AGU PUBLICATIONS
JGR
Journal of Geophysical Research: Atmospheres

RESEARCH ARTICLE
10.1002/2016JD025737

Key Points:
- Backward trajectories from eastern Australian observation sites produce a climatology of dust pathways explicitly linked to dust presence
- In linking pathways back to prominent interior source regions both the likely source of observed dust and its transport are coupled
- Trajectories show that existing models of continental pathways are coarse and a North East dust pathway from Australia is significant

Correspondence to:
M. Baddock,
m.c.baddock@lboro.ac.uk

Citation:
O'Loingsigh, T., T. Chubb, M. Baddock, T. Kelly, N. J. Tapper, P. De Deckker, and G. McTainsh (2017), Sources and pathways of dust during the Australian "Millennium Drought" decade, *J. Geophys. Res. Atmos.*, *122*, 1246–1260, doi:10.1002/2016JD025737.

Received 2 AUG 2016
Accepted 4 JAN 2017
Accepted article online 5 JAN 2017
Published online 19 JAN 2017

Sources and pathways of dust during the Australian "Millennium Drought" decade

Tadhg O'Loingsigh[1], Thomas Chubb[1], Matthew Baddock[2], Tyler Kelly[3], Nigel J. Tapper[1], Patrick De Deckker[4], and Grant McTainsh[3]

[1]School of Earth, Atmosphere and Environment, Monash University, Melbourne, Victoria, Australia, [2]Department of Geography, Loughborough University, Loughborough, UK, [3]Griffith School of the Environment, Griffith University, Nathan, Queensland, Australia, [4]Research School of Earth Sciences, Australian National University, Canberra, ACT, Australia

Abstract From the late 1990s to mid-2010, Australia was affected by a prolonged period of drought, the "Millennium Drought," during which numerous severe dust storms crossed the continent. We inspect this period to produce the first continental-scale climatology of air-parcel trajectories that is specific to dust and use it to gain new insights into dust transport dynamics over the eastern half of Australia. The analysis is based upon dust arrival times from airport meteorological observations made at nine mostly coastal cities for 2000–2009. The Hybrid Single-Particle Lagrangian Integrated Trajectory model was used to calculate 1.26 million backward trajectories from receptor cities, with only those trajectories associated with a dust storm observation considered in the analysis of dust transport. To tie dust trajectories from receptors to likely emission sources, trajectories were linked to six known major dust source regions in and around the Lake Eyre Basin. The Lake Eyre North ephemeral lake system, alluvial-dominated Channel Country, and agricultural Mallee-Riverina regions emerge as important sources for the period, providing variable contributions to different parts of the seaboard as controlled by different front-related wind systems. Our study also provides new detail regarding dust pathways from continental Australia. For the Millennium Drought we identify that the broadly established Southeast Dust Path may be more accurately subdivided into three active pathways, driven by prefrontal northerly winds and a variation in the influence of frontal westerlies. The detail of these pathways has implications for dust delivery from specific Australian sources to different marine environments.

1. Introduction

In the predawn hours of 23 September 2009, one of the largest and most intense dust storms in Australian recorded history reached Sydney, leaving residents to wake up to an event dubbed "Red Dawn" by the media. To date, approximately 20 studies have been published on this particular event and a series of smaller dust storms that occurred throughout the month of September 2009. These papers have explored a range of dust-related research areas such as respiratory health and air quality [*Holyoak et al.*, 2011; *Jayaratne et al.*, 2011; *Barnett et al.*, 2012; *Merrifield et al.*, 2013; *Aryal et al.*, 2015], economic and aviation disruption [*Tozer*, 2012; *Baddock et al.*, 2013; *Tozer and Leys*, 2013], aerosol remote sensing [*Li et al.*, 2010; *Tramutoli et al.*, 2010; *Jones and Christopher*, 2011; *De Deckker et al.*, 2014], airflow modeling [*Gunawardena et al.*, 2013], receptor site sampling and meteorology [*Leys et al.*, 2011; *McGowan and Soderholm*, 2012], marine biology [*Hallegraeff et al.*, 2014; *Gabric et al.*, 2015], and geochemistry [*Box et al.*, 2010; *Radhi et al.*, 2010; *Aryal et al.*, 2012; *Gunawardena et al.*, 2013; *De Deckker et al.*, 2014; *Reynolds et al.*, 2014]. In contributing across a suite of geoscientific and environmental topics, these studies demonstrate the wide areas in which mineral dust has emerged as an important study area in Earth system science [*Shao et al.*, 2011; *Bryant*, 2013]. This group of Australian studies—and others like them that characterize the impact of dust on human and environmental health around the world [*Shao et al.*, 2011; *Goudie*, 2014]—highlights the significance of improving our understanding of the sources of dust events, as well as the paths they take to reach affected receptor sites.

The Red Dawn event was the largest in a decade of heightened dust activity which was associated with a prolonged period of drought in Australia, known as the Millennium Drought [*Verdon-Kidd and Kiem*, 2009; *Ummenhofer et al.*, 2009; *Mitchell et al.*, 2010; *Cai et al.*, 2014; *O'Loingsigh et al.*, 2015a]. While in terms of long-term rainfall deficit the Millennium Drought persisted from 1997 to 2010 [*Timbal and Fawcett*, 2013; *Verdon-Kidd et al.*, 2014], meteorological observation records indicate that the period of enhanced dust activity had a later onset and occurred between 2000 and 2009 [*O'Loingsigh et al.*, 2015a]. The majority of research undertaken on the Australian dust events during the Millennium Drought has tended to focus on particular aspects of individual dust storms that occurred within the decade [e.g., *McGowan and Clark*, 2008b]. Often these studies have not provided specific detail on the sources of dust emission, with the source of entrained sediment at best usually broadly attributed to the Lake Eyre Basin (LEB) (Figure 1), a 1.2×10^6 km^2 region of central Australia with a diverse range of geomorphic surfaces, recognized as one of the most significant dust source regions in the Southern Hemisphere [*Prospero et al*., 2002; *Washington et al*., 2003], with hundreds of discrete dust source locations within it [*Bullard et al*., 2008; *Baddock et al*., 2009; *O'Loingsigh*, 2009]. Studies which have provided more detailed information on source locations, for instance *Leys et al*. [2011] and *De Deckker et al*. [2014] in the case of the Red Dawn dust storm, in turn have not always offered a full picture of the transport pathways taken by dust from its sources. The focus of the majority of the Millennium Drought-based studies has in fact been on the arrival of suspended dust at different receptor sites and its subsequent sampling at some of these sites [e.g., *Chan et al*., 2005; *De Deckker et al*., 2014]. The most prominent drawback of these works is the absence of a clear methodology to determine where the detected dust came from. Few studies have linked precise arrival times of dust during the Millennium Drought to sources using air-parcel modeling, in the way, for instance, *Gunawardena et al*. [2013] linked dust detected in southern Queensland to a southern LEB source region in September 2009.

Air-parcel trajectory modeling is a well-developed technique to link dust arriving at receptor sites to its upwind source or sources, where most studies analyzing trajectories generally focus on single or relatively few dust events [e.g., *Radhi et al*., 2010; *Gunawardena et al*., 2013]. Studies using air-parcel trajectory modeling have offered considerable insights into facets of Australian dust transport [*McGowan et al*., 2000; *Bui et al*., 2015]. One major study by *McGowan and Clarke* [2008a] featured the analysis of air-parcel trajectories departing from a point 500 m above an assumed Lake Eyre source on a daily basis at 12:00 for the entire period of 1980 to 2000. While successfully providing a decadal-scale climatology of potential dust transport pathways, a limitation of this work is that it did not discriminate between dusty and nondusty air trajectories [see also *Neff and Bertler*, 2015]. Other authors have been more selective in creating dust-only air parcel climatologies for studies of dust arriving in China [*Zhang et al*., 2008]; Iraq, Kuwait, and Saudi Arabia [*Draxler et al*., 2001; *Notaro et al*., 2013]; Spain [*Escudero et al*., 2005, 2006]; Greece [*Kaskaoutis et al*., 2010]; or Iran [*Givehchi et al*., 2013], but no dust observation-led study has ever been conducted for the Australian continent.

Critical for our understanding of Australian dust dynamics is that between the numerous case studies of individual dust events at one end, and the multiyear nondust-specific climatology of *McGowan and Clark* [2008a] at the other, a knowledge gap regarding the characteristic transport pathways exists. With the absence of a systematic air trajectory study led by known dust observations, the precise role of the Lake Eyre Basin source in providing dust to the heavily populated Australian east coast remains uncertain.

Our paper addresses this knowledge gap by conducting the first long-term, dust-specific air parcel trajectory study for the Australian continent. In achieving this, we present one of the first continental-scale, spatiotemporal trajectory climatology studies that are specifically constrained by the presence of dust, as led by subdaily dust observations. By cross-referencing the modeled trajectories with known dust source regions in and around the Lake Eyre Basin, one of the Southern Hemisphere's most intense dust emission regions, we aim to characterize the contributing source/s as well as the transport routes of dust affecting the east coast. In doing so, this paper aims to address aspects of both dust raising and its subsequent transport, two fundamental phases of the Australian continental-scale dust cycle, during one of Australia's driest decades.

