing visibility at the airport to 0.4 km. This exceeds the 19 November, 8 January 1942 and 11 December 1944 events when dust reduced visibility to 1 km. Named “Red Dawn” by the media, the 2009 dust storm greeted the people of Sydney with a morning sky that glowed an eerie red. The global interest created by this dust storm was enormous, with images of iconic Sydney landmarks disappearing into the red dust cloud. Locally the Sydney Morning Herald newspaper published a story entitled “Sydney turns red: dust storm blankets city” and it was the most “clicked” publication by the newspaper in 2009 with close to 600,000 page hits (http://www.smh.com.au/digital-life/digital-life-news/what-you-clicked-on-smhcomau-in-2009-20091220-l742.html).

Studies of Australian dust storms indicate that millions of tonnes of dust are deposited both on land and off the coast. Dust deposited on the land can have positive impacts such as contributing to soil development (Butler and Hutton, 1956; Cattle et al. 2002; Cattle et al. 2009; Knight et al. 1995; Raupach et al. 1994), while iron rich dust deposited in oceans can be linked to blooms in phytoplankton populations in high nutrient-low chlorophyll (HNLC) oceans, such as the Southern Ocean (Boyd et al. 2004) and make major contributions to marine sediments (McTainsh 1989; Hesse and McTainsh, 2003).

Dust deposition can also have negative impacts such as increasing nutrient levels in water ways (Leys and McTainsh, 1998) and pollution in urban areas (Chan et al. 2005) that result in increased respiratory disease (Rutherford et al. 1999). During Red Dawn, the media reported increased hospitalisation related to asthma (Ramachandran 2009). The impact of dust storms on urban areas can result in significant costs to the economy (Huszar and Piper, 1986). American (Piper and Huszar, 1989) and Australian (Williams and Young, 1999) studies report increased costs associated with damage to houses and infrastructure and cleaning of cars, houses, businesses, machinery and air conditioners. During Red Dawn, other costs related to disruption of communications, recreational and sporting activities and even cancellation of transport (air, road and ferries) were reported in the mass media (Ramachandran, 2009). Large dust concentrations increase car accidents which have resulted in fatalities (Yerman, 2009) along with loading up power transformers and lines leading to disruption to power supplies (Williams and Young, 1999).

Dust storms are a natural part of the Australian landscape and are common in the arid inland of Australia (McTainsh et al. 2005) but their occurrence on the east coast of Australia is rare. In the 75 years prior to Red Dawn, dust storms with a visibility less than 1 km have only been measured in Sydney on three other days, all in the 1940s (identified above). Other Australian capital cities have recorded dust events over the last thirty years. Some of the more notable dust events occurred in Melbourne on 8 February 1983 (Raupach et al. 1994), in Brisbane on 1 December 1987 (Knight et al. 1995), in Adelaide on 1 February 1983 (Williams and Young, 1999) and 24 May 1994 (Raupach et al. 1994), Sydney 25 May 1994 (Raupach et al. 1994), and Sydney and Brisbane on 23 October 2002 (McTainsh et al. 2005).

During dust storms large quantities of top soil are moved. Two approaches have been used in Australia to quantify the extent, size and dust loads of dust storms: 1) numerical simulation (Shao and Leslie, 1997; Shao et al. 2007) and 2) empirical calculation based on surface measurements (Raupach et al. 1994). The latter method calculates the dust load M (g) by:

$$M = AhC \qquad (1)$$

where A (m^2) is the estimated area of the plume, h (m) is the observed or estimated plume height and C (g/m^3) is the average concentration within the plume (Knight et al. 1995; McTainsh et al. 2005). The majority of studies have derived dust concentration from various equations that convert visibility to dust concentration (Chepil and Woodruff, 1957; Patterson and Gillette, 1977; Shao et al. 2003; Tews, 1996; McTainsh et al. 2008). Raupach et al. (1994) conservatively estimated the dust load using equation 1 for the 1983 Melbourne dust storm at 2 ±1 million tonne (Mt). Knight et al. (1995) for the 1 December 1987 dust storm calculated the losses from the source area at 5.5 to 6.3 Mt and that 1.9 to 3.4 Mt was lost off the continent. McTainsh et al. (2005) for the 23 October 2002 event calculated the dust load of the plume at a single time using equation 1 to produce a dust load of 4.2 Mt. For the October 2002 event Shao et al. (2007) modelled the dust load over the continent in hourly time steps and then calculated the total dust load by integration of the dust load over the domain (5 to 45°S and 110 to 155°E). The modelling estimate of the total dust load was 6 Mt of which 2.13 Mt was calculated to leave the continent and be deposited to the ocean. Despite the severity of many dust storms prior to 1983 and in particular the dust storms in the early 1940s, estimates of dust storm load prior to 1983 are rare if not non-existent.

The empirical methods have had few temporal measurements of dust concentrations because they have almost solely relied on Bureau of Meteorology (BoM) synoptic visibility observations which are available at best in three hourly intervals, but can be as low as one observation per day. For the 1983 Melbourne event, a single visibility recording in Melbourne was used (0500 UTC 8 February 1983). The estimates of dust load for the 1987

Brisbane event were done over five time steps covering 18 hours and used visibility readings from 28 BoM stations. For the 2002 October event, 33 visibility observations taken at 2300 UTC 23 October 2002 from 33 BoM stations were used. One study of the October 2002 event (Chan et al. 2005) did use hourly urban air quality data from the Environmental Protection Agencies (EPA) in Queensland and New South Wales (NSW) to test their modelled results and report on health and amenity guidelines in four coastal cities. No attempt was made to calculate the dust load or the mass of dust lost off the coast.

Hourly air quality data has the major advantage of being a standardised direct measure of dust concentration. Air quality data generally only considers the particulate matter less than 10 micrometres (PM_{10}) due to its relationship to human health (Chan et al. 2005) and as such does not represent the total suspended particulate matter (TSP), that is all particle sizes, in the atmosphere. The location of these stations is primarily in highly populated urban centres, which in Australia, tends to be along the coast. On the east coast of Australia, there are networks of air quality stations around Sydney, Brisbane, Gladstone, Mackay and Townsville. They are complemented by a small number of inland stations at Albury, Wagga Wagga, Bathurst, Tamworth, Toowoomba and Mt Isa. The limited spatial distribution away from the coast severely limits the capacity to estimate the extent and size of dust storms; however, they do offer the opportunity to study dust storm transport processes and evaluate the mass transport of dust off the coast.

Previous Australian studies (Raupach et al. 1994; Knight et al. 1995; McTainsh et al. 2005; Shao et al. 2007) suggested that estimates of dust load could be improved if the spatial extent of the dust storm was more adequately described and better dust concentration data was available. These improvements can be achieved for part of the dust plume that passed over

Sydney because the air quality monitoring network (AQMN) of the NSW Department of Environment, Climate Change and Water (DECCW) had four inland air quality stations monitoring PM_{10} and another 20 stations along a 200 km length of the NSW coast around Sydney. These data sources provide a unique opportunity to describe the spatial and temporal detail of the worst dust storm (in terms of reduced visibility) to have passed through Sydney since the 1940s.

The aims of this paper are to: (i) describe the spatial patterns and temporal changes of surface PM_{10} dust concentrations; (ii) calculate the mass transport rate through a 182 km wide section of the plume near Sydney; and (iii) to estimate the total dust mass of PM_{10} and TSP dust that left the coast in the Red Dawn plume.

2. Material and methods

2.1. Dust concentration

Dust concentration measurements were sourced from selected stations of the DECCW AQMN (www.environment.nsw.gov.au/aqms) (Figure 1). AQMN measures particle mass < 10 micrometers (PM_{10}) concentration using a Tapered Element Oscillating Element instrument (TEOM). The TEOM is a gravimetric instrument that draws air from an inlet height z = 3m through a filter at a constant flow rate, continuously weighing the filter and calculating mass concentrations. The ambient air sample is conditioned through the PM_{10} inlet, only allowing particles smaller than 10 μm in diameter to pass through. The filter is weighed every two seconds and a rolling hourly average calculated. Data quality control is according to Australian Standard 3580.9.8 and includes automatic checks both within the instrument, in the AQMN database and manual data control by field and office staff.

Figure 1. Location of AQMN stations and BoM stations used in this study

2.2. Visibility dust concentration relationship

Visibility (V) can be used to estimate total suspended particle concentration using empirical relationships (Chepil and Woodruff, 1957; Patterson and Gillette, 1977). In the present study; however, it is the PM_{10} concentration (c) that is measured and therefore a V to c relationship is required. In a similar approach, Wang et al. (2008) report a range of equations to calculate visibility from hourly nephelometer and TEOM data in China. Of these equations we adopt the most conservative predictor of c for a given V (Zhangbei) and therefore use Equation 2 in this study.

$$c = 6\text{ E+06 } V^{-1.1303} \qquad (2)$$

where V is in km. In Australia the BoM classifies dust storms as follows: severe dust storms (SDS) are when $V \leq 200$ m; moderate dust storms (MDS) are $V > 200$ to $\leq 1{,}000$ m. There is no formal classification of event for $V > 1000$ m, so for the purpose of this study we define V

> 1,000 m to 10,000 m as hazes and they are divided into severe dust hazes (SDH when $V >$ 1000 to ≤ 5,000 m) and moderate dust hazes (MDH when $V >$ 5000 to ≤ 10,000 m). Equation 2 is used to convert the measured c to V and the corresponding dust event class is given in Table 1.

Table 1. Dust event class for each visibility and hourly averaged PM10 concentration using the Zhangbei equation from Wang et al. (2008).

Dust Event Class	Visibility (km)	PM_{10} (µg/m^3)
Severe Dust Storm	≤ 0.2	20,055
Moderate Dust Storm	> 0.2 – 1.0	3,252
Severe Haze	> 1.0 – 5.0	527
Moderate Haze	> 5.0 – 10.0	240

2.3. Dust transport calculations

In this study, a time integrated approach is used; that is, the dust flux through a distance perpendicular to the wind direction was calculated each hour for 24 hours and summed to give the mass of dust transported through this window. This approach deviates from previous Australian studies which have been able to calculate plume area and therefore dust load through the use of equation 1. Unfortunately the spatial extent of the AQMN is not detailed enough to determine the entire area of the plume.

The calculation of the PM_{10} dust transport Q_D is defined in Equation 3.

$$Q_D = \int_{t=t_1}^{t=t_2} \int_{y=y_1}^{y=y_2} \int_{z=z_1}^{z=z_2} (c_{t,y,z} * u_{t,y,z}) dt\_dy\_dz \qquad 3)$$

Where:

Q_D = PM_{10} dust transport in kg

c = PM_{10} dust concentration in mg/m^3

u = wind velocity in m/s

t = time in seconds (s) with the integration limits of t_1 = beginning of dust storm and t_2 = end of dust storm

y = width of segment in m perpendicular to wind direction that dust passes through in m with the integration limits of y_1 = start of analysed segment and y_2 = end of analysed segment.

z = height in m with integration limits of z_1 = ground level and z_2 = ceiling of dust storm.

Several assumptions were made for the calculation of Q_D and these are outlined below.

1. The time integral (t): the start and end time of the integration were set 22 September 1400 to 23 September 1300. At the start of the calculations c was < 25 µg/m^3 for all stations with the exception of Tamworth with 26 µg/m^3 and at the end c was < 32 µg/m^3 for all stations with the exception of Tamworth with 80 µg/m^3. Note that in this study, all times are given in UTC.

