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Review article

Airborne dust traffic from Australia in modern and Late Quaternary times

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ABSTRACT

A review is provided of first-documented occurrences of dust transport within Australia for the last century, but which later on were considerably improved as a result of access to satellite observations and extensive ground observations. This was followed by the use of the HYSPLIT tracking models that enabled people to determine the major sources of dust in Australia. As a result of several important studies, the Lake Eyre Basin in central Australia is now considered to be the main source of dust entrainment, although other regions do contribute to dust production.

This is followed by examination of the occurrence over the last few decades of dust transport and deposition within Australia and across the Tasman Sea, with dust being deposited even as far as New Zealand. After that, consideration is given to the deposition of dust not only at sea around Australia but also in New Zealand during the Holocene and Late Quaternary. As a consequence of these observations, a shift in the direction of dust plumes exiting Australia is noted. For example, during the Last Glacial Maximum (LGM), a substantial northerly shift of the Trans-Tasman dust plume is recorded and this coincides with stronger westerlies and an equatorward shift of oceanic fronts such as the Intertropical Convergence and Subpolar and Antarctic Fronts that were located closer to Australia compared to today. Strengthening of the winds during the LGM may have prevented dust plumes from travelling over the southern part of the Tasman Sea, even perhaps reaching Antarctica. Examination of the dust components in cores in the western Pacific Ocean would address this question.

The second part of the paper examines the geochemical fingerprints of dusts from Australia, South America and those recovered from Antarctic ice cores.

Examination of atmospheric conditions that prevailed in the Southern Ocean around Antarctica during a major dust storm event that occurred in Australia in October 2002 helps identify how dust can be entrained around cold fronts and eventually reach the Antarctic mainland.

Once again, it appears that Australian dust did travel as far as Antarctica more frequently during the Holocene, than prior to that time. New Zealand as a dust source to some Antarctic sites is also discussed. Examination of the isotopic fingerprints in Antarctic ice cores point to South America being the main source of dust during the Last Glacial Maximum and previous glacial periods, with intermittent occurrences likely to have come from Australia and New Zealand as well. It is postulated that Australian dust plumes did travel mostly over the Tasman Sea, and eventually over the western Pacific Ocean during the LGM, and frequently less so towards Tasmania and the Southern Ocean as a result of the strengthening of the westerlies and their northward shift. It transpires that the dust flux from Australia was much higher during the glacial periods. It appears also that the dust plumes that traverse the eastern Indian Ocean remained unchanged during the LGM.

Finally, this paper concludes by identifying that there is a need to either obtain larger dust samples from ice cores, or use more elaborate analytical techniques to combine more than two isotopes to fingerprint the origin of dusts recovered in ice cores. Perhaps a combination of not only isotopes, but also rare earth elements and major elements would eventually provide a better definition of atmospheric circulation in the Southern Hemisphere for comparison between glacial and interglacial periods.

1. Introduction

Following a recent review of Australia as a potential source of dust and relevant source areas by De Deckker (2019), the logical step would be to assess the transport of dust from potential dust sources (PSAs) from the Australian continent so as to determine where and how the dust particles travel, and where they eventually end up. This is the purpose of the present paper. Before determining the whereabouts of

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Australian dust particles/deposits and Australian dust elsewhere, it is necessary to examine current knowledge on present-day dust events and storms in Australia, and identify where their 'products' end up. Following on from this, it is necessary to determine current knowledge on past dust transport within Australia and, following on from that, document occurrences of dust transport across the Tasman Sea and into the eastern Indian Ocean located off the coast of northwestern Western Australia.

The paper will then examine the chemistry of ancient dust samples recovered from ice cores in Antarctica and assess their links to PSAs in the Southern Hemisphere. Finally, an attempt will be made concerning atmospheric circulation during contrasting interglacial and glacial periods during which time dust was delivered to the Antarctic continent.

2. Present-day traffic in Australia and surrounding oceans

2.1. Early records before satellite imagery

Marshall (1903) and Chapman and Grayson (1903) were the first to discuss the evidence of dust deposited in the New Zealand Alps and documented the content of some of the dust that fell in several locations in Melbourne. In that paper, mention is already made of 'a shower of red rain' that also contained frustules of the siliceous diatom algae that fell over a large area of the state of Victoria. Additional evidence of rain containing red dust is presented for 1902, also in parts of Victoria, with an estimate of 50 tons of dust, with an estimate of 35.5 tons per square mile, having fallen on March 28, 1903. Other occurrences on the previous year are also discussed by Chapman and Grayson (1903) for dust falls in the states of New South Wales, Victoria and Tasmania (reported in *Nature*, 1903, vol. 67, p.203). These events coincided with an extensive drought period coined the 'Federation Drought' that lasted from 1896 to 1902. Chapman and Grayson (1903) reported on the presence of pollen and spores in the dust, including numerous pieces of vegetable (sic) tissue, as well as diatoms as already found in red rain that fell in 1896. These authors provide an ample list of recognised diatom taxa as well as bacteria. Finally, a detailed list of the minerals recognised in the dust is also provided.