2. Data and Methods

2.1. Temporal and Spatial Identification of Dust Storms: The Meteorological Terminal Aviation Routine Approach

We selected nine observer sites along the east coast of Australia (Figure 1) to capture the full latitudinal range of dust exit points from the interior to the Coral and Tasman Seas as derived from key studies such as *McTainsh et al*. [2005] and *De Deckker et al*. [2008] on large dust storms that occurred during the Millennium Drought. To identify the times and dates of the arrivals of dust storms at the nine observer sites we used high temporal resolution (5–30 min intervals) airport visibility records that form part of Meteorological Terminal Aviation Routine (METAR) weather reports. METAR records are generated by meteorological observers to inform pilots of weather conditions at the airport to aid with takeoff and landing. Apart from their high frequency, another significant advantage of these records is that under airport lighting

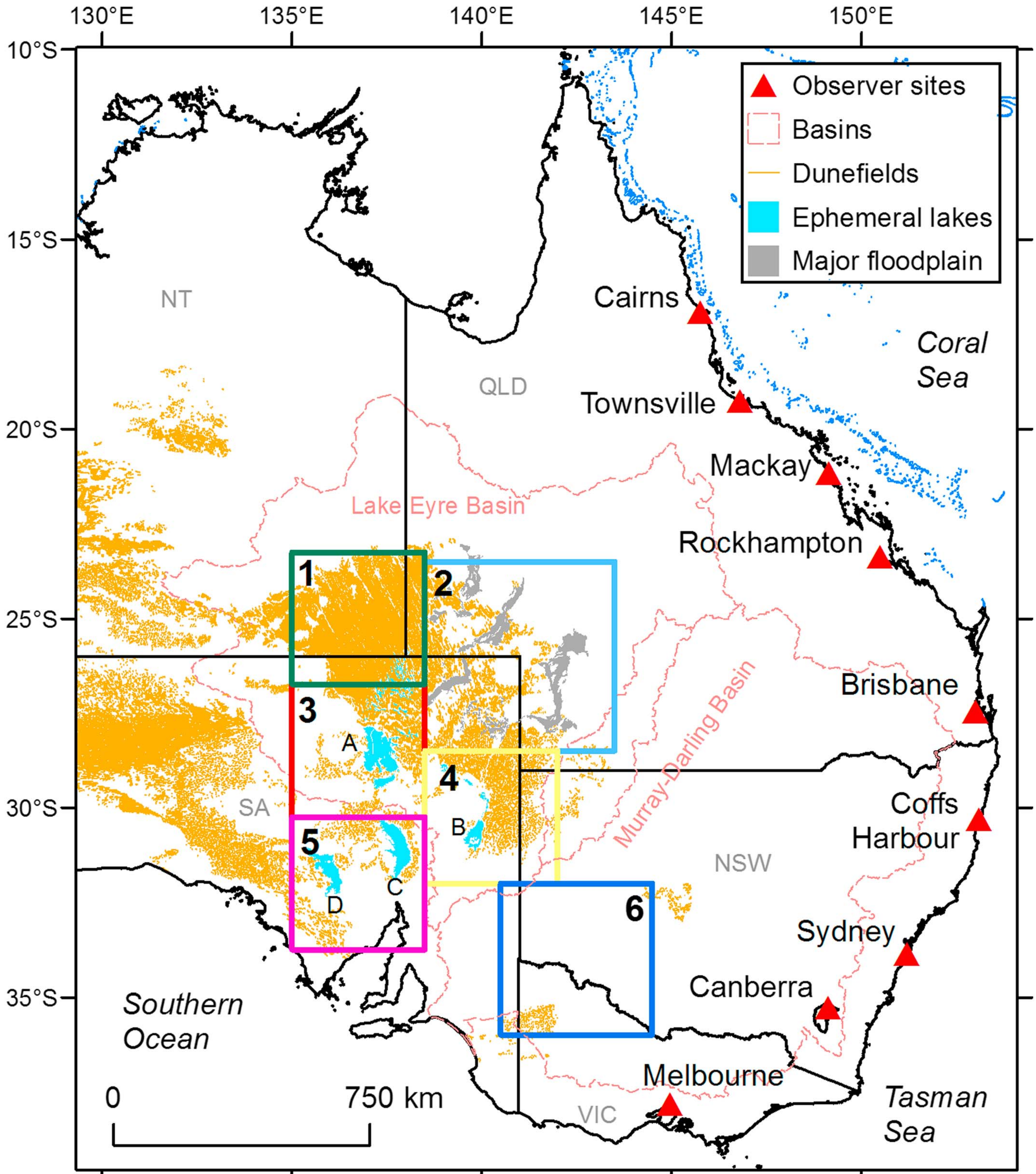

Figure 1. Eastern half of the Australian continent showing the nine coastal receptor/observer sites and the location of the six source sectors (see Table 1): (1) Northern Simpson desert, (2) Queensland Channel Country, (3) Lake Eyre (A) and South Simpson desert ephemeral lakes region, (4) South Strzelecki desert and Lake Frome (B) subbasin, (5) Lakes Torrens (C) and Gairdner (D) region, and (6) Mallee and Western Riverina regions. The colors of the boxes are relevant to the analysis later in the paper. States and territories are abbreviated as NT (Northern Territory), QLD (Queensland), NSW (New South Wales), VIC (Victoria), and SA (South Australia). Basemap data are from Geoscience Australia GEODATA TOPO 2.5M 2003 data set.

conditions, visibility can still be estimated at night, allowing for a full 24 h record. Furthermore, unlike Australian Bureau of Meteorology (ABM) 3–6 hourly Synoptic Observation (SYNOP) records that use World Meteorological Organization (WMO) protocol [see *O'Loingsigh et al.*, 2010] where dust storm classifications are based on strict visibility criteria rarely seen along the Australian east coast (i.e., $<$200 m for severe and $<$1000 m for moderate dust storms), airport METAR observers can record the passage of a dust storm independently of a visibility threshold. As a result, METAR observers tend to report dust more frequently and for longer duration (in active events) than SYNOP observers. In this study, we restricted the number of observations analyzed to those characterized as dust "storms" by the observers, with visibility values less than 5 km. We found that these dates corresponded well to published LEB dust storm dates in the literature [e.g., *Bullard et al.*, 2008; *O'Loingsigh*, 2009; *De Deckker et al.*, 2008, 2014].

2.2. Dust Source Sectors

Numerous studies have been published on Australian dust storms during the Millennium Drought, and some of these contain useful, but incomplete, information on the locations of sources. We found that the most detailed studies were by *Bullard et al.* [2008] and *O'Loingsigh* [2009], who applied the *Ackerman* [1997] brightness temperature difference technique or the *Miller* [2003] dust enhancement method to Moderate Resolution Imaging Spectroradiometer (MODIS) satellite imagery to derive high spatial resolution inventories of dust point sources [*Baddock et al.*, 2009]. To facilitate analysis we grouped these source point data into six broad regions (or sectors) covering the LEB as well as central South Australia and the Mallee-Riverina agricultural region of Victoria and New South Wales, with the latter two lying outside of the LEB (Figure 1 and Table 1). These sectors of frequent dust emission are confirmed in longer-term assessments of wind erosion intensity produced from meteorological records by *McTainsh and Pitblado* [1987] and a multiyear analysis of Total Ozone Mapping Spectrometer aerosol index [*Prospero et al.*, 2002] or MODIS dust products [*Ginoux et al.*, 2012]. A similar approach of establishing broad-scale source sectors has been adopted for trajectory-based dust event source analysis in North Africa [*Escudero et al.*, 2006] and in the Middle East [*Givehchi et al.*, 2013].

The Millennium Drought was experienced across all of eastern Australia and not just within the LEB or its neighboring source regions as defined in this study. As such, many of the agricultural or pastoral regions lying between the LEB and the eastern coast of Australia also had the potential to contribute additional suspended soil to dust events that originated in the LEB [see, for example, *De Deckker et al.*, 2014]. However the potential of any contribution to LEB-sourced dust events from eroding surfaces upwind and downwind of the designated source sectors is not considered in this study. Accurately accounting for additional dust emission from agricultural or rangeland locations downwind of the major LEB sources is problematic. Remote sensing is limited for instance by the fact that once a large plume is visible in the imagery, it is difficult, if not impossible, to identify any additional entrainment occurring under that plume [*Lee et al.*, 2012; *O'Loingsigh et al.*, 2015b]. Meteorological observers may also have reduced line of sight to the surrounding landscape and are therefore less likely to accurately comment on the relative contribution of their immediate local area to the passing dust storm. Furthermore, even if observers had a clear line of sight to the local surroundings (up to 50 km by WMO standards), a passing severe dust storm with visibility $<$200 m would make it difficult for the observer to determine what contribution the local surface might be making to the dust storm. Finally, sampling instruments designed to monitor the ambient dust concentration cannot differentiate between locally sourced dust and dust passing through from upwind sources, as shown for instance in the lower LEB by *Baddock et al.* [2015]. It is therefore beyond the scope of this study to consider any possible additional dust contribution occurring from surfaces located downwind of the source sectors yet upwind of the nine coastal observer sites.