2. The integration time step (Δt): was set to hourly because the data from the BoM and the AQMN are available as hourly averages.

3. The height integral (z): the vertical dust ceiling (z_2) was estimated using information provided by QANTAS security staff at Sydney airport (G. Renni, 2009, personal communication) and irregularities found in the wind speed profiles (radar, radiosonde and modelled). The dust ceiling above ground level (z_2 = 2500m) was assumed to remain constant for the duration of the event. The integration height step (Δz) depended on the velocity profiles (u_z) utilised (radar, radiosonde or modelled) and varied between 10m near the ground and 250m at height.

4. Wind velocity profiles (u_z): Three data sources were assessed. These included modelled, using The Australian Pollution Model (TAPM) and measured (radiosonde and Doppler radar) wind velocity profiles which were assessed for accuracy and availability. All methods produced similar wind velocity profiles.

5. Dust concentration profiles (c_z): In the absence of any measured dust concentration profiles for this event, the c_z relationship of McTainsh et al. (2005) (equation 4) was used. McTainsh et al. (2005) verified the vertical dust distributions published by Nickling et al. (1999) with vertical dust measurements undertaken using a kite to 500 m height. The equation used was:

$$\ln\left[\frac{C_z}{C_{measured}}\right] = -0.28\ln\left[\frac{z}{z_{measurement}}\right] \qquad (4)$$

Where $c_{measured}$ is the concentration measured at the instrument inlet height $z_{measurement} = 3$ m.

6. Integration width: The integration width (y) for equation 2 was set to 182 km, being the distance covered by the AQMN stations along the coast (Figure 2). The transect runs between Albion Park in the south to Newcastle in the north. Five other AQMN stations near the coast lie within the 182 km width. To account for the changing dust concentration along the coast, the coastline y was divided into 6 segments ($\Delta y1$ to $\Delta y6$) each confined by two AQMN stations (Figure 2).

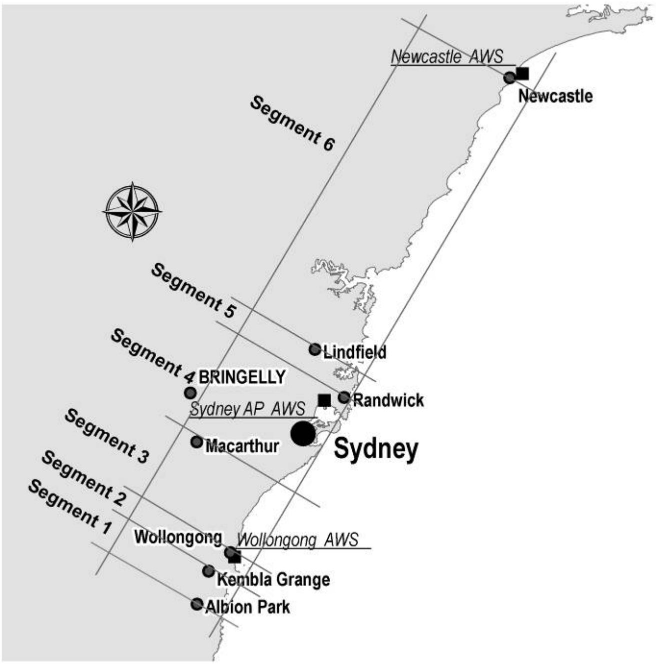


Figure 2. Spatial layout of AQMN stations along the NSW coast

7. Perpendicular wind direction: The coastal segments between Albion Park and Newcastle have a bearing of approximately 30 degrees. Wind directions perpendicular to this direction (i.e. 120˚) would represent 100% of Q_D off the coastline. Any other direction would introduce an error expressed as Equation 5 and would require a vector analysis to determine the proportion of Q_D perpendicular to the coast line.

$$q_{error} = 1 - \sin(\alpha) \tag{5}$$

Analysis of wind direction itself requires assumptions to be made. The ground level (10 m) wind directions are only indicative of directions at higher altitudes and the BoM only report wind directions in 10˚ increments; therefore, a diversion of ±30˚ in direction was considered within the margin of acceptable error. The maximum error ($q_{error\ max}$) introduced to Q_D at ±30˚ would be 13% where

$$q_{error_{MAX}} = 1 - \sin(30°) = 1 - \frac{\sqrt{3}}{2} \quad (6)$$

Ninety four percent of the wind direction measurements at the coastal stations were within 30°, so a vector analysis did not offer any significant improvement to the overall accuracy of the calculation.

3. Results and Discussion

3.1. Climate conditions prior to Red Dawn

South-eastern Australia had been experiencing drought for several years prior to the Red Dawn event. Figure 3 shows large parts of the country received below average rainfall for the previous 3 and 36 months. This low rainfall combined with a large number of temperature and rainfall anomalies including:

(i) +1.4°C warmer than average temperatures for September 2009 (Bureau of Meteorology 2009);

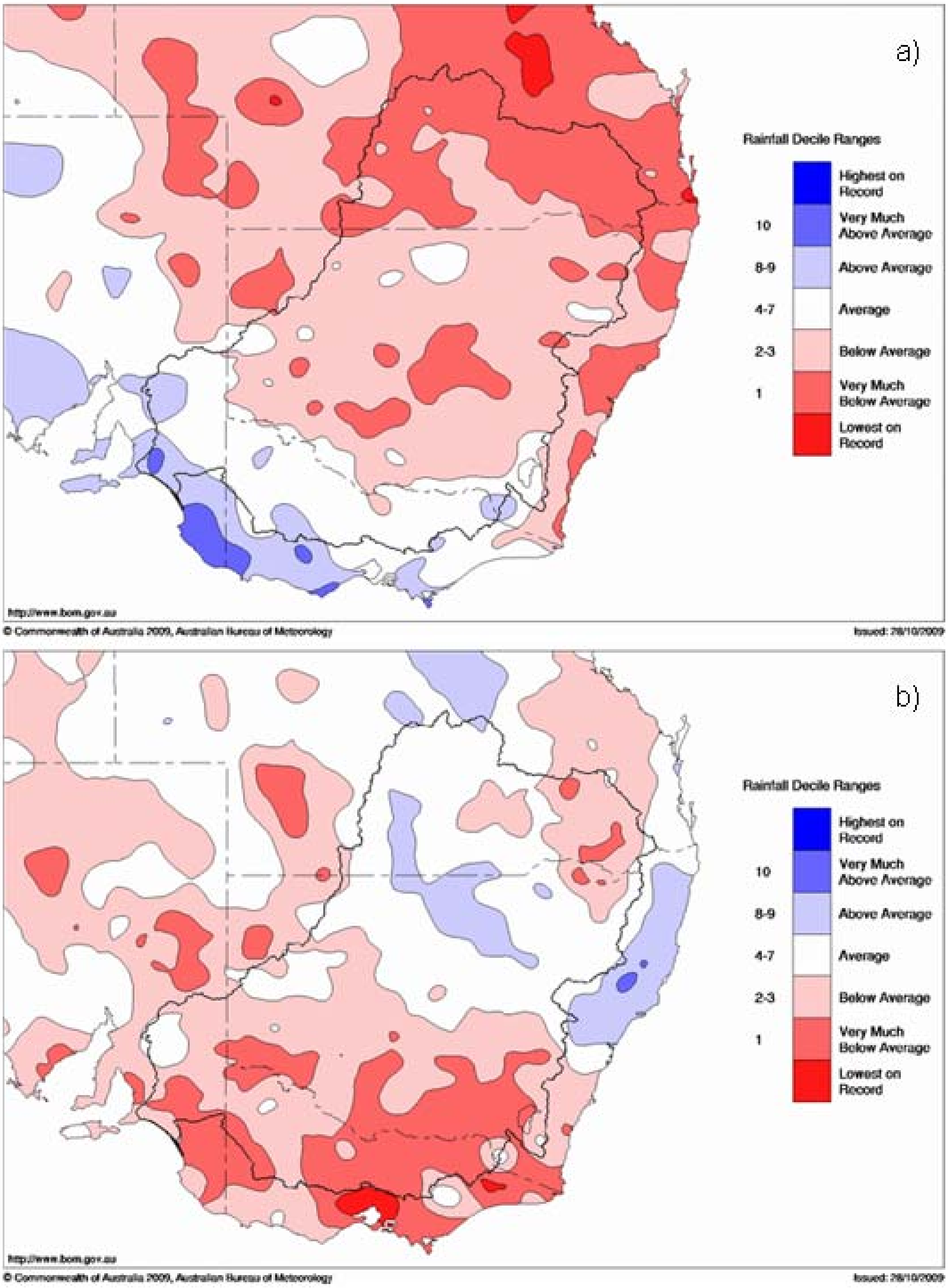
(ii) 2009 was the warmest year on record;

(iii) NSW in 2009 had the record for the highest average minimum temperatures;

(iv) the ninth consecutive year with below average rainfall;

(v) 13th consecutive year with above average maximum temperatures; and

(vi) 13th consecutive year with above average mean temperatures (Bureau of Meteorology 2010).



http://www.bom.gov.au
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Issued: 28/10/2009

Figure 3. Rainfall decile maps for a) 3months and b) 36 months prior to September 2009

There were many extreme climate conditions in 2009. McTainsh and colleagues posed a question in their 2005 paper (McTainsh et al. 2005); if the extreme weather conditions that preceded the October 2003 dust storm were “the product of global warming, or natural climate variation ?” McTainsh et al. (2005) then ask “If the former, then there is the real prospect that such extreme wind erosion events as this one will become more frequent.” The Red Dawn event is one more “extreme” event with corresponding record breaking climate conditions, it provides further data for consideration within the global climate change debate.

The extreme dry and hot climate conditions leading up to September 2009 resulted in extremely low vegetation cover levels in many parts of the landscape, and very dry exposed soils that were highly erodible. This condition was particularly pervasive in the semi arid and arid areas of western NSW and north eastern South Australia. Evidence of this increasing erodibility is seen in the DustWatch reports published during 2009 (http://www.environment.nsw.gov.au/dustwatch/reports.htm). The DustWatch report dated 09-12-14, states that during the period July 2009 to 14 December, 2009, “the DustWatch nodes have recorded more than twice the number of hours of severe dust hazes and moderate dust storms than the average of the last four years (July 2005 to June 2009). Also, that “There has been a steady increase in dust storms and severe dust hazes since 2006-07.” Finally the report concludes with “It seems that when dust events of the last 18 months occur they are more intense and last longer.”

So the combination of gale force winds (discussed below), a high level of landscape erodibility brought about by low rainfall and a large number of temperature anomalies combined to deliver the worst dust storm to Sydney since reliable records commenced in the 1940s.

3.2. Synoptic conditions during Red Dawn

On 22 and 23 September 2009 two cut-off low pressure systems maintained a broad area of low pressure over south-eastern Australia (Figure 4a). A cold front stretched from 28° S to 37° S and a large low pressure trough stretched from 12° S to 35° S. Over the next 18 hours, the two lows converged on the south-east coast of NSW; the cold front grew in length (25° S to 38° S) and the trough length diminished (14° S to 24° S) (Figure 4a,b,c,d).