Some dust source sectors, such as the Mallee-Riverina in Figure 1, represent a region that can act both as a dust source in its own right, or a region capable of contributing sediment to dust storms that originated further west and upwind, in the LEB. For more northerly observer sites on the coast, especially in Queensland, only large-scale dust storms generated in the LEB typically by strong cold front episodes [*McTainsh et al.*, 2005] can provoke the sort of visibility attenuation resulting in dust "storm" status being recorded at the coast by METAR observers. Localized dust storms, for example, like those formed by thunderstorm downdraughts in central South Australia, western New South Wales, or Queensland are spectacular and can be reported by several observer stations at the same time, but these do not persist to be detected along the coast. Suspended dust from those localized inland downdraught dust storms is unlikely to reach

Table 1. Spatial Details of the Six Dust Source Sectors Shown in Figure 1

Source Region	Coordinates of Center Point	Distance from Center Point to Box Edge (Degrees)	Approximate Area (km^2)
Northern Simpson desert (red dunes)	25°S, 136.75°E	1.75	137,000
Channel Country	26°S, 141°E	2.5	278,000
Lake Eyre and South Simpson lakes region	28.5°S, 136.75°E	1.75	132,000
South Strzelecki desert and Lake Frome	30.25°S, 140.25°E	1.75	130,000
Lake Torrens and Gairdner region	32°S, 136.75°E	1.75	128,500
Mallee and Western Riverina region	34°S, 142.5°E	2	165,000

the coast, or does so usually in the form of dust haze, a type of diffuse dust event deliberately excluded by the use of dust storm observations in this study.

2.3. Trajectory Modeling

In this study, we used the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model to create dust transport climatologies based on all the dust arrival times identified in the METAR record [*Draxler and Hess*, 1998]. The use of HYSPLIT to investigate dust transport is now well established in the literature [e.g., *Gassó and Stein*, 2007; *Rivera Rivera et al*., 2010; *Uno et al*., 2009; *Neff and Bertler*, 2015], and a comprehensive review of the utility and mechanics of the model has been provided in a recent 30 year perspective [*Stein et al*., 2015]. The input meteorological data set used in this study was the mesoscale version of the ABM Limited Area Prediction System (LAPS) [*Puri et al*., 1998], known as MesoLAPS. The MesoLAPS model was run twice daily with a horizontal grid resolution of 0.125° (approximately 12.5 × 12.5 km for Australia) and for 29 vertical layers (10 m to 20 km altitude). Using these data, 72 h long back trajectories were created to depart from the observer sites every 3 h from January 2000 to December 2009. The 72 h trajectory runs were found to be a duration sufficient to link coastal receptor sites to source regions but short enough so that inaccuracies associated with trajectory length were limited as much as possible [e.g., *Stohl*, 1998]. Trajectories were run for five starting altitudes (50, 100, 500, 1000, and 2000 m above ground level). The maximum analysis height was 2000 m based on findings by *Leys et al*. [2011] and *McGowan and Soderholm* [2012], who reported that the Red Dawn dust plume reached an altitude of 1500–2000 m as it crossed the coast. There are few plume height estimations for any of the other dust storms analyzed in this study so we ran trajectories at all five heights for all events. In total, we produced 40 trajectories per site per day (5 heights × 8 three-hourly model time steps) or a total of 1.26 million trajectories across the 9 sites between 2000 and 2009.

2.4. Cross-Referencing Between Observer Sites and Source Sectors

After the source sector, the METAR and then HYSPLIT data sets were established; these elements were cross-referenced to each other. Of the 1.26 million backward trajectories arriving at five heights for each of the nine receptors in 2000–2009, only those coinciding with METAR dust observation times were retained for further analysis of dust transport characteristics. These trajectories, explicitly associated with dust, were then spatially cross-referenced with the source sectors to establish their relationship with the LEB and the regions they were most likely to originate from. Trajectories were linked to sources using a Python script, which analyzed each path to determine whether any of the 3 hourly iterations of the dusty trajectories occurred within one or more of the source sectors.

For the frequency analysis of the dust-associated trajectories, the nature of LEB sources and the boxes used to represent them meant that trajectories often crossed more than one source region. For example, a dusty trajectory arriving in Brisbane may have passed over both the neighboring North Simpson dunes and neighboring Channel Country regions en route to being detected at the coast (Figure 1). In cases when two or more source regions were crossed by a trajectory, we assumed that (a) the dust would come from at least one of the sources and (b) contributions to the dust plume most likely came from all the source regions the trajectory crossed. These assumptions are underpinned by the fact that based on our analysis of the literature, (i) all six source regions were active during the 2000–2909 Millennium Drought, (ii) all trajectories analyzed were known to be associated with dust (METAR analysis), and (iii) there were no other source surfaces upwind (west) or downwind (east) of the identified source regions with a potential to emit plumes of sufficient magnitude to cause observers at the coast to record dust storms. These assumptions are further legitimized by the fact that in large-scale dust events, many parts of the landscape can be seen to be actively emitting over broad areas; thus, multiple source surfaces may well be contributing dust in

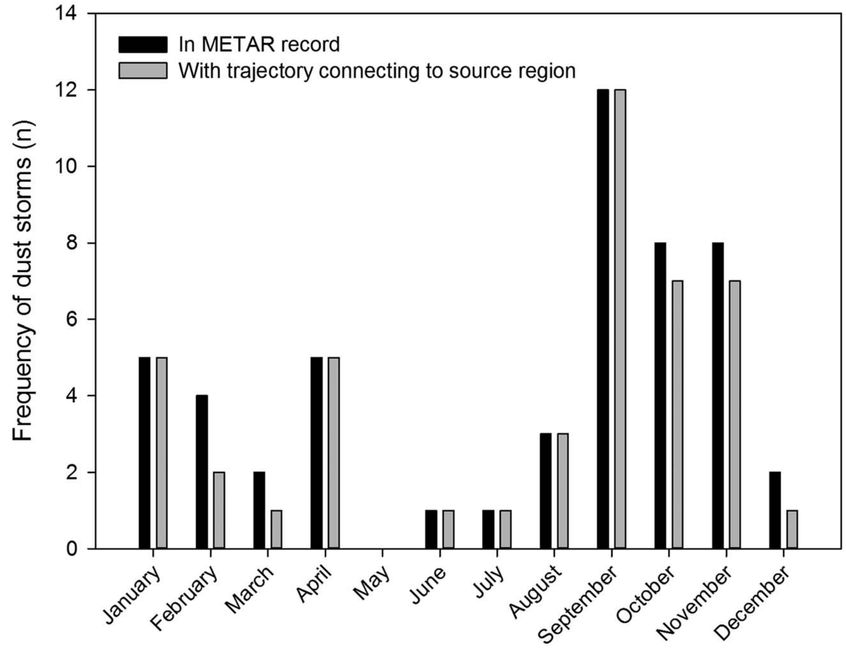

Figure 2. Frequency of dust storms recorded along the Australian east coast by month for 2000–2009 as derived from METAR records (black; $n = 51$) and number of these whose trajectory connected to source sectors shown in Figure 1 (gray; $n = 45$).

individual storms [*Gillette*, 1999; *Bullard et al.*, 2008; *O'Loingsigh*, 2009; *Mitchell et al.*, 2010], especially during an extensive, decade-long drought. For analysis purposes, therefore, if a trajectory crossed two or more source boxes, it was counted as one overpass for each source.

3. Results and Discussion

3.1. General Characteristics of Dust Trajectories

Across the 9 eastern Australia observer sites there were 193 METAR dust observations in total for the study period, reported on 51 different dust days. Of these, 160 observations (82.9% of trajectories) over 45 days (88.2% of days) could be traced back to 1 or more of the 6 identified source sectors (Figure 2). Of the remaining 33 dust observations, where trajectories did not connect to a source, 20 occurred on days when same-day trajectories run at a different time to the dust arrival did successfully link to a source sector. This indicated that the dust event detected on those days was most likely linked to the LEB but that the trajectory modeling result may not have been synchronized with observations of dust at the sites. Only 13 (6.7%) observations were associated with trajectories that did not track back to any of the source sectors on the date of the dust storm. The majority of these were recorded in Cairns on 24 October 2002, the day after one of the largest dust storms that decade [*McTainsh et al.*, 2005; *De Deckker et al.*, 2008]. On that particular day, it was extremely likely that Cairns observers were recording recirculating dust in relatively long-term suspension (haze) that had been drawn in from the Coral Sea [*Chan et al.*, 2005], but which had originated in the LEB at a time longer than the 72 h trajectories used in this study.

The majority of dust storms reaching the east coast from 2000 to 2009 occurred during the austral spring months of September, October, and November (Figure 2), especially from October 2002 and September 2009 when large dust storms occurred [*McTainsh et al.*, 2005; *De Deckker et al.*, 2008, 2014]. Dust storms in Australia are most common in spring and summer months [*McTainsh and Leys*, 1993; *McTainsh et al.*, 1998], but this is characteristic of central Australia where total dust storm frequency is highest. For dust storms to reach the east coast, hundreds of kilometers from the primary sources in the LEB, strong wind conditions associated with cold fronts are required [*Ekström et al.*, 2004; *Strong et al.*, 2011]. *Ekström et al.* [2004] explain that during austral spring months these cold fronts are able to penetrate over the southeast corner of the continent and carry dust from the LEB to the coast, but during the subsequent summer months, large

Table 2. Frequency and Uniqueness of Dust Storm Days at Each Observer Site and Summary of Arrival Height for All Trajectories That Passed Over One or More Source Sectors (Shown in Figure 1)

Observer Site	Latitude	Days of Dust (*n*)	Percent of Dust Days Unique to Site	Total Trajectories Arriving at Site (*n*)	Trajectories Arriving at 50 or 100 m agl (Percent of Total)	Trajectories Arriving at 500 or 1000 m agl (Percent of Total)	Trajectories Arriving at 2000 m agl (Percent of Total)
Cairns	16.9°S	4	0	102	46 (45)	38 (37)	18 (18)
Townsville	19.3°S	9	11.1	194	54 (28)	76 (39)	64 (33)
Mackay	21.2°S	11	27.3	120	37 (31)	43 (36)	40 (33)
Rockhampton	23.4°S	4	0	49	15 (31)	22 (45)	12 (25)
Brisbane	27.5°S	7	28.6	232	95 (41)	93 (40)	44 (19)
Coffs Harbour	30.3°S	8	50	97	23 (24)	39 (40)	35 (36)
Sydney	33.9°S	13	61.5	129	29 (22)	55 (43)	45 (35)
Canberra	35.3°S	7	71.4	77	19 (25)	30 (39)	28 (36)
Melbourne	37.8°S	10	100	86	27 (32)	33 (38)	26 (30)
			Total	1086	345	429	312

high-pressure cells typically dominate over the Great Australian Bight, preventing fronts from penetrating inland over Australia [*Sturman and Tapper*, 2006]. This phenomenon is noticeable in the METAR records where frequency of events reaching the coastal observers is less in the December, January, and February, summer period compared to spring (Figure 2).

By cross-referencing the METAR dates and times of dust arrival, the HYSPLIT trajectories run at different heights from observer sites, and the successful linkage of a path back to a source sector, a total of 1086 trajectories were identified for analysis across all observer sites. Each airport observer site experienced between 4 (Cairns) and 13 (Sydney) dust storm days in the decade, and the majority of receptor sites were connected to source sectors most frequently by midlevel trajectories arriving at 500 or 1000 m above ground level (Table 2).

Of the 45 dust storm days that were found to connect to the LEB source sectors, 12 were dates when dust was recorded at more than one of the receptor sites, and 33 had dust observed only at a single location. The spatial distribution of dust observation is exemplified by the fact that a large dust storm on 22–23 October 2002 (described in detail by *McTainsh et al*. [2005] and *De Deckker et al*. [2008]) was recorded at between two and five of the nine coastal sites and that dust during the 8 day period of broad-scale dust storm activity from 22 to 29 September 2009 was recorded at between two and six of the sites, depending on the day. The major 23 September 2009 Red Dawn dust storm for instance was seen in the METAR records at six of the sites. The results further reveal that dust storm days detected at the more northern observer sites were more likely to have also been detected at the other sites. For example, none of the 4 days of dust observation for Rockhampton and Cairns were unique to those cities, and only around 10% of Townsville's dust days were unique to that city (Table 2) (for locations, refer to Figure 1). Conversely, sites located south of the New South Wales and Queensland border (>30°S) were more likely to experience dust days not detected elsewhere along the coast. In Melbourne, for instance, none of the 10 dust storm days recorded there during the decade coincided with dust storm observations from any of the other selected observer sites, a characteristic that is discussed later.

3.2. Source Apportioning of Dust Trajectories

The six source sectors combine to cover an area of approximately 1.0×10^6 km^2 (Table 1). To refine the analysis of the trajectories summarized in Table 2, we cross-referenced the dust trajectory data spatially with the six regions. A simple frequency plot identifies a role for the major ephemeral lake systems that are recognized as prominent dust sources, with the Lake Eyre-South Simpson sector linked to over 15% of trajectories (Figure 3). A notable contribution is the smaller one from the North Simpson, a sector dominated by mainly vegetation-stabilized linear dunes. While this sector was linked to <10% of trajectories, this provides evidence that the sector did behave as a dust-contributing land surface to some extent. Active dune fields are typically not regarded as intense emitters due to their lack of dust-sized sediment [*Prospero et al*., 2002], but remote sensing and field evidence from the Simpson have previously shown that sedimentological and environmental

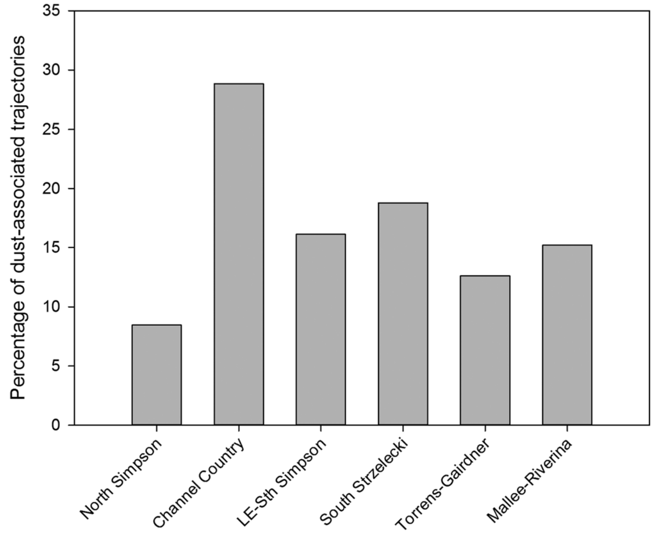

Figure 3. Association of all dust trajectories ($n = 1086$) with the six source sectors.

conditions can allow this largely stabilized dune field to act as a dust source, especially following disturbance by fire [*Bullard et al.*, 2008; *Strong et al.*, 2010].

The greatest frequency of nearly 30% of dust-associated trajectories passed over the Queensland Channel Country on their way to the coast, while nearly 19% were linked to the South Strzelecki desert (Figure 3). While some insights about the contribution by source during the Millennium Drought can be made from Figure 3, a consequence of the fact that trajectories in this analysis can be associated with multiple source sectors is the implication that sectors on the downwind side of the general westerly flow are likely to have a greater frequency of trajectories associated with them as dust transits through them. This will in part explain the highest frequencies of trajectories seen for the Queensland Channel Country and the South Strzelecki desert in Figure 3 (sectors 2 and 4 in Figure 1). While these sectors, and the Mallee-Riverina, are the dominant transit regions for dust following its emission from upwind sources such as Lake Eyre North, the widespread erodibility of the LEB and Mallee during the Millennium Drought however (discussed in section 2.4) provides a high confidence that surfaces in the downwind source sectors will also likely have contributed when wind speeds exceeded emission thresholds during dust events. The southern Strzelecki lake systems for instance were highly active throughout 2003–2005 [*Bullard et al.*, 2008], such that there can be confidence that the results here reflect the broad-scale provenancing of dust to the receptor sites through the decade, even if number of trajectories cannot be used to estimate magnitude of source activity.

While the broad source contributions are revealed in Figure 3, the actual frequency of the dust-associated trajectories by height, receptor, and source is shown in Figure 4. The source sector analysis shows that dust storms detected at the coastal Queensland observer sites (north of 30°S) had a strong link with the Queensland Channel Country, irrespective of what other source region the dust may have been emitted from (Figure 4). This is not altogether surprising based on the form of the dust trajectories to these sites (Figure 5, discussed later), plus the likelihood of dust passing through the Channel Country from source sectors further west. Although the Channel Country region is subject to intermittent flooding [*McTainsh et al.*, 1999; *Costelloe et al.*, 2003], which causes periodic responses in soil moisture and vegetation cover that reduce dust entrainment, during dry conditions such as those of the Millennium Drought, fine alluvial sediments become available for emission [*McTainsh et al.*, 1999; *Bullard et al.*, 2008]. This region can be seen to be an important potential source of dust transport to inhabited regions north of 30°S and therefore toward the Great Barrier Reef. In Rockhampton there is a stronger relationship of trajectories from the Lake Eyre and South Simpson sector at lower arrival heights (50–500 m), while source sectors further south, such as the Lakes Torrens-Gairdner or Mallee-Riverina regions, better connect to this receptor site at higher arrival altitudes. This demonstrates how longer trajectory lengths associated with faster airflow at higher levels is better linked to those sources at greater upwind distances [*McGowan and Clark*, 2008a] (Figure 4).

The contribution from the northern Simpson desert and the neighboring Queensland Channel Country region is much reduced south of 30°S (e.g., Coffs Harbour), with the South Strzelecki desert emerging as the dominant source for more southerly receptors along with the Lake Eyre and Torrens-Gairdner regions (Figure 4). In Sydney, the main source of dust arriving at or below 100 m is the South Strzelecki, joined by the Mallee-Riverina and Lakes Torrens-Gairdner sectors for dust arrival at higher altitude (>500 m). In Canberra, the effect of the mixed dust arrivals in the form of both prefrontal northerly and postfrontal westerly flows shown in Figure 5 is noticeable. At lower altitudes (<500 m; Figure 4) the main source remains