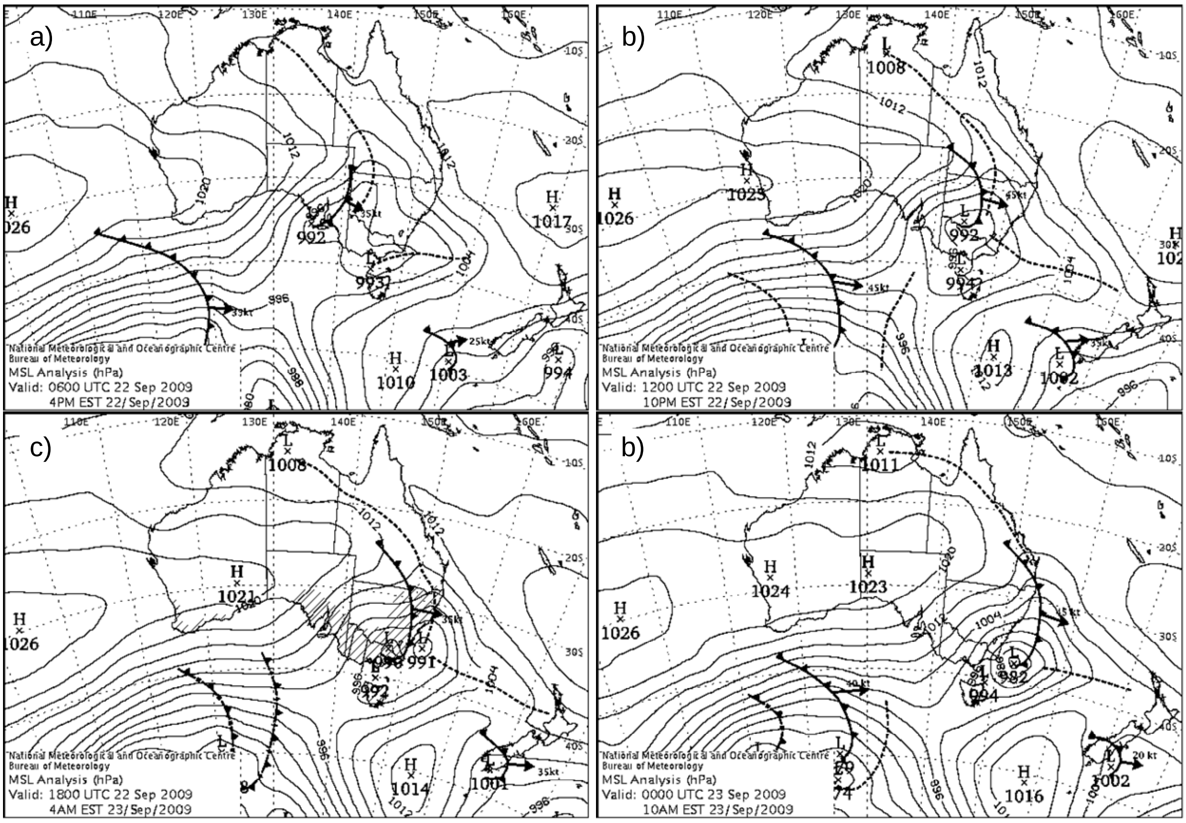


Figure 4. Synoptic charts for the Red Dawn event a) 0600 UTC 22 September 2009, b) 1200 UTC 22 September 2009; c) 1800 UTC 22 September 2009; d) 0000 UTC 23 September 2009.

With the passage of the trough and the cold front from west to east (Figure 4a,b,c,d) wind directions changed dramatically. Using the surface wind records from the BoM stations, the pre-trough winds were south-westerly to northerly and then with the passage of the low pressure trough and cold front they turned north-westerly then westerly. This pattern of wind systems associated with cold fronts and troughs is consistent with longer term patterns as described by several authors over the last seventy years (Loewe, 1943; Sprigg, 1982; Strong et al. 2010). As the front passed across south eastern Australia, a deep low pressure system (992 hPa) (centred around 35 to 36° S) behind the front intensified, creating storm force westerly winds that gusted at 25 to 28 m/s (Figure 5). It was this extreme westerly wind field over much of South Australia and the western parts of NSW that entrained and transported the dust to the east coast of Australia.

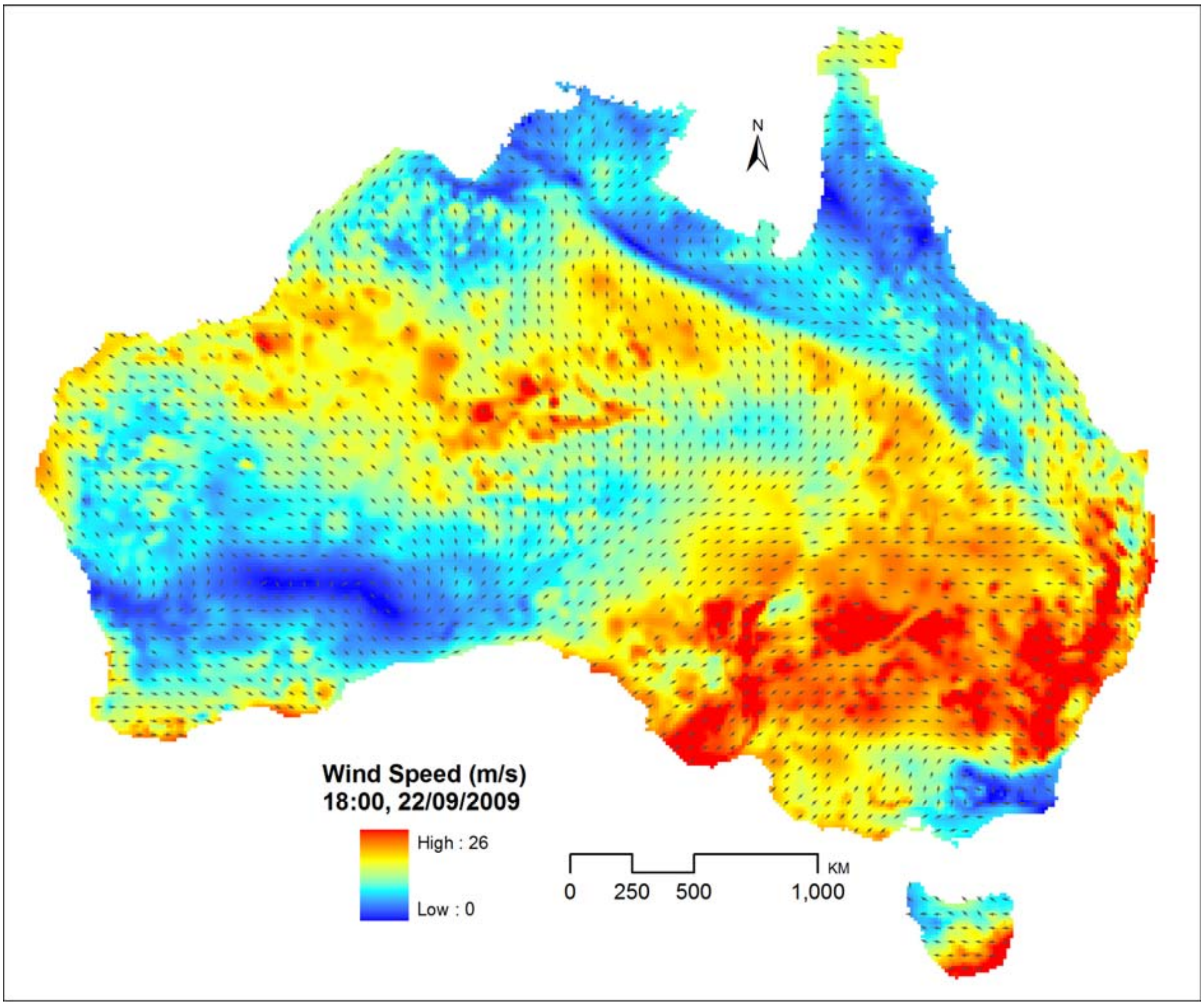


Figure 5. Modelled wind field map from the Bureau of Meteorology's Meso-scale Limited Area Prediction System (Meso-LAPS).

The Bureau of Meteorology Meso-scale Limited Area Prediction System (Meso-LAPS) prognosis map for 22 September at 1800 (Figure 5) shows the very strong north westerly to westerly airstream that was present just before Red Dawn hit the east coast. By this time a moderate dust storm (MDS) had been recorded at Bathurst (west of Sydney) and severe dust haze (SDH) at Wagga Wagga (Table 2). By 2300 on 22 September winds were strong to very strong and still north westerly, and moderate dust storm (MDS) conditions had been experienced from Bathurst and Albion Park through Sydney and Newcastle to Tamworth, with dust engulfing all coastal towns north to the NSW - Queensland border (Figure 6).