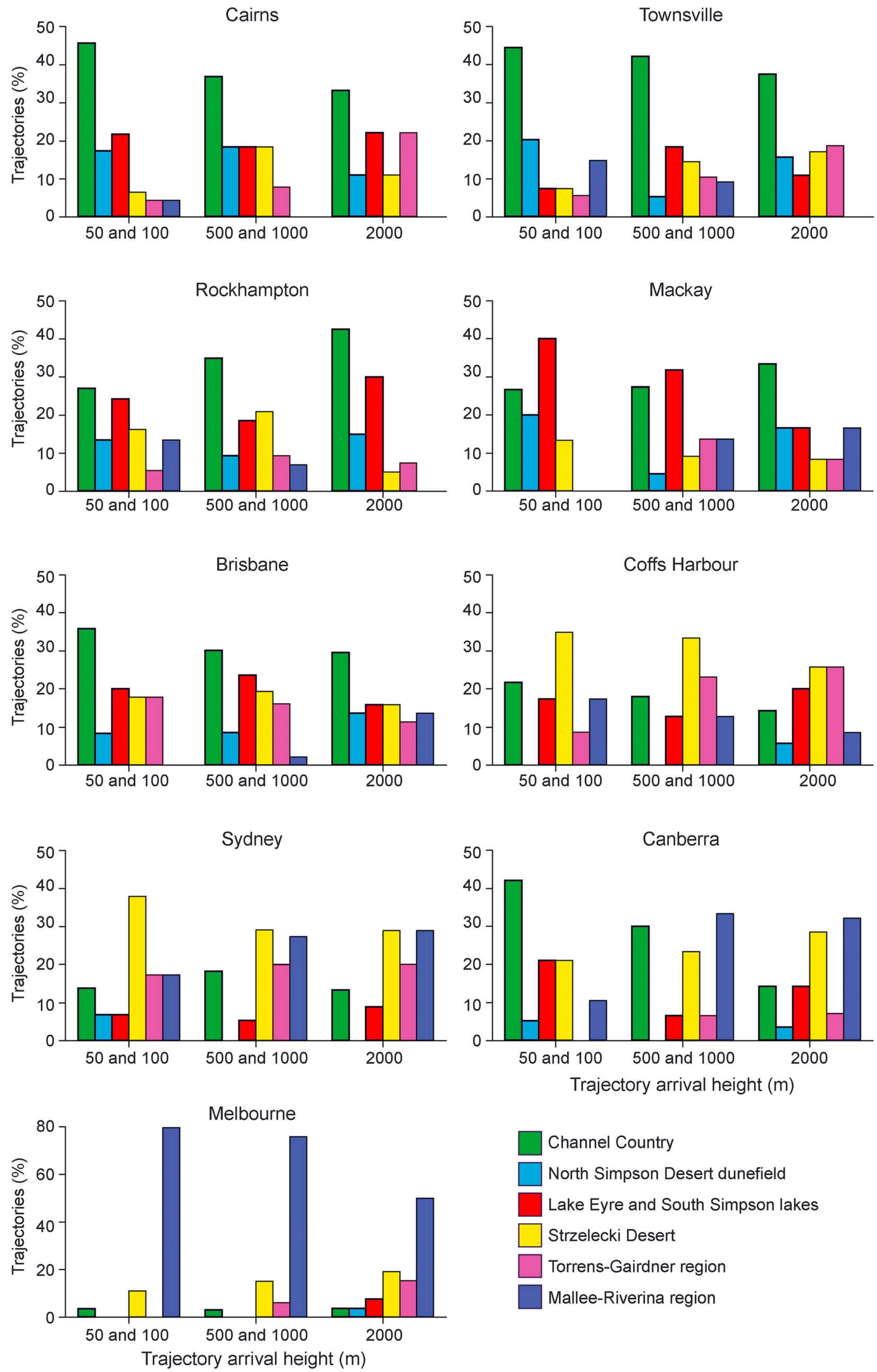

Figure 4. Frequency (percent), by height, of trajectories arriving at each observer site according to the principal source regions they passed over. Bar colors correspond to source boxes in Figure 1.

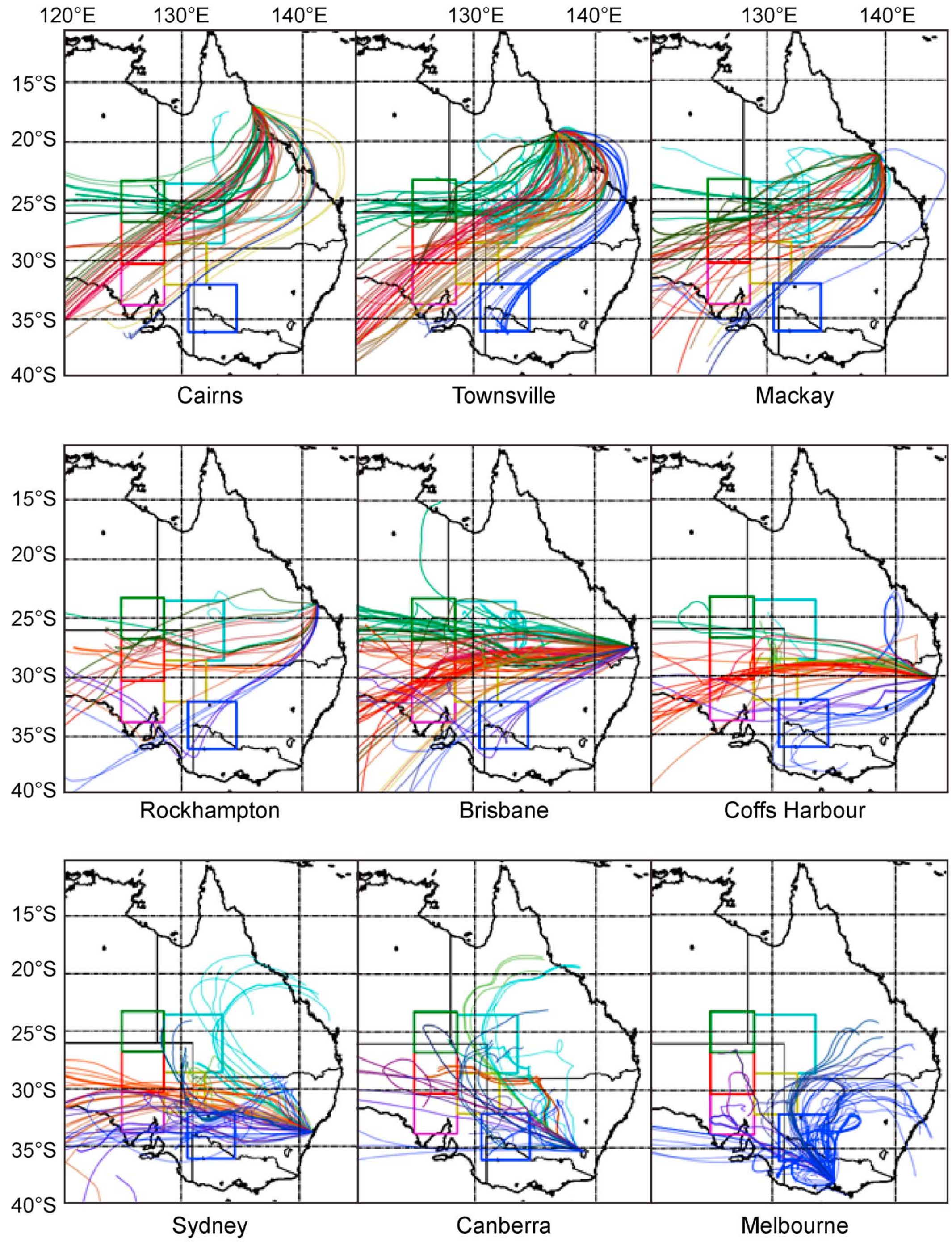

Figure 5. Paths of all dust-associated trajectories arriving at each of the nine coastal observer sites. Plots are organized latitudinally from most northern (Cairns) to southern (Melbourne). Colors of trajectories relate to colors of dust source sectors defined in Figure 1 (see text).

the Channel Country, with this lower level flow associated with prefrontal northerlies along the leading edge of the front, advecting dust southward to Canberra [*Strong et al.*, 2011; *Baddock et al.*, 2015]. As fronts approach Canberra and frontal westerly winds exert more influence on airflow at higher altitudes, the effect can be seen as sources further afield (Mallee-Riverina and Lakes Torrens-Gairdner regions) become the dominant source for dust arriving at or above 500 m. Dust impacting Melbourne is nearly entirely sourced from the

Mallee-Riverina region (Figure 4). This is not surprising due to the proximal location of Melbourne in relation to that source region and the fact that nearly all reported dust storms reaching this city were seen to do so on north and northwest winds (Figure 5).

3.3. The Role of Wind Systems

The previous section began to show how particular wind systems were responsible for transporting LEB dust to the east coast, based on the arrivals at certain receptors from different sources during the Millennium Drought. However, considerably more detailed inferences about the wind patterns driving dust transport in eastern Australia are provided for the period when the individual trajectories for each receptor site are examined (Figure 5). Arrivals by source are quantified in Table 2 and Figure 4. Figure 5 illustrates the source sectors associated with different trajectories, with the modeled paths colored according to the source boxes they passed over. If two source sectors were crossed by the same trajectory (e.g., Lake Eyre and the Southern Simpson lakes (Red) and the South Strzelecki desert (Yellow)), the trajectory blends both colors (e.g., orange).

Overall, Figure 5 shows that during the 2000–2009 Millennium Drought, the trajectories that took dust from the emissive center of the continent to the east coast are typical of cold front-induced dust storms over the eastern half of the continent. In general terms, the established conceptual model for the region originally described by *Sprigg* [1982], that the passage of frontal systems can result in dust transported by three wind systems: prefrontal northerlies, frontal westerlies or postfrontal southerlies, holds in the light of the present evidence. The influence of these latter two winds has been taken to contribute to an overall Southeast Dust Pathway for eastern Australia. Figure 5 however provides significant new detail of dust paths. From our data set, here we show that the original Southeast Dust Path can actually be subdivided for the Millennium Drought into three dust paths, which become evident on moving up the east Australian coast from south to north in Figure 5. Below 35°S, prefrontal northerlies transport dust south within the Southern Dust Path, as evidenced at the Melbourne receptor site. The Southern Dust Path appears to be quite narrow to the south coast of Victoria as indicated by 100% of Melbourne's dust event days being unique to that city (Table 2).