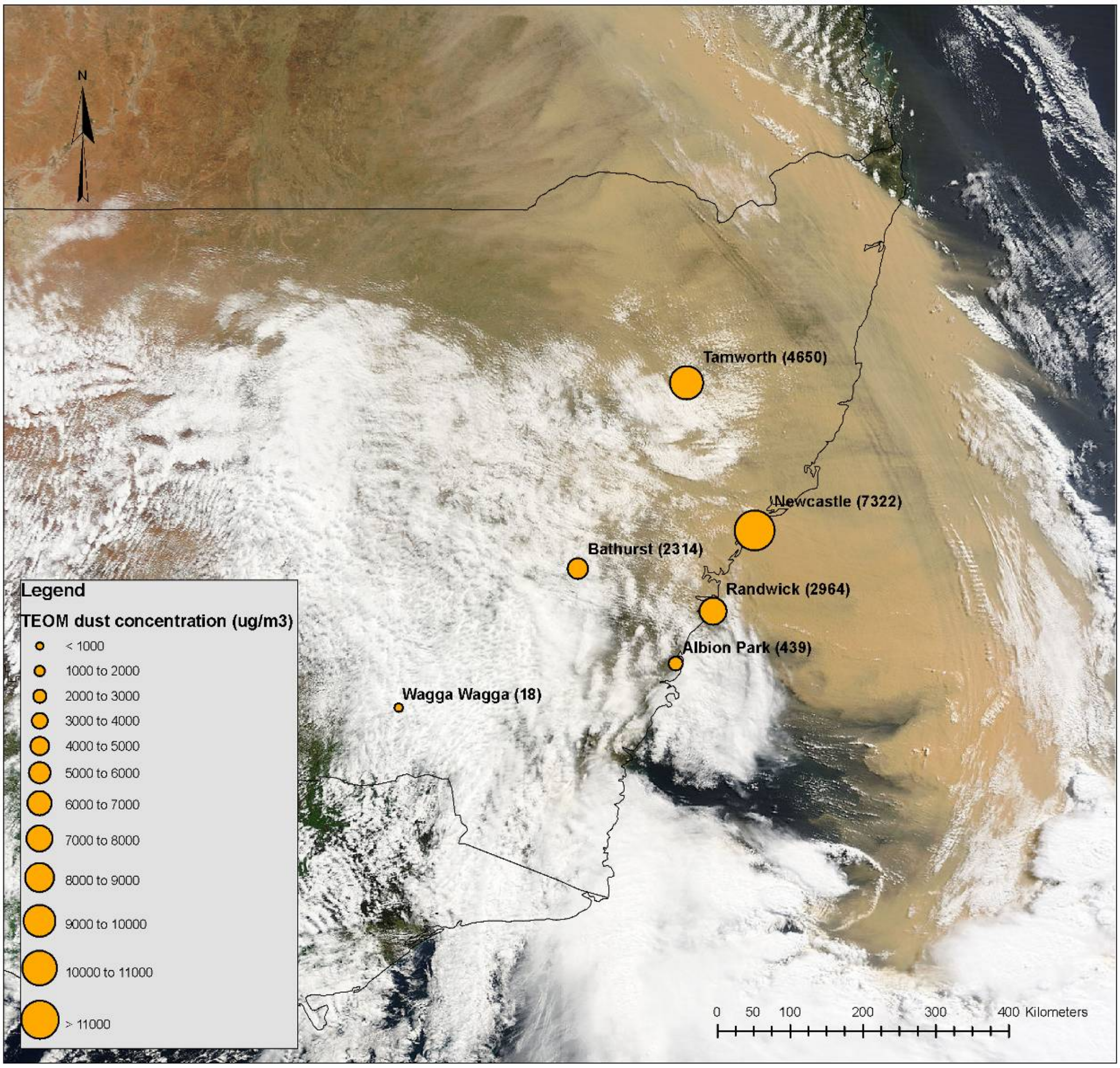
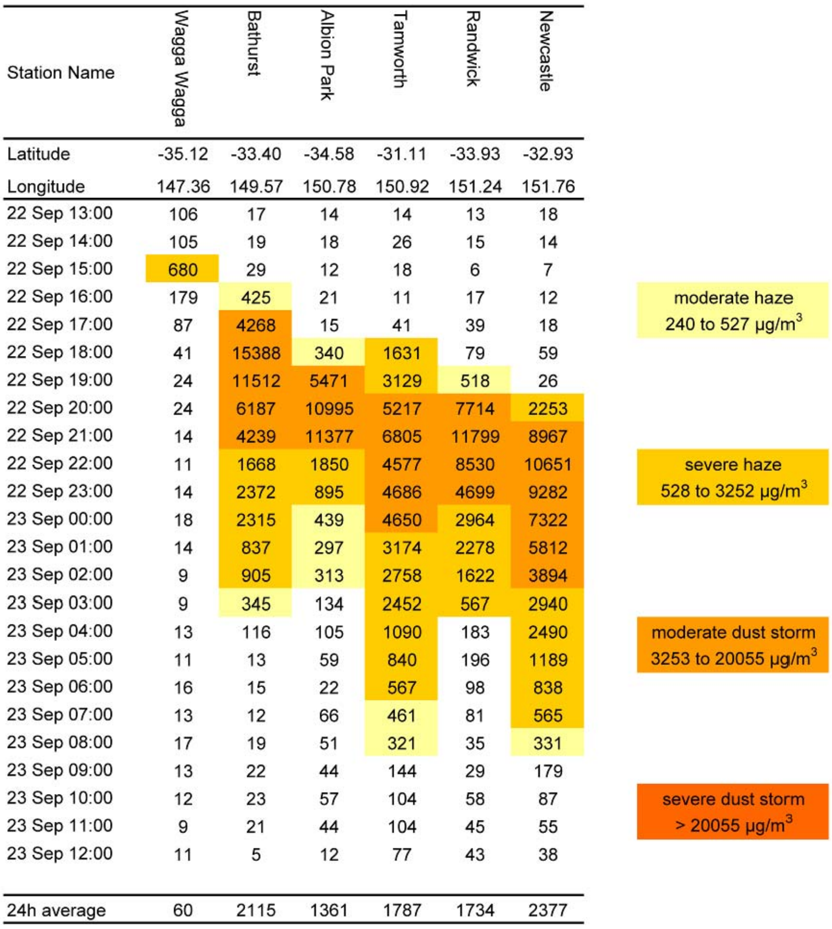


Figure 6. MODIS image for 0000 23 September 2009 showing Red Dawn extending from south of Sydney to the Queensland / NSW border and the PM10 concentrations at that time.

Table 2. PM10 concentrations for AQMN stations and associated dust event class



Station Name	Wagga Wagga	Bathurst	Albion Park	Tamworth	Randwick	Newcastle
Latitude	-35.12	-33.40	-34.58	-31.11	-33.93	-32.93
Longitude	147.36	149.57	150.78	150.92	151.24	151.76
22 Sep 13:00	106	17	14	14	13	18
22 Sep 14:00	105	19	18	26	15	14
22 Sep 15:00	680	29	12	18	6	7
22 Sep 16:00	179	425	21	11	17	12
22 Sep 17:00	87	4268	15	41	39	18
22 Sep 18:00	41	15388	340	1631	79	59
22 Sep 19:00	24	11512	5471	3129	518	26
22 Sep 20:00	24	6187	10995	5217	7714	2253
22 Sep 21:00	14	4239	11377	6805	11799	8967
22 Sep 22:00	11	1668	1850	4577	8530	10651
22 Sep 23:00	14	2372	895	4686	4699	9282
23 Sep 00:00	18	2315	439	4650	2964	7322
23 Sep 01:00	14	837	297	3174	2278	5812
23 Sep 02:00	9	905	313	2758	1622	3894
23 Sep 03:00	9	345	134	2452	567	2940
23 Sep 04:00	13	116	105	1090	183	2490
23 Sep 05:00	11	13	59	840	196	1189
23 Sep 06:00	16	15	22	567	98	838
23 Sep 07:00	13	12	66	461	81	565
23 Sep 08:00	17	19	51	321	35	331
23 Sep 09:00	13	22	44	144	29	179
23 Sep 10:00	12	23	57	104	58	87
23 Sep 11:00	9	21	44	104	45	55
23 Sep 12:00	11	5	12	77	43	38
24h average	60	2115	1361	1787	1734	2377

moderate haze
240 to 527 μg/m^3

severe haze
528 to 3252 μg/m^3

moderate dust storm
3253 to 20055 μg/m^3

severe dust storm
> 20055 μg/m^3

The dust that travelled eastwards did not come from the entire landscape west of the east coast; rather it was from defined areas which are described in the next section.

3.3. Dust source areas

For the 23 October 2003 event, Shao et al. (2007) identified the major source areas as the lower Lake Eyre Basin (LEB) in South Australia, the grazing lands of north western NSW and the mining areas around Cobar and Broken Hill. The DustWatch report of 28 September 2009 (http://www.environment.nsw.gov.au/resources/dustwatch/DWNL090928.pdf) identifies these same areas are the source areas of Red Dawn, with the addition of the Channel Country of western Queensland. The identification of the lower LEB and north western NSW is further supported by DustWatch observer reports and photos, a field survey under taken by the lead author in November 2009, and the fact that on 15 October 2009 the north west of NSW, which is predominantly rangelands on red sandplain, was officially declared a “Natural Disaster Area” by the NSW government (Kelly and MacDonald 2009) after inspection of the area and submission to government by the NSW Department of Industry and Investment, Primary Industries Division.

The dry lake beds and alluvial channels of the LEB are important long term suppliers of dust Bullard and McTainsh, (2003). During 2003-06, 59 % of the dust events identified by Bullard et al. (2008) were sourced in lake beds and alluvial channels. In the months prior to Red Dawn the MODIS satellite image archive clearly shows Lakes Eyre and the Strzelecki Lakes (Lakes Gregory, Blanche and Callabonna) all emitting dust. Analysis of dust deposited in Sydney during Red Dawn also shows traces of halite and high Cl/Si ratios (Radhi et al. 2010) which could support a lake bed source. However, based upon DustWatch reports, the MODIS imagery, at the time of the event, the field survey undertaken by the lead author soon after the event that revealed large areas of sand drift, and the red/orange/yellow colour of the dust, we conclude that the rangelands in the vicinity of the lake systems were the dominant dust source areas. Another paper in preparation by the authors will utilise the 28 inland DustWatch stations (see map at http://www.environment.nsw.gov.au/dustwatch/) to further localise the dust source for Red Dawn.

3.4. Hourly spatial and temporal patterns of wind and dust concentration of Red Dawn

The generalised synoptic description of the wind and dust conditions can be enhanced by examining the hourly wind data from the AQMN and BoM AWS network (Figure 1) and the PM_{10} data from the AQMN, and this forms the basis of this section.

3.4.1. Maximum dust concentrations

The Red Dawn event produced the highest PM_{10} readings ever recorded by the AQMN network (which commenced in the 1950s). Normal hourly average background PM_{10} levels in the Sydney region are in the order of 20 μg/m^3 for the AQMN stations. The highest hourly averaged reading during Red Dawn was 15,388 μg/m^3 (recorded at Bathurst at 1800 on 22 September). In the Sydney region, the highest recorded reading was 15,366 μg/m^3 at Bringelly (33° 55' 60S, 150° 43' 60E), 45 km west south west of Sydney at 2000 on 22 September at a wind velocity of 8.6 m/s. The consistency of c between Bathurst and Sydney is indicative of dust in transport through the region rather than of dust being emitted within the region, because local entrainment tends to produce discrete dust plumes resulting in short distance changes in dust concentration (Butler et al. 1996).

Comparing Red Dawn with the 23 October 2002 dust storm (Chan et al. 2005), Sydney had a peak PM_{10} concentration of 266 μg/m^3, Brisbane had 841 μg/m^3, and Mackay had 899 μg/m^3 in 2002. These concentrations were all measured with TEOMs and are comparable with the AQMN data. In contrast, Red Dawn had dust concentrations 40 times greater in Sydney than during the 23 October 2002 event. Similarly the wind speeds in the Red Dawn source areas peaked with gusts of 27 m/s at White Cliffs (22 September at 0700 and 1000), which is markedly higher than the maximum gust of 20 m/s reported for the 23 October 2002 by McTainsh et al. (2005).

The air pollution literature has a range of PM_{10} values reported for different time periods e.g. 5 mins, hourly, daily. The Australian standard (National Environment Protection Council

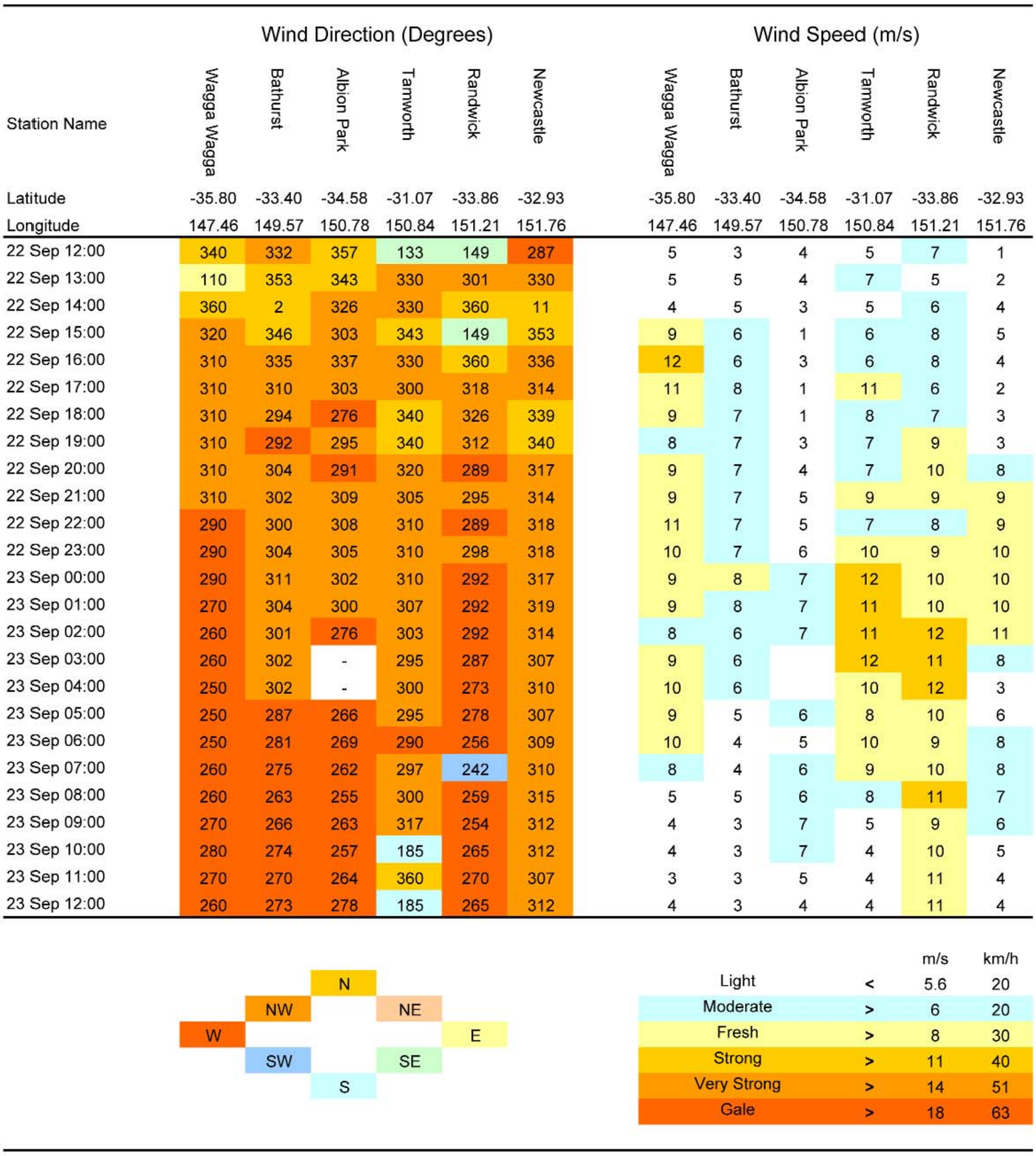
1998) 24 hour PM_{10} average is 50 µg/m^3. For the six AQMN stations the maximum 24 h average PM_{10} concentrations calculated between 22 September at 0000 and 23 September 1200 were (in decreasing order); Newcastle 2,426 µg/m^3, Bathurst 2,116 µg/m^3, Tamworth 1,787 µg/m^3, Randwick (station closest to Sydney CBD) 1,734 µg/m^3, Albion Park 1,365 µg/m^3, and Wagga Wagga 123 µg/m^3. The stations with the higher Red Dawn PM_{10} dust concentrations are among the highest reported in the literature.

Other published daily PM_{10} concentrations include: Kuwait ,with approximately 2,700 µg/m^3 (Draxler et al. 2001); Lubbock, Texas in the USA, with a 24 h average PM_{10} of 364 µg/m^3 and an hourly peak concentration of > 1200 µg/m^3 at El Paso Texas (Lee et al. 2009). In China, between 2001 and 2006 the highest daily PM_{10} values were 7,414 µg/m^3 at Tazhong in western China (Wang et al. 2008) and about 2,700 µg/m^3 at Zhurihe in north eastern China (Gong and Zhang 2008). While the Tazhong daily PM_{10} value is three times higher than the Newcastle reading, it should be noted that the Tazhong reading is at-source whereas Newcastle is 700 to 1,200 km downwind of the source area. The Zhurihe and Newcastle readings are more directly comparable, as Zhurihe is also some distance down wind of source. Given that these daily PM_{10} values are very similar (2,700 µg/m^3 for Zhurihe and 2,426 µg/m^3 for Newcastle), it is reasonable to suggest that Red Dawn dust concentrations are on a par with this large Chinese dust storm.

3.4.2. Timing and spatial extent

The timing and spatial extent of the dust storm can be seen in Table 2 and the *c* values are loosely linked to the wind speeds and directions in Table 3. The data in Tables 2 and 3 have been sorted by AQMN longitude, so that stations in the west are on the left and stations in the east are on the right of the tables.

Table 3. Wind speed and direction readings at 10m height from AQMN stations except for Tamworth and Wagga Wagga where Bureau of Meteorology station



	Wind Direction (Degrees)						Wind Speed (m/s)					
Station Name	Wagga Wagga	Bathurst	Albion Park	Tamworth	Randwick	Newcastle	Wagga Wagga	Bathurst	Albion Park	Tamworth	Randwick	Newcastle
Latitude	-35.80	-33.40	-34.58	-31.07	-33.86	-32.93	-35.80	-33.40	-34.58	-31.07	-33.86	-32.93
Longitude	147.46	149.57	150.78	150.84	151.21	151.76	147.46	149.57	150.78	150.84	151.21	151.76
22 Sep 12:00	340	332	357	133	149	287	5	3	4	5	7	1
22 Sep 13:00	110	353	343	330	301	330	5	5	4	7	5	2
22 Sep 14:00	360	2	326	330	360	11	4	5	3	5	6	4
22 Sep 15:00	320	346	303	343	149	353	9	6	1	6	8	5
22 Sep 16:00	310	335	337	330	360	336	12	6	3	6	8	4
22 Sep 17:00	310	310	303	300	318	314	11	8	1	11	6	2
22 Sep 18:00	310	294	276	340	326	339	9	7	1	8	7	3
22 Sep 19:00	310	292	295	340	312	340	8	7	3	7	9	3
22 Sep 20:00	310	304	291	320	289	317	9	7	4	7	10	8
22 Sep 21:00	310	302	309	305	295	314	9	7	5	9	9	9
22 Sep 22:00	290	300	308	310	289	318	11	7	5	7	8	9
22 Sep 23:00	290	304	305	310	298	318	10	7	6	10	9	10
23 Sep 00:00	290	311	302	310	292	317	9	8	7	12	10	10
23 Sep 01:00	270	304	300	307	292	319	9	8	7	11	10	10
23 Sep 02:00	260	301	276	303	292	314	8	6	7	11	12	11
23 Sep 03:00	260	302	-	295	287	307	9	6		12	11	8
23 Sep 04:00	250	302	-	300	273	310	10	6		10	12	3
23 Sep 05:00	250	287	266	295	278	307	9	5	6	8	10	6
23 Sep 06:00	250	281	269	290	256	309	10	4	5	10	9	8
23 Sep 07:00	260	275	262	297	242	310	8	4	6	9	10	8
23 Sep 08:00	260	263	255	300	259	315	5	5	6	8	11	7
23 Sep 09:00	270	266	263	317	254	312	4	3	7	5	9	6
23 Sep 10:00	280	274	257	185	265	312	4	3	7	4	10	5
23 Sep 11:00	270	270	264	360	270	307	3	3	5	4	11	4
23 Sep 12:00	260	273	278	185	265	312	4	3	4	4	11	4

	N	
NW		NE
W		E
SW		SE
	S	

		m/s	km/h
Light	<	5.6	20
Moderate	>	6	20
Fresh	>	8	30
Strong	>	11	40
Very Strong	>	14	51
Gale	>	18	63

The timing and spatial extent of the event described below is confined to when conditions reached moderate dust storm (MDS) or severe (SDH) status as defined by the visibility and PM_{10} concentrations in Table 1. The easterly progression of Red Dawn is evident as the dust passed through Wagga Wagga then Bathurst in the west on 22 September at 1700 then through Newcastle (the most easterly station) eight hours later on 23 September at 0200 (locations in Figure 1). Table 3 shows that Wagga Wagga and Bathurst experienced moderate to strong northwest to westerly winds which increased in speed towards Sydney.

By 23 September at 0000 the dust plume had progressed further north and east (Figure 6). Hourly air quality data measured with TEOMs from Queensland Department of Environment and Resource Management (DERM) indicate that MDS conditions hit Brisbane at 0200 on 23 September. Within the south east air quality region that includes Brisbane, the three stations with the highest values of *c* were Flinders View (27° 39' 10" S and 152° 46' 27") with 7,099 µg/m^3, Toowoomba (27° 33' 01" and 151° 57' 11") with 6,834 µg/m^3 and Brisbane CBD (27° 28' 39 S and 153° 1' 41") with 6,459 µg/m^3, which are about half that of Sydney values. Further north in Queensland the dust storm did not reach MDS concentrations (i.e. $c < 3,252$ µg/m^3) but it did reach SDH levels. Example *c* values include: 1,790 µg/m^3 at Mt Isa (20° 43' 35.04" S and 139° 29' 51.72) on 22 September at 1600, 1,074 µg/m^3 at Townsville Port (19° 15' 0.7194" S and 146° 49' 49.4394") on 23 September at 1600, 625 µg/m^3 at Boat Creek (23° 49' 11.64" S and 151° 9' 13.6794") near Gladstone on 23 September at 1400, and 353 µg/m^3 at Mackay (21° 8' 49.92" S and 149° 9' 37.44") on 23 September at 1600.

In Queensland, the highest *c* was recorded in the south east with *c* values in Brisbane being about 60% that of Randwick. In comparison to Brisbane, Gladstone and Mackay, which are further north along the coast, had *c* values 10 to 20 times lower than Brisbane respectively. Near the maximum northerly extent of the plume at Mt Isa and Townsville, *c* values were 4 to 6 times less than that of Brisbane respectively. Considering that the total plume length was in the order of 3,000 km (estimated from satellite imagery) it is not surprising that there was large variation in *c* along its length. The general trend was for *c* values to decrease from south to north. The likely explanation for this lies in the distance the plume travelled to get to the air quality stations and the amount of dust emitted from the source area. The further the plume travels from source the greater the deposition (Chan et al. 2005) and the distance to source (LEB or north west NSW or Channel Country) for Sydney was in the order of 700 to 1,200 km and for Brisbane it was 900 to 1,300 km. Interestingly for Mt Isa and Townsville it is only 300 to 600 km to the Channel Country and 900 and 1200 km to the LEB yet these stations have lower *c* than Brisbane suggesting some other mechanism, such as wind speeds being lower or that the Channel Country was not as strong a source on this occasion as previously thought.

All of the AQMN stations had similar peak *c* of around 10,000 $\mu g/m^3$; with the exception of Wagga Wagga. However, there are differences in the rising and falling limbs of the *c* curves (Figure 7). Most stations have a rapid rise in their *c* profiles at the beginning of the event indicating the rapid onset of the dust and further supporting the suggestion that the dust was being transported to the eastern part of the state with the cold front. However, the falling limbs of the *c* curves are quite different. The southern stations have a more rapid decline in *c* than the northern stations suggesting that the northern stations were down wind of a stronger source area which supplied more dust over a longer period of time. This is partially supported by average wind speed data for the dust event (defined as when *c* is > SDH in Table 2). In the north, winds were between 9 and 10 m/s for Tamworth, Randwick and Newcastle but lower in the south for Bathurst (7 m/s) and Albion Park (4 m/s). Stronger winds over a longer period would raise more dust that would last longer at the northern stations.