In the 35°S to 30°S latitudinal zone (Canberra and Sydney receptor sites; Figure 5) the influence of the prefrontal northerlies weakens in favor of the frontal westerlies as the Eastern Dust Path is entered. The Eastern Dust Path also becomes wider as moving north up the southeastern seaboard, as indicated by 71.5% of Canberra's dust days being unique to that city and 61.5% of those at Sydney (Table 2). In the 30°S to 25°S latitudinal zone (Coffs Harbour to Brisbane), frontal westerlies become clearly the dominant dust-transporting wind systems, representing the main course of the Eastern Dust Path, as evidenced at these two receptor sites. The Eastern Dust Path can also be seen to widen as we move north, with 50% of Coffs Harbour's dust days being unique to that city and only 28.6% of those at Brisbane (Table 2).

North of 25°S (Rockhampton and other more northern receptor sites) postfrontal south westerlies become the dominant dust-transporting wind systems as we enter the North East Dust Path. Above 20°S (Townsville and Cairns) the southwesterly winds become southerly then southeasterly as the dust plumes of the North East Dust Path pass offshore and recirculate back onshore along the far north Queensland coast. Essentially, this split in trajectory behavior occurring north and south of 25°S represents a point of bifurcation for dust transported to the eastern side of Australia out of the emissive center. In retrospect, this bifurcation of east Australian dust plumes was clearly apparent in satellite imagery of the 23 October 2002 dust storm analyzed by *McTainsh et al*. [2005], and the significance of the northern arm of this bifurcation was interpreted by *Mackie et al*. [2008] as possibly reflecting a separate dust path. Similarly, the recirculation of dust plumes back onshore during the same dust event was shown by *Chan et al*. [2005], who recorded the arrival of dust from an easterly direction at Mackay (21°S) during October 2002. Onshore dust trajectories were also shown north of Cairns by *Bui et al*. [2015]. As a result of this recirculation and the increasing distance from source, the North East Dust Path is a much wider dust path than the two dust paths seen further south, with only $<$27% of dust event days being unique to the four northern cities (Table 2).

While the focus of this study is dust transport from source to coast, our findings concerning the dust exit routes from the continent offer some useful insights for longer-range transport of Australian dust, for instance the eastern pathway associated with dust export to New Zealand [*Marx et al*., 2005], and the potential of dust delivery to marine systems. In particular, our division between the three dust paths provides important indicators for the exit of dusts from different source areas with different mineral and sedimentological characteristics being deposited into oceanic systems [*Cropp et al*., 2013]. *Shaw et al*. [2008] describe a possible phytoplankton response to dust deposition in the Great Barrier Reef, postulated to be driven by dust from what we now know to be the North East Dust Path. Similarly, *Gabric et al*. [2015] described another potential response of phytoplankton to dust deposition in the here-defined Eastern Dust Path over the Tasman Sea. The potential for dust-induced phytoplankton blooms in the Southern Ocean [e.g., *Boyd et al*., 2004] is most likely to occur as a result of the Southern Dust Path.

4. Conclusions

By examining modeled air parcel movements that are coupled to the specific timing of dust observations at meteorological stations, this study has produced the first long-term study of dust pathways in eastern Australia that combines trajectory modeling with a high confidence that trajectories represent dust transport. The approach has demonstrated the most probable routes of dust to different east coast receptor sites for the 2000–2009 Millennium Drought decade, a heightened period of widespread dust activity in Australia. By linking the trajectories to likely source areas, the work identifies broad-scale linkages between two key elements of the eastern Australian dust cycle, entrainment, and transport of dust, providing insights into the dynamics of this dust region of hemispheric prominence.

The study improves our understanding of Australian dust transport by revealing the variable routing of dust trajectories reaching the east coast and the detail of the pathways that are common to given coastal receptor sites. The Millennium Drought dust storm trajectories clearly reveal the different wind systems responsible for the delivery of dust, along with a strong latitudinal variation in the influence of these winds. The potential for any significant northerly component of dust transport over eastern Australia and the delivery of aeolian inputs to the Coral Sea occurs north of 25°S, driven by postfrontal southwesterly flow. This can be seen as significant evidence for a North East dust pathway that is not adequately considered in existing conceptual models. South of this, trajectories for the study period help better define the northern boundary of the continent's main Southeast Dust Path. This is marked by the flow patterns seen for Brisbane and Coffs Harbour (28°S and 30°S), which shows a dominance of zonally directed arrival paths associated with frontal westerlies, forming an Eastern Dust Path. South of this, the increasing importance of prefrontal northerly flows in contributing to an Australian Southern Dust Path becomes apparent.

The pathways and patterns of dust observation frequency also reveal the greater likelihood of sites south of 30°S to be the sole receptor of dust for a single dust event. This indicates that more spatially discrete events characterize dust outbreaks impacting southern receptors such as Sydney, Canberra, and Melbourne. When locations north of 30°S receive dust, the course of the plumes northward along the coast means dust detection typically occurs at multiple coastal cities on this part of the seaboard.

The upwind portions of the trajectories provide some general information about source activity, including the prominence of the Lake Eyre North-Southern Simpson, Queensland Channel Country, and Mallee-Riverina source regions through the Millennium Drought, but limited benefits for understanding dust raising processes, as trajectories offer no representation of magnitude of source emission. Of more interest is the linking of sources to the coast, such as the clear relationship existing between the Mallee source and Melbourne, or the Channel Country and receptors north of 25°S. This demonstrates how the fine sediment characteristics of specific sources are likely to be preferentially delivered along different pathways, and by extension, to different marine environments (e.g., Mallee to Southern Ocean and Channel Country to Coral Sea).

Overall, this work has shown the effectiveness of an approach led by meteorological observation in producing a dust trajectory climatology for a specific period of time representing significant dust activity in Australia. Future work can employ the approach used here to further consider trajectories in conjunction with synoptic data sets to understand the specific weather systems responsible for activating the different dust pathways, e.g., those resulting in recirculation of dust over the Great Barrier Reef. Furthermore, having focused on dust receptor points on the east coast, consideration of the principal pathway to the northwest of the continent can next build a complete picture of the dust transport system for the whole Australian continent.

Acknowledgments
The authors gratefully acknowledge the NOAA Air Resources Laboratory for the provision of the HYSPLIT transport and dispersion model (http://www.ready.noaa.gov/), the Australian Bureau of Meteorology for the data, and the Australian Research Council (DP0772180) for funding this research. The METAR data used in this study can be obtained from the Australian Bureau of Meteorology, HYSPLIT is made freely available, and the trajectories used here are available on request through the authors. Comments on the paper from Peter Neff and an anonymous reviewer were much appreciated.

References

Ackerman, S. A. (1997), Remote sensing aerosols using satellite infrared observations, *J. Geophys. Res.*, *102*(D14), 17,069–17,079, doi:10.1029/96JD03066.

Aryal, R., D. Kandel, D. Acharya, C. Meng Nan, and S. Beecham (2012), Unusual Sydney dust storm and its mineralogical and organic characteristics, *Environ. Chem.*, *9*(6), 537–546, doi:10.1071/en12131.

Aryal, R., S. Beecham, M. Kamruzzaman, S. Conner, and B.-K. Lee (2015), Temporal change of PM_{10} and its mass fraction during a dust storm in September 2009 in Australia, *Air Quality Atmos. Health*, *8*, 483–494, doi:10.1007/s11869-014-0297-0.

Baddock, M. C., J. E. Bullard, and R. G. Bryant (2009), Dust source identification using MODIS: A comparison of techniques applied on the Lake Eyre Basin, Australia, *Remote Sens. Environ.*, *113*(7), 1511–1528, doi:10.1016/j.rse.2009.03.002.

Baddock, M. C., C. L. Strong, P. S. Murray, and G. H. McTainsh (2013), Aeolian dust as a transport hazard, *Atmos. Env.*, *71*, 7–14, doi:10.1016/j.atmosenv.2013.01.042.

Baddock, M. C., K. Parsons, C. L. Strong, J. F. Leys, and G. H. McTainsh (2015), Drivers of Australian dust: A case study of frontal winds and dust dynamics in the lower Lake Eyre Basin, *Earth Surf. Process. Landf.*, *40*, 1982–1988, doi:10.1002/esp.3773.

Barnett, A. G., J. E. Fraser, and L. Munck (2012), The effects of the 2009 dust storm on emergency admissions to a hospital in Brisbane, Australia, *Int. J. Biometeorol.*, *56*(4), 719–26, doi:10.1007/s00484-011-0473-y.

Box, M. A., M. Rahdi, and G. P. Box (2010), The great Sydney dust event: Size-resolved chemical composition and comparison, *IOP Conf. Series: Earth Environ. Sci.*, *2010*(11), 012015, doi:10.1088/1755-1315/11/1/012015.

Boyd, P. W., G. H. McTainsh, V. Sherlock, K. Richardson, S. Nichol, M. Ellwood, and R. Frew (2004), Episodic enhancement of phytoplankton stocks in New Zealand subantarctic waters: Contribution of atmospheric and oceanic iron supply, *Global Biogeochem. Cycles*, *18*, GB1029, doi:10.1029/2002GB002020,2004.

Bryant, R. G. (2013), Recent advances in our understanding of dust source emission processes, *Prog. Phys. Geog.*, *37*, 397–421, doi:10.1177/0309133313479391.

Bullard, J. E., M. Baddock, G. H. McTainsh, and J. Leys (2008), Sub-basin scale dust source geomorphology detected using MODIS, *Geophys. Res. Lett.*, *35*, L15404, doi:10.1029/2008GL033928.

Bui, E., A. Chappell, T. Kelly, and G. H. McTainsh (2015), Linked fluvial and aeolian processes fertilize Australian bioregions, *Aeolian Res.*, *17*, 255–262, doi:10.1016/j.aeolia.2014.12.001.