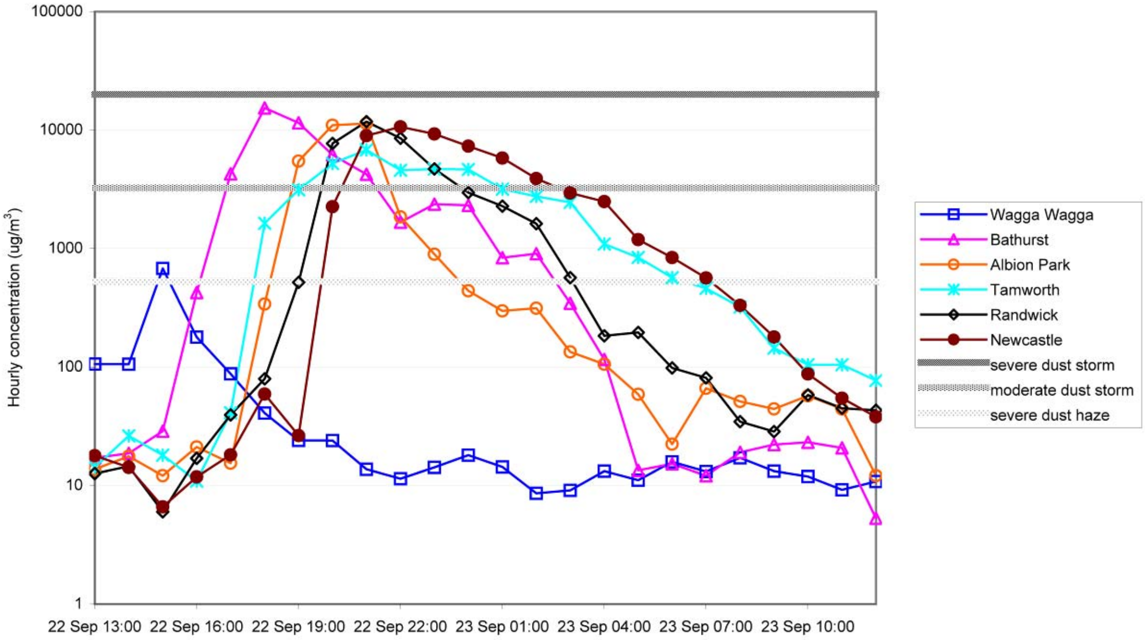


Figure 7. PM10 concentrations AQMN stations. Horizontal lines represent equivalent severe and moderate dust storm and severe dust

Bathurst and Randwick provide a downwind transect (due to the north westerly winds) with about a three hour separation (Figure 7). The shape of their *c* curves is similar except that Bathurst has a slightly higher peak *c* and the duration of the MDS and SDH is one hour longer for each event type. This is consistent with Bathurst being closer to the source area, albeit 160 km, and there being deposition and a resultant drop in *c* between Bathurst and Randwick. This seems reasonable as the landscape east of Bathurst is aerodynamically rougher, i.e. is hilly and forested, and this would aid deposition.

The time series for the AQMN stations (Figure 7) clearly shows the magnitude and duration of the dust event for each station. Wagga Wagga was on the southern edge of the plume and only recorded one hour of SDH conditions on 22 September at 1500 when the wind was from the north west at 9 m/s (Tables 2 and 3). The timing of the MDS reaching the other two inland stations of Bathurst and Tamworth (Figure 1) was 1700 and 2000 respectively on the

22 September and both stations reached their peak *c* one hour later. Wind directions were largely from the north west and wind speeds moderate. Wind speeds were lower than the threshold wind speed for dust emission of approximately 10 m/s at both stations indicating that the dust was transported from the north west to the station rather than emitted locally.

On the coast, it was the southern coastal stations (Albion Park, 22 September at 1900) that were the first to experience MDS conditions. Over the next two hours Red Dawn progressed up the coast through Randwick, 22 September at 2000 and Newcastle at 2100. For both Albion Park and Newcastle the wind was from the north west while Randwick was slightly more westerly. Wind speeds were moderate to fresh but still below threshold for dust entrainment (10m/s) with the exception of one hour of wind at Randwick, which is in agreement with the proposition that dust was transported to the coast rather than emitted locally.

The magnitude of *c* values at each station is a function of their spatial location and the wind conditions. The general pattern was that the wind direction changed from northerly to north westerly and wind speeds decreased overnight as the front moved east. Wind speeds (hourly) in the source area in western NSW were gale force (21 m/s) on 22 September at 0800 but decreased to fresh winds closer to the coast by 2000.

Generally, the peak *c* occurred one to five hours before the peak wind speeds, which tended to disperse the dust later in the day (Figure 8). There is no clear relationship between wind speed and *c* at the inland stations, suggesting that there are no source areas near the stations and that a more complex interaction between the synoptic conditions and the transport of the dust is occurring (Figure 8). This is shown by comparing the wind and *c* time series for

Tamworth and Bathurst. The dust storm at Tamworth begins with moderate breeze winds (7 - 8 m/s) but *c* reaches its peak with 9 m/s winds. During the falling limb of the *c* curve the winds slowly increase from 7 to 12 m/s over six hours, during which time *c* continues to fall. Then the winds decrease over the next nine hours to 4 m/s and the *c* continues to fall at a slightly higher rate than after the peak *c*. Conversely, at Bathurst the event begins with wind speeds increasing from 5 to 8 m/s and the *c* rises rapidly to its peak. Winds remain fairly constant at around 7 m/s for six hours as *c* falls, then the wind increases up to 8 m/s for two hours and then decreases again to 4 m/s during which time the *c* plummets. Winds slowly fall to 3 m/s over the next seven hours but now *c* remains fairly constant. The above comparison demonstrates the utility of the high resolution data (one hour) for revealing the complex structure of a dust plume. It also indicates how transported dust is not coupled to wind speed like it is during the emission phase of the dust storm. Finally, the satellite image in Figure 6 clearly shows areas of low and high concentration throughout the plume further supporting the idea that dust storms are very variable in space and time.

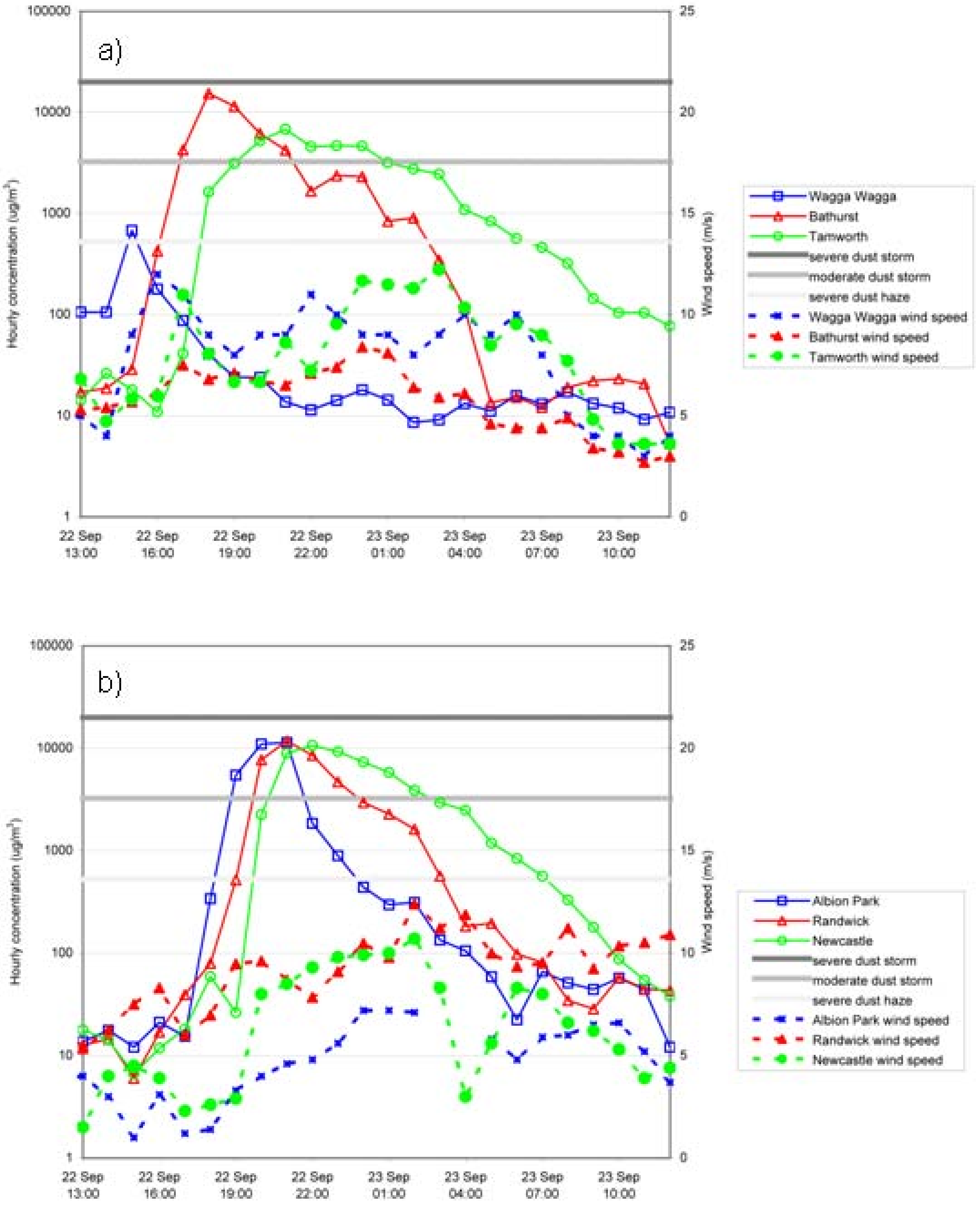


Figure 8. Hourly PM10 concentrations at 3 m height and wind speed readings taken at 10m height for inland (top) and coastal (bottom) AQMN stations

There is less complexity in plume concentrations near the coast, which is probably due to the smaller distances between the stations (< 182 km). The pattern is similar to that of Tamworth in that as wind speed increases slowly, the *c* values quickly rise to their peak. Wind speeds continue to increase but *c* is dropping, at Randwick and Albion Park, then wind speeds remain fairly constant and *c* continues to fall, while at Newcastle the wind speeds decrease steadily after reaching a maximum and *c* declines at a slightly faster rate as the wind speeds decrease. So like the inland stations wind speed is not coupled directly to *c*.

The above discussion indicates the extreme heterogeneity of *c* within the plume and the importance of having a good spatial and temporal data to understand the transport processes operating within the plume, as previously identified by both modelling (Shao et al. 2007) and empirical studies (McTainsh et al. 2005). It also highlights some challenges to our understanding:

- Unlike dust source areas, where dust emission is closely linked to the friction velocity (Nickling et al. 1998) and therefore wind speed, this study is located hundreds of kilometres down wind of source where there is little relationship between wind speed and *c*. The reasons for this require attention.
- Red Dawn dust arrived at the coast before the maximum wind speeds and without a significant change of wind direction. Raupach et al. (1994) found that for the Melbourne 1983 dust storm most of the dust was directly associated with the cold front and that the highest wind speeds (20 m/s) were at the nose of the cold front. The reason for this may lie with the synoptic weather conditions that produced the strong winds, but this requires more detailed attention.

- The concentration curves (Figure 7) at all stations are steep at the beginning and taper away after the peak, but the tapering varied between stations from south to north. The reason for this requires attention.

The processes that are driving these effects are most likely to do with meso-scale meteorological conditions. While there have been a few studies in Australia of the links between dust storms and meteorological conditions (Raupach et al. 1994; Ekstrom et al. 2004; Strong et al. 2010) the high resolution data emerging from the current study may cause a re-evaluation of this research. Work in north west China on relationships between dust storms and meso-scale cold fronts in the Tarim Basin (Aoki et al. 2005) has helped our understanding of entrainment and local transport processes by showing how the synoptic scale air mass behind the cold front is the cause of the dust storms. Applying this knowledge to Australian dust storms is worthy of further investigation as also suggested by Strong et al. (2010).

3.4.3 Duration of dust storm

The Red Dawn dust storm was also distinctive for the prolonged period that it increased dust concentrations in Australia’s eastern cities. Table 4 reports the hours of MDS and SDH conditions for each AQMN station between 13:00 h 22 September to 12:00 h 23 September 2009. The inland stations (Bathurst – 10 h and Tamworth – 13 h) had a longer dust event (MDS + SDH conditions) than the coastal cities (Newcastle – 12 h, Randwick – 8 h, Albion Park – 5 h and Wagga Wagga – 1 h). The event duration was longer in the north as far as Brisbane (11 h) but decreased further north at Townsville (7 h) and Mt Isa (8 h). These patterns are a function of synoptic wind conditions and the distance to dust source.

The storm duration for Red Dawn at Randwick (Sydney) and Newcastle are the longer than that reported for the Melbourne dust event of 1983 (Raupach et al. 1994) and the 23 October 2002 dust event (Chan et al. 2005). The 1983 Melbourne event, while more intense than Red Dawn (visibility of 100m), lasted less than three hours. The 2002 dust event did not lead to SDH conditions in Sydney, but in Brisbane and Mackay the SDH conditions lasted for 3 and 10 h respectively. So Red Dawn produced the longest duration dust storm reported to date for the major coastal cities of Sydney, Newcastle and Brisbane

Table 4. Duration in hours of moderate dust storm (MDS) and severe dust haze (SDH) for each AQMN station

Station	MDS	SDH	Total
Wagga Wagga	0	1	1
Bathurst	5	5	10
Albion Park	3	2	5
Tamworth	5	8	13
Randwick	4	4	8
Newcastle	6	6	12

The duration was a function of the position of the cut-off low pressure system over south east Australia and the passage of the cold front and associated low pressure trough (Figure 4). These metrological conditions provided a combination of gale force winds over the source areas and persistent strong frontal north westerly winds towards the coast.

As a result of the high dust concentrations, the long event duration and the intense media interest, one of the most commonly asked questions was; “How much soil has been lost”. In the next section, this question will be addressed by examining the mass of dust transported off the NSW coast between Albion Park and Newcastle.

3.5. Spatial and temporal patterns of dust mass transport off the coast

In simplest terms, the dust that is blown off the continent can be described as “lost” as it can no longer be deposited and returned to soils on the continent. This section aims to firstly, calculate the tonnes of PM_{10} dust being transported through a one kilometre cross-wind section of the storm at each AQMN station, each hour of the dust event. Secondly, the mass of dust blown off the coast is calculated between Albion Park and Newcastle, and finally, an estimate of dust leaving the coast during the entire dust storm is presented.

To measure the transported dust (Q_D), using equation 3, requires c profiles and wind velocity profiles to the top of the dust ceiling (z) at each station in hourly intervals. To achieve this surface level PM_{10} concentration data from each station are used in Equation 4 to calculate the PM_{10} concentration profiles (McTainsh et al. 2005). Obtaining measured wind profiles for all stations was not possible so modelled profiles were calculated using TAPM. The next section outlines a critical analysis of these TAPM profiles.

3.5.1. Wind velocity profiles

Two sources of measured velocity profile data were available for Red Dawn; wind finding Doppler radar and radiosonde balloon data. The aim was to calculate Q_D in hourly time steps; therefore, velocity profiles for each hour at each station were required. Only modelled data was able to satisfy these requirements because radiosonde data is limited to some airports. However, it was possible to test the TAPM profiles against co-incident Doppler radar and radiosonde data at Sydney airport at 1100 on 23 September; towards the end of the dust event. During the Red Dawn event the regular radiosonde balloon launch in Sydney at 2000 on 22 September and 0500 on 23 September did not eventuate, possibly due to the extreme weather conditions at those times.

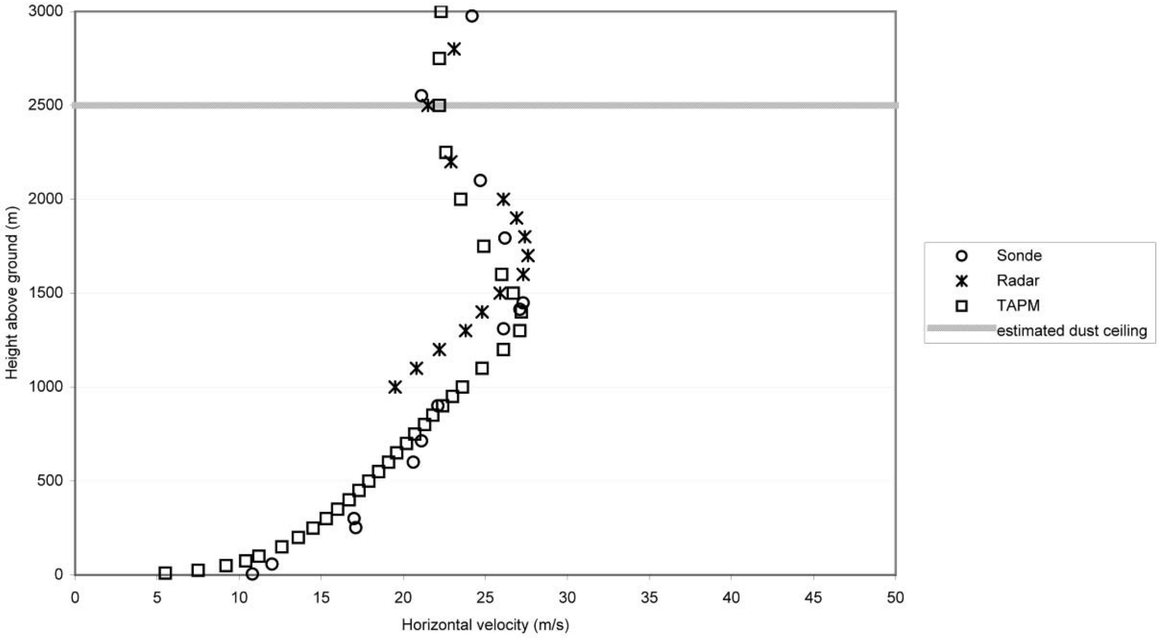


Figure 9. Measured radiosonde, radar and modelled TAPM wind profiles at Sydney airport at 1100 23 September 2009

A comparison of Doppler radar, radiosonde and TAPM profiles are given in Figure 9. There is good agreement between the radiosonde and TAPM profiles up to about 1500 m with the curves having similar shape and peak values. There is a similarity in shape and peak values of the radar and TAPM profiles; however the radar is displaced vertically about 300 m. The TAPM profile has a much narrower peak relative to the radiosonde profile. Above 1500m TAPM slightly underestimates the velocity by about 1.5 m/s compared to the radiosonde until they become the same at 2500m. There is less agreement between the radar and TAPM profiles with a maximum discrepancy of about 4 m/s. The reliability of Doppler radar wind profiles at high dust concentrations is unknown, with the differences between radio sonde data (the only “in-situ” measurement) and Doppler radar data indicating that the extreme number of particles in the atmosphere might have interfered with the radar accuracy.

To estimate the errors associated with using the Doppler radar instead of the TAPM wind profiles, the hourly Q_D for segment 4 of AQMN (Sydney) were calculated. The analysis showed that TAPM results in the total Q_D being 15% greater than when using radar data. Despite the differences in the velocity profiles we assume that the errors associated with the modelled profile to be less than using the radar or radiosonde data from limited stations and times.

3.5.2. Mass transport during Red Dawn

Unlike previous studies that require a knowledge of the area of the plume to use equation 1 to calculate the dust load, this study uses a time integrated approach (equation 3) to calculate the Q_D each hour through a distance (y) parallel to the coast. Two calculations were then done to calculate the total Q_D over 24 hours: 1) with y set to 1 km at each AQMN station to allow comparisons of Q_D at each station and thereby determine the spatial variability in total Q_D, and 2) the total Q_D for each segment of the coast line as shown in Figure 2 between Albion Park and Newcastle to estimate the total mass of sediment lost during Red Dawn near Sydney.

The time series for the Q_D with $y = 1$ km for each station enables comparisons between stations and is given in Figure 10. The highest hourly Q_D was recorded in Bathurst with Q_D of 597 t/km/h on 22 September at 1800 while Newcastle, Randwick and Albion Park were about 20% lower with peak hourly Q_D between 489 and 458 t/km/h. The Tamworth peak hourly Q_D was about 60 % lower than Bathurst with 279 t/km/h and Wagga Wagga was only 15 t/km/h. This pattern suggests that for the inland stations, Q_D was concentrated in a west-east corridor around Bathurst which extended downwind to the three coastal stations of Albion Park, Randwick and Newcastle that all had similar peak Q_D (Figure 10).

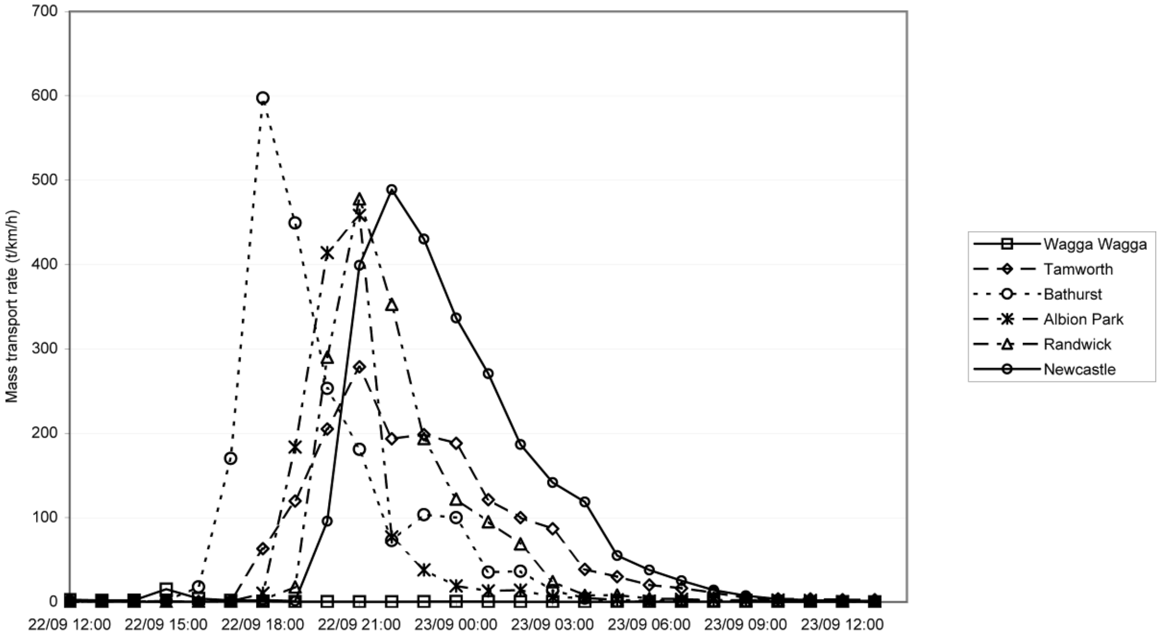


Figure 10. Time series of mass transport rate for each AQMN station

Table 5. Total QD [t/km] for period 22 September 2009 at 1400 to 23 September 2009 at 1300 for Red Dawn for the AQMN stations with three dust ceiling heights