Cai, W., et al. (2014), Increasing frequency of extreme El Niño events due to greenhouse warming, *Nat. Clim. Change*, *4*, 111–116.

Chan, Y. C., G. McTainsh, J. Leys, H. McGowan, and K. Tews (2005), Influence of the 23 October 2002 dust storm on the air quality of four Australian cities, *Water Air Soil Pollut.*, *164*, 329–348.

Costelloe, J. F., R. B. Grayson, R. M. Argent, and T. A. McMahon (2003), Modelling the flow regime of an arid zone floodplain river, Diamantina River, Australia, *Environ. Model. Software*, *18*(8), 693–703.

Cropp, R. A., A. J. Gabric, M. Levasseur, G. H. McTainsh, A. Bowie, C. S. Hassler, C. S. Law, H. McGowan, N. Tindale, and R. V. Rossel (2013), The likelihood of observing dust-stimulated phytoplankton growth in waters proximal to the Australian continent, *J. Mar. Syst.*, *117*, 43–52, doi:10.1016/j.jmarsys.2013.02.013.

De Deckker, P., R. M. M. Abed, D. deBeer, K. U. Hinrichs, T. O'Loingsigh, E. Schefuß, J. B. W. Stuut, N. J. Tapper, and S. van der Kaars (2008), Geochemical and microbiological fingerprinting of airborne dust that fell in Canberra, Australia, in October 2002, *Geochem. Geophys. Geosyst.*, *9*, Q12Q10, doi:10.1029/2008GC002091.

De Deckker, P., C. I. Munday, J. Brocks, T. O'Loingsigh, G. E. Allison, J. Hope, M. Norman, J. B. W. Stuut, N. J. Tapper, and S. van der Kaars (2014), Characterisation of the major dust storm that traversed over eastern Australia in September 2009; A multidisciplinary approach, *Aeolian Res.*, *15*, 133–149, doi:10.1016/j.aeolia.2014.07.003.

Draxler, R. R., and G. D. Hess (1998), An overview of the HYSPLIT_4 modeling system for trajectories, dispersion, and deposition, *Aust. Meteorol. Mag.*, *47*, 295–308.

Draxler, R. R., D. A. Gillette, J. S. Kirkpatrick, and J. Heller (2001), Estimating PM_{10} air concentrations from dust storms in Iraq, Kuwait and Saudi Arabia, *Atmos. Env.*, *35*, 4315–4330, doi:10.1016/S1352-2310(01)00159-5.

Ekström, M., G. H. McTainsh, and A. Chappell (2004), Australian dust storms: Temporal trends and relationships with synoptic pressure distributions (1960–99), *Int. J. Climatol.*, *24*, 1581–1599.

Escudero, M., S. Castillo, X. Querol, A. Avila, M. Alarcon, M. M. Viana, A. Alastuey, E. Cuevas, and S. Rodriguez (2005), Wet and dry African dust episodes over eastern Spain, *J. Geophys. Res.*, *110*, D18S08, doi:10.1029/2004JD004731.

Escudero, M., A. F. Stein, R. R. Draxler, X. Querol, A. Alastuey, S. Castillo, and A. Avilla (2006), Determination of the contribution of northern Africa dust source areas to PM_{10} concentrations over the central Iberian Peninsula using the Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT) model, *J. Geophys. Res.*, *110*, D18S08, doi:10.1029/2005JD006395.

Gabric, A., R. Cropp, G. H. McTainsh, H. Butler, B. Johnston, T. O'Loingsigh, and D. Tran (2015), Tasman Sea biological response to dust storm events during the austral spring of 2009, *Mar. Freshwater Res.*, *67*, 1090–1102.

Gassó, S., and A. F. Stein (2007), Does dust from Patagonia reach the sub-Antarctic Atlantic Ocean?, *Geophys. Res. Lett.*, *34*, L01801, doi:10.1029/2006GL027693.

Gillette, D. A. (1999), A qualitative geophysical explanation for hot spot dust emitting source regions, *Contrib. Atmos. Phys.*, *72*, 67–77.

Ginoux, P., J. M. Prospero, T. E. Gill, N. C. Hsu, and M. Zhao (2012), Global-scale attribution of anthropogenic and natural dust sources and their emission rates based on MODIS Deep Blue aerosol products, *Rev. Geophys.*, *50*, RG3005, doi:10.1029/2012RG000388.

Givehchi, R., M. Arhami, and M. Tajrishy (2013), Contribution of the Middle Eastern dust source areas to PM_{10} levels in urban receptors: Case study of Tehran, *Iran. Atmos. Environ.*, *75*, 287–295, doi:10.1016/j.atmosenv.2013.04.039.

Goudie, A. S. (2014), Desert dust and human health disorders, *Environ. Int.*, *63*, 101–113, doi:10.1016/j.envint.2013.10.011.

Gunawardena, J., A. M. Ziyath, T. E. Bostrom, L. K. Bekessy, G. A. Ayoko, P. Egodawatta, and A. Goonetilleke (2013), Characterisation of atmospheric deposited particles during a dust storm in urban areas of eastern Australia, *Sci. Total Environ.*, *461–462*, 72–80, doi:10.1016/j.scitotenv.2013.04.080.

Hallegraeff, G., F. Coman, C. Davies, A. Hayashi, D. McLeod, A. Slotwinski, L. Whittock, and A. Richardson (2014), Australian dust storm associated with extensive *Aspergillus sydowii* fungal "bloom" in coastal waters, *Appl. Environ. Microbiol.*, *80*(11), 3315–3320, doi:10.1128/AEM.04118-13.

Holyoak, A. L., P. J. Aitken, and M. S. Elcock (2011), Australian dust storm: Impact on a statewide air medical retrieval service, *Air Med. J.*, *30*(6), 322–327, doi:10.1016/j.amj.2010.12.010.

Jayaratne, E. R., G. R. Johnson, P. McGarry, H. C. Cheung, and L. Morawska (2011), Characteristics of airborne ultrafine and coarse particles during the Australian dust storm of 23 September 2009, *Atmos. Environ.*, *45*(24), 3996–4001.