	Q_D (2000 m)	Q_D (2500 m)	Q_D (3000 m)
Newcastle	2,179	2,622	3,072
Bathurst	1,726	2,043	2,368
Tamworth	1,353	1,693	2,070
Randwick	1,439	1,681	1,911
Albion Park	1,102	1,257	1,403
Wagga Wagga	28	32	35

Even though peak hourly Q_D were fairly consistent around Sydney the *c* and wind speed varied between stations and this has an effect on the total Q_D for each station (Table 5). Using a dust ceiling of 2500 m, Newcastle had the highest total Q_D off the coast with 2,622 t/km for the 24 h period 22 September 2009 at 1400 to 23 September 2009 at 1300. Randwick total Q_D was about two thirds of Newcastle and Albion Park was about a half. This further indicates

that Red Dawn on the coast was worse, in terms of dust loss, in the northern part of the plume. This raises the question of where was the peak in total Q_D off the NSW coast?
The next monitoring station north of Newcastle on the coast is Brisbane and, as indicated above, the Brisbane CBD c was only 60 % that of Sydney (Randwick) so it is likely that the peak total Q_D off the NSW coast was closer to Newcastle than Brisbane. This assumption is supported by the total Q_D of the inland stations. Tamworth is an inland station between Newcastle and Brisbane, is located about 400 km north east of Bathurst, and had a total Q_D 17% lower than Bathurst; therefore, if the total Q_D is lower 400 km north of Bathurst then it is highly likely that the total Q_D will also be lower 400 km north east of Sydney.

Total Q_D (t/km) for each station is also presented in Table 5 for three dust ceiling heights (z) due to uncertainties in this parameter. This study used z =2500m and this was supported by a visual report of 8,000 feet (2438 m) by QANTAS security staff at Sydney airport (G. Renni, 2009, personal communication) and visual inspection of the Doppler and radiosonde profiles. Visual inspection of the Doppler radar velocity profiles at Sydney indicates a kink in the profile between 2000 m and 3000 m depending on the time of the day. Changing the dust ceiling to 2000 m or 3000 m changes the total Q_D off the coast by -15.1% and +14.8%, respectively.

3.5.3. Dust lost off the coast

In this section the aims are to: 1) calculate the mass transport off the coast for a 182 km segment of the coast near Sydney, and 2) calculate the of mass transport off the east coast of Australia.

To estimate the total mass transport (Q_D) off the coast near Sydney seven AQMN stations that were close to the coast between Albion Park and Newcastle were chosen (Figure 2) and the Q_D was calculated for each of the six segments, and then summed for the total cross-section (Table 6). For the 24 hour period, 22 September 2009 at 1400 to 23 September 2009, 305,333 t of PM_{10} dust was transported off the coast between Albion Park and Newcastle with a maximum hourly rate of 71,015 t/h on 22 September at 2100.

Table 6. Total QD [t/segment length y] for period 22 September 2009 at 1400 to 23 September 2009 at 1300 for Red Dawn for the six segments along the coast around Sydney at dust ceiling of 2500 m

Segments as per Figure 2	y (km)	Q_D (2500 m)
Segment 1 (Albion Park)	11	13,711
Segment 2 (Wollongong)	6	7,006
Segment 3 (Macarthur)	38	41,294
Segment 4 (Sydney / Randwick)	15	21,122
Segment 5 (Lindfield)	12	20,081
Segment 6 (Newcastle)	99	202,120
TOTAL	182	305,333

One of the limitations of this study is the short length of the plume that was sampled; however, the advantage is the high level of precision and understanding of the assumptions behind that estimate. This detailed understanding can be used to develop a conversion factor for stations without velocity and dust concentration profiles.

The big question that is addressed here is: how much sediment was exported off the coast by Red Dawn? Given the data available we can estimate this in two ways: 1) by scaling up the dust loss from the Sydney section of the plume to the total plume length, and 2) by using the lateral surface PM_{10} concentration and surface wind speed data to describe the variation along the length of the plume.

The scaling up of the 305,333 t measured over the 182 km-long segment to the total plume length of Red Dawn will result in an over-estimate as we know that Q_D of the plume was highly variable even within the AQMN domain (Table 5) and we also know that c decreased up the Australian coast from Sydney to Brisbane to Townsville; as such this method will not be used here.

As there was no access to TAPM data outside NSW, it is not possible to use the same methods on the surface PM_{10} concentration data up the coast, as used in the Sydney region. To utilise the surface PM_{10} concentrations Q_D was calculated by two methods:

1. $Q_{D\ eq2}$ = hourly Q_D for the six AQMN stations using equation 2, (i.e. the same method as in section 3.5.2.) which assumes u and c are not constant with height, and
2. $Q_{D\ constant}$ = the hourly Q_D using the same six AQMN stations but assuming a constant u and c between ground level and the dust ceiling of 2500m.

The relationship between the two methods is linear and highly correlated ($r^2 = 0.94$) and results in equation 7.

$$Q_{D\ eq2} = Q_{D\ constant} / 1.67 \qquad (7)$$

The total plume length of 3000 km was then divided in to six segments based on the locations of: the AQMN segment in the Sydney region, a segment extending south to the end of the plume and segments defined by air quality stations up the coast to Townsville. These segments are detailed in Table 7 and the average hourly $Q_{D\ constant}$ values and the total 24 h $Q_{D\ constant}$ estimates are given for each segment and the total plume. To convert the $Q_{D\ constant}$ values to the equivalent $Q_{D\ eq2}$ we simply apply equation 7. To convert the 24 h total $Q_{D\ eq2}$, which is a PM_{10} mass, to the total suspended sediment (TSP) mass we apply the TSP/PM_{10} ratio of 0.6 (reported in Radhi et al. 2010). Using this method the total TSP mass transported off the Australian coast is 2,541,073 t for Red Dawn. The above estimate is more appropriate, but produces a lower estimate, than scaling up the 182 km AQMN segment to the total plume length because of the lower *c* values and lower wind speeds in the Queensland domain compared to the AQMN segment. This 2.54 Mt estimate is greater than the 2.13 Mt modelled estimate of Shao et al. (2007) of dust deposited off the coast for the October 2002 event. Comparison of the plumes in the satellite imagery of the 2002 event and Red Dawn indicates that the Red Dawn plume looks longer, wider and denser so the higher value for Red Dawn seems logical. Despite the different methods used in this study (measured concentrations) and the 2002 event (numerical model), it appears that Red Dawn is the largest Australian dust storm ever reported in the literature to date.

Table7. Total plume segment lengths, average hourly (QD constant) PM10 mass transport rate and 24 hour (Total QD constant) PM10transport mass (calculated assuming constant concentration and wind velocity profiles to 2500m) off the coast for the entire Red Dawn event. Note these QD constant estimates can be compared to Table 5 if multiplied by 24 h.

Segments	*Y* (km)	$Q_{D\ constant}$ (2500 m) (t/km/h)	*Total* $Q_{D\ constant}$ (2500 m) (t/24 h)
Townsville	1,078	12.564	194,642
Mackay	350	11.320	56,940
Gladstone	415	8.748	52,171
Brisbane	825	55.996	663,910
AQMN	182	69.902	305,333
South of AQMN	150	69.902	251,648
TOTAL	3,000		1,541,073

4. Conclusions

The Red Dawn dust storm on 22 and 23 September 2009 was huge in spatial extent, being about 3,000 km long and maintained moderate dust storm intensity (visibility ≤ 1 km) in Sydney for four hours and in Newcastle for six hours. Red Dawn resulted in the lowest visibility ever recorded in Sydney (400 m) since records began in 1940. The maximum hourly PM_{10} concentration measured in the Sydney area was 15,366 $\mu g/m^3$ at Bringelly 45 km to the west south west of Sydney CBD and is the highest ever recorded for Sydney and possibly any Australian capital city. The Australian air quality standard is measured over a 24 hour period and the station closest to the Sydney CBD (Randwick) recorded 1,734 $\mu g/m^3$. The highest 24 h PM_{10} was at Newcastle with 2,426 $\mu g/m^3$. The Randwick value is large even by world standards and was about 10% less than a value reported by Wang et al. (2008) at Zhurihe, a Chinese city down wind of the Mongolian desert.

Red Dawn was such a large dust storm in extent and intensity because of the coupling of the drought conditions with extreme wind conditions. The drought led to large areas of semi-arid lands of eastern Australia, mainly the lower Lake Eyre Basin, north west NSW and the Channel Country in Queensland, having dry, loose topsoil with inadequate groundcover to stop wind erosion. These areas were the source area for the dust and have been identified in both previous studies of the 23 October 2002 dust storm, via satellite mapping of dust plume sources in 2003-06 and via elemental analysis of dust deposited in Sydney during Red Dawn. While there is evidence that the lakes and riverine landscapes (grey and light coloured soils) are traditional dust source areas, large areas of rangelands, particularly the sandplains, showed signs of erosion after Red Dawn. Both DustWatch data and satellite imagery supports this but the most convincing evidence is the colour of the dust that entered Sydney - red. This means that the dust recorded in Sydney was transported in the order of 700 to 1200 km from the rangelands and riverine landscapes of semi-arid Australia.

The extreme weather conditions were driven by a low pressure trough and cold front associated with a deep cut-off low pressure system centred about the southern NSW border that generated gale force westerly winds over the areas with low ground cover and transported the huge dust emissions to the east coast of Australia from north of Townsville to south of Sydney, a distance of about 3000 km.

For the 24 hour period, 22 September 2009 at 1400 to 23 September 2009, 305,333 t of PM_{10} dust was transported off the coast between Albion Park and Newcastle (182 km) with a maximum hourly rate of 71,015 t/h on 22 September at 2100. The integrated mass transport rate (Q_D) for a 182 km length of the Red Dawn plume between Albion Park and Newcastle is not directly comparable with the 23 October 2003 event, the largest dust storm reported to date in Australia. This is because scaling the 182 km length up to 3000 km will result in an obvious over-estimate, especially since this study has shown that the plume was very heterogeneous. This is shown by the 24 hour PM_{10} dust transport rates off the coast at Sydney (1678 t/km/24h), Brisbane (804 t/km/24 h), Gladstone (126 t/km/ 24h), Mackay (163 t/km/24 h) and Townsville (180 t/km/24 h).

The best estimate for the total suspended sediment mass of the 3000 km plume blown off the coast taking into account the variable c and wind speeds along the plume between south of Albion Park and north of Townsville and by using a PM_{10} to TSP ratio in of 0.6 is 2,541,073 t with a plume height of 2500 m.

The Red Dawn estimate of 2.54 Mt is now first and the largest off-continent loss of soil ever reported using measured dust concentrations for Australia.

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