Kaskaoutis, D. G., P. T. Nastos, P. G. Kosmopoulos, and H. D. Kambezidis (2010), The combined use of satellite data, air-mass trajectories and model applications for monitoring dust transport over Athens, *Greece. Int. J. of Rem. Sens.*, *31*, 5089–5109.
Jones, T. A., and S. A. Christopher (2011), Assessment of temperature and humidity changes associated with the September 2009 dust storm in Australia, *IEEE Geosci. Rem. Sens. Lett.*, *8*(2), 268–272, doi:10.1109/LGRS.2010.2063693.
Lee, J. A., M. C. Baddock, M. J. Mbuh, and T. E. Gill (2012), Geomorphic and land cover characteristics of aeolian dust sources in West Texas and eastern New Mexico, USA, *Aeolian Res.*, *3*, 459–466, doi:10.1016/j.aeolia.2011.08.001.
Leys, J. F., S. K. Heidenreich, C. L. Strong, G. H. McTainsh, and S. Quigley (2011), PM_{10} concentrations and mass transport during "Red Dawn"—Sydney 23 September 2009, *Aeolian Res.*, *3*, 327–342, doi:10.1016/j.aeolia.2011.06.003.
Li, X., L. Ge, Y. Dong, and H.-S. Chang (2010), Estimating the greatest dust storm in eastern Australia with MODIS satellite images, in *IGARSS 2010*, *IEEE International Geoscience and Remote Sensing Symposium*, *Proceedings*, 5649212:1039-1042.
McGowan, H., and A. Clark (2008a), Identification of dust transport pathways from Lake Eyre, Australia using HYSPLIT, *Atmos. Environ.*, *42*, 6915–6925, doi:10.1016/j.atmosenv.2008.05.053.
McGowan, H. A., and A. Clark (2008b), A vertical profile of PM_{10} dust concentrations measured during a regional dust event identified by MODIS Terra, western Queensland, Australia, *J. Geophys. Res.*, *113*, F02S03, doi:10.1029/2007JF000765.
McGowan, H. A., and J. Soderholm (2012), Laser ceilometer measurements of Australian dust storm highlight need for reassessment of atmospheric dust plume loads, *Geophys. Res. Lett.*, *39*, L02804, doi:10.1029/2011GL050319.
McGowan, H. A., G. H. McTainsh, P. Zawar-Reza, and A. P. Sturman (2000), Identifying regional dust transport pathways: Application of kinematic trajectory modelling to a trans-Tasman case, *Earth Surf. Process. Landf.*, *25*, 633–647.
McTainsh, G. H., and J. F. Leys (1993), Soil erosion by wind in land degradation processes in Australia, in *Land Degradation Processes in Australia*, edited by G. McTainsh and W. C. Broughton, pp. 188–233, Longman, Melbourne.
McTainsh, G. H., and J. R. Pitblado (1987), Dust storms and related phenomena measured from meteorological records in Australia, *Earth Surf. Process. Landf.*, *12*, 415–424.
McTainsh, G. H., A. W. Lynch, and E. K. Tews (1998), Climatic controls upon dust storm occurrence in eastern Australia, *J. Arid Environ.*, *39*, 457–466.
McTainsh, G. H., J. F. Leys, and W. G. Nickling (1999), Wind erodibility of arid lands in the Channel Country of western Queensland, Australia, *Z. Geomorphol.*, *116*, 113–130.
McTainsh, G., Y.-C. Chan, H. McGowan, J. Leys, and K. Tews (2005), The 23rd October 2002 dust storm in eastern Australia: Characteristics and meteorological conditions, *Atmos. Environ.*, *39*, 1227–1236.
Mackie, D. S., P. W. Boyd, G. H. McTainsh, N. W. Tindale, T. K. Westberry, and K. A. Hunter (2008), Biogeochemistry of Australian dust—From eolian uplift to marine uptake, *Geochem. Geophys. Geosyst.*, *9*, Q03Q08, doi:10.1029/2007GC001813.
Marx, S., B. S. Kamber, and H. McGowan (2005), Estimates of Australian dust flux into New Zealand: Quantifying the eastern Australian dust plume pathway using trace element calibrated ^{210}Pb as a monitor, *Earth Planet. Sc. Lett.*, *239*, 336–351, doi:10.1016/j.epsl.2005.09.002.
Merrifield, A., S. Schindeler, B. Jalaludin, and W. Smith (2013), Health effects of the September 2009 dust storm in Sydney, Australia: Did emergency department visits and hospital admissions increase?, *Environ. Health*, *12*, 32, doi:10.1186/1476-069X-12-32.
Miller, S. D. (2003), A consolidated technique for enhancing desert dust storms with MODIS, *Geophys. Res. Lett.*, *30*(20), 2071, doi:10.1029/2003GL018279.
Mitchell, R. M., S. K. Campbell, and Y. Qin (2010), Recent increase in aerosol loading over the Australian arid zone, *Atmos. Chem. Phys.*, *10*, 1689–1699.
Neff, P. D., and N. A. N. Bertler (2015), Trajectory modelling of modern dust transport to the Southern Ocean and Antarctica, *J. Geophys. Res. Atmos.*, *120*, 9303–9322, doi:10.1002/2015JD023304.
Notaro, M., F. Alkolibi, E. Fadda, and F. Bakhrjy (2013), Trajectory analysis of Saudi Arabian dust storms, *J. Geophys. Res. Atmos.*, *118*, 6028–6043, doi:10.1002/jgrd.50346.
O'Loingsigh, T. (2009), Dust storms in the Lake Eyre Basin: Evaluation of their sources, their frequency and their content, PhD Thesis, p. 478, Monash University.
O'Loingsigh, T., G. H. McTainsh, N. J. Tapper, and P. Shinkfield (2010), Lost in code: A critical analysis of using meteorological data for wind erosion monitoring, *Aeolian Res.*, *2*, 49–57, doi:10.1016/j.aeolia.2010.03.002.
O'Loingsigh, T., G. H. McTainsh, K. P. Parsons, C. L. Strong, P. Shinkfield, and N. J. Tapper (2015a), Using meteorological observer data to compare wind erosion rates during two great droughts in eastern Australia; the World War II Drought (1937–1946) and the Millennium Drought (2001–2010), *Earth Surf. Process. Landf.*, *40*, 123–130, doi:10.1002/esp.3668.
O'Loingsigh, T., R. M. Mitchell, S. K. Campbell, N. A. Drake, G. H. McTainsh, N. J. Tapper, and D. L. Dunkerley (2015b), Correction of dust event frequency from MODIS Quick-Look imagery using in-situ aerosol measurements over the Lake Eyre Basin, Australia, *Rem. Sens. Environ.*, *169*, 222–231, doi:10.1016/j.rse.2015.08.010.
Prospero, J. M., P. Ginoux, O. Torres, S. E. Nicholson, and T. E. Gill (2002), Environmental characterization of global sources of atmospheric soil dust identified with the Nimbus 7 Total Ozone Mapping Spectrometer (TOMS) absorbing aerosol product, *Rev. Geophys.*, *40*(1), 1002, doi:10.1029/2000RG000095.
Puri, K., G. Dietachmeyer, G. A. Mills, N. E. Davidson, R. M. Bowen, and L. W. Logan (1998), The new BMRC Limited Area Prediction System, LAPS, *Aust. Meteorol. Mag*, *47*, 203–223.
Radhi, M., M. A. Box, G. P. Box, R. M. Mitchell, D. D. Cohen, E. Stelcer, and M. D. Keywood (2010), Size-resolved mass and chemical properties of dust aerosols from Australia's Lake Eyre Basin, *Atmos. Environ.*, *44*, 3519–3528.
Reynolds, R. L., S. R. Cattle, B. M. Moskowitz, H. L. Goldstein, K. Yauk, C. B. Flagg, T. S. Berquó, R. F. Kokaly, S. Morman, and G. N. Breit (2014), Iron oxide minerals in dust of the Red Dawn event in eastern Australia, September 2009, *Aeolian Res.*, *15*, 1–13, doi:10.1016/j.aeolia.2014.02.003.
Rivera Rivera, N. I., T. E. Gill, M. P. Bleiweiss, and J. L. Hand (2010), Source characteristics of hazardous Chihuahuan desert dust outbreaks, *Atmos. Environ.*, *44*, 2457–2468, doi:10.1016/j.atmosenv.2010.03.019.
Shao, Y., et al. (2011), Dust cycle: An emerging core theme in Earth system science, *Aeolian Res.*, *2*, 181–204, doi:10.1016/j.aeolia.2011.02.001.
Shaw, E. C., A. J. Gabric, and G. H. McTainsh (2008), Impacts of aeolian dust deposition on phytoplankton dynamics in Queensland coastal waters, *Mar. Freshwater Res*, *59*(11), 951–962.
Sprigg, R. C. (1982), Some stratigraphic consequences of fluctuating Quaternary sea levels and related wind regimes in southern and central Australia, in *Quaternary Dust Mantles, China, New Zealand and Australia*, edited by R. J. Wasson, pp. 211–240, Australian National University, Canberra.
Stein, A. F., R. R. Draxler, G. D. Rolph, B. J. B. Stunder, M. D. Cohen, and F. Ngan (2015), NOAA's HYSPLIT atmospheric transport and dispersion modelling system, *Bull. Am. Meteorol. Soc.*, *96*, 2059–2077, doi:10.1175/BAMS-D-14-00110.1.

Stohl, A. (1998), Computation, accuracy and applications of trajectories—A review and bibliography, *Atmos. Environ.*, *32*(6), 947–966, doi:10.1016/S1352-2310(97)00457-3.

Strong, C. L., J. E. Bullard, G. H. McTainsh, C. Dubois, and M. C. Baddock (2010), Impact of wildfire on interdune ecology and sediments: An example from the Simpson desert, Australia, *J. Arid Env.*, *74*, 1577–1581, doi:10.1016/j.jaridenv.2010.05.032.

Strong, C. L., K. Parsons, G. H. McTainsh, and A. Sheehan (2011), Dust transporting wind systems in the lower Lake Eyre Basin, Australia: A preliminary study, *Aeolian Res.*, *2*, 205–214.

Sturman, A., and N. Tapper (2006), *The Weather and Climate of Australia and New Zealand*, 2nd ed., pp. 541, Oxford Univ. Press, Melbourne.

Timbal, B., and R. Fawcett (2013), A historical perspective on southeastern Australian rainfall since 1865 using the instrumental record, *J. Clim.*, *26*, 1112–1129, doi:10.1175/JCLI-D-12-00082.1.

Tozer, P. (2012), The cost of Red Dawn to the NSW economy, presented to the Australian Agricultural and Resource Economics Society Annual Meeting, Fremantle, 8–10 Feb.

Tozer, P., and J. Leys (2013), Dust storms: What do they really cost?, *Rangeland J.*, *35*, 131–142.

Tramutoli, V., C. Filizzola, F. Marchese, G. Mazzeo, R. Paciello, N. Pergola, C. Pietrapertosa, and F. Sannazzaro (2010), A Robust Satellite Technique (RST) for dust storm detection and monitoring: The case of 2009 Australian event, in IGARSS 2010, *IEEE Int. Geosci. Remote Sen. Symp., Proc.*, *5650621*, 1707–1709.

Ummenhofer, C. C., M. H. England, P. C. McIntosh, G. A. Meyers, M. J. Pook, J. S. Risbey, A. Sen Gupta, and A. S. Taschetto (2009), What causes southeast Australia's worst droughts?, *Geophys. Res. Lett.*, *36*, L04706, doi:10.1029/2008GL036801.

Uno, I., K. Eguchi, K. Yumimoto, T. Takemura, A. Shimizu, M. Uematsu, Z. Liu, Z. Wang, Y. Hara, and N. Sugimoto (2009), Asian dust transported one full circuit around the globe, *Nat. Geosci.*, *2*, 557–560, doi:10.1038/ngeo583.

Verdon-Kidd, D. C., and A. S. Kiem (2009), Nature and causes of protracted droughts in southeast Australia: Comparison between the Federation, WWII, and Big Dry droughts, *Geophys. Res. Lett.*, *36*, 22, doi:10.1029/2009GL041067.

Verdon-Kidd, D. C., A. S. Kiem, and R. Moran (2014), Links between the Big Dry in Australia and hemispheric multi-decadal climate variability—Implications for water resource management, *Hydrol. Earth Syst. Sc.*, *10*, 13,539–13,593, doi:10.5194/hess-18-2235-2014.

Washington, R., M. Todd, N. J. Middleton, and A. S. Goudie (2003), Dust-storm source areas determined by the Total Ozone Monitoring Spectrometer and surface observations, *Ann. Assoc. Am. Geogr.*, *93*, 297–313, doi:10.1111/1467-8306.9302003.

Zhang, B., A. Tsunekawa, and M. Tsubo (2008), Contributions of sandy lands and stony deserts to long-distance dust emission in China and Mongolia during 2000–2006, *Global Planet. Change*, *60*, 487–504, doi:10.1016/j.gloplacha.2007.06.001.