Concerning dust traffic between Australia and New Zealand, Kidson (1930) had already addressed this issue based on evidence obtained during an earlier dust storm across the Tasman Sea in October 1928. This phenomenon is now better documented having access to satellite images and through evidence of dust deposited on the ground and on ice in New Zealand. This will be discussed further below.

Walker and Costin (1971) reported on dust deposition in the snowfield of the Australian Alps that occurred in 1968. They commented on the amount of dust fall in the area, but their information was too scant to come up with suitable values. They also reported on other dust falls in Australia prior to that event.

McTainsh (1989) in his important review of dust entrainments and their respective locations, discussed 7 events of Trans-Tasman dust transport between 1903 and 1987. For this 1987 event, he concluded that the dust storm was driven by a strong cold front that lifted 'soil' (sic) from 100,000 to 200,000 km^2 of the Simpson Desert, Channel Country and semi-arid woodlands of Queensland for some 18 h. McTainsh et al. (1989) also determined that between 6.3 and 5.5 10^6 tons of 'soil' were lost from the Australian continent, some of which (3 to 1.7 ton) traversed the Tasman Sea in its way to New Zealand. This author also looked at possible pathways for dust at sea around Australia based on knowledge of that time of sediment mineralogies found on the sea floor. He also discussed the possibility of exposed shelves during periods of low sea level, such as for the Great Australian Bight, that contributed carbonate-rich sediments deposited inland. McTainsh and Pitblado (1987) provided an important map of the annual frequency of dust events covering the period of 1957–1984 for the Australian continent. Further, McGowan et al. (2000) examined dust transport pathways between Australia and New Zealand and identified, especially for dust storms that occurred on May 23 and 24, 1994 trajectories were in fact quite diverse, even during a single weather event. These authors also suggested that both wet and dry deposition of dust may have occurred in May 1994, and that the dust plume on May 24 travelled first in a southeasterly direction into the Southern Ocean towards the centre of a strong depression. This type of pattern was also documented by De Deckker et al. (2010) for February 1, 2005 which is illustrated in their HYSPLIT simulation in their Appendix D.

For additional information on past dust events over the last century in Australia, refer to the review by De Deckker (2019).

2.2. Satellite images and HYSPLIT tracking

Characteristic examples of dust plumes exiting the Australian mainland are shown for different periods of the year in various panels of Fig. 2 and will bear relevance when discussing dust trajectories and dust traffic exiting the Australian mainland.

In a significant paper, McGowan and Clark (2008) used the Hybrid Single-Particle Lagrangian Integrated Trajectory Model (HYSPLIT-4) to categorise the active source of dust over the 1980–2000 period in central Australia for Kati Thanda-Lake Eyre (KT-LE) and the Lake Eyre Basin that encompasses it (Figs. 1, 2C). The trajectories consisted of 8 days starting from KT-LE at 500 m above the ground. Trajectory density maps were constructed for five different levels (0-500 m, 500-1000 m, 1000-1500 m, 1500-2000 m, and 2000-5000 m). These authors found that the trajectories can be achieved to far away distances within a few days. Nevertheless, the important findings are summarised here in Table 1 so as to clearly see that there are seasonal differences for the trajectories. McGowan and Clark (2008) also importantly pointed out that the highest concentration of trajectories of < 500 m originate from the NW of KT-LE in the austral summer. The surprise was to see that some air masses (likely to be laden with dust) travel in a northerly direction (Fig. 2C), and can reach parts of Indonesia, the Timor Sea, New Guinea and even southern parts of the Philippines. These authors also concluded that dust transport from KT-LE could reach Antarctica in the South as well as Pacific and Southern Oceans. Finally, McGowan and Clark (2008) indicated that on rare occasions trajectories that originate from KT-LE can reach the coast of northern Victoria and George V Lands in Antarctica and southern Chile in < 8 days.

Already, Bullard and McTainsh (2003) claimed that the Lake Eyre Basin is the most active dust storm region in Australia and up to 82 events per year had been registered. Their observations relied on MODIS images.

Bullard et al. (2008), using MODIS data of the Lake Eyre Basin (Fig. 1) determined that the source of dust for some 529 dust plumes that occurred over the 2003–2006 periods was 37% originating in areas of dust deposits, 30% where alluvial deposits occur and finally 29% from ephemeral and playa lake floors.

Strong et al. (2011) revisited the original idea that dust entrainment in Australia were linked to frontal systems, and found that for the period of 2005–2006 during which 160 dust event days wad been recorded that 51% were associated with fronts and pre-frontal troughs (with 35% associated with fronts and 16% with pre-frontal troughs), whereas heat troughs and high pressure systems were responsible (24% and 22%, respectively) for the remaining dust event days; only 3% of the days were associated with low pressure systems.

It is also necessary to consult the review by De Deckker (2019) that discusses two major dust events in Australia (October 2002 and September 2010) that attracted not only much media coverage, but also resulted in a vast array of scientific observations and papers (see De Deckker, *op. cit.*). These two events, which are now confined to what is called the 'Millennium Drought' (spanning the late 1990s to 2010 period), have been very well documented because satellite imagery now provides much information on dust pathways that could be linked to atmospheric conditions for the period of 2000–2009. O'Loingsigh et al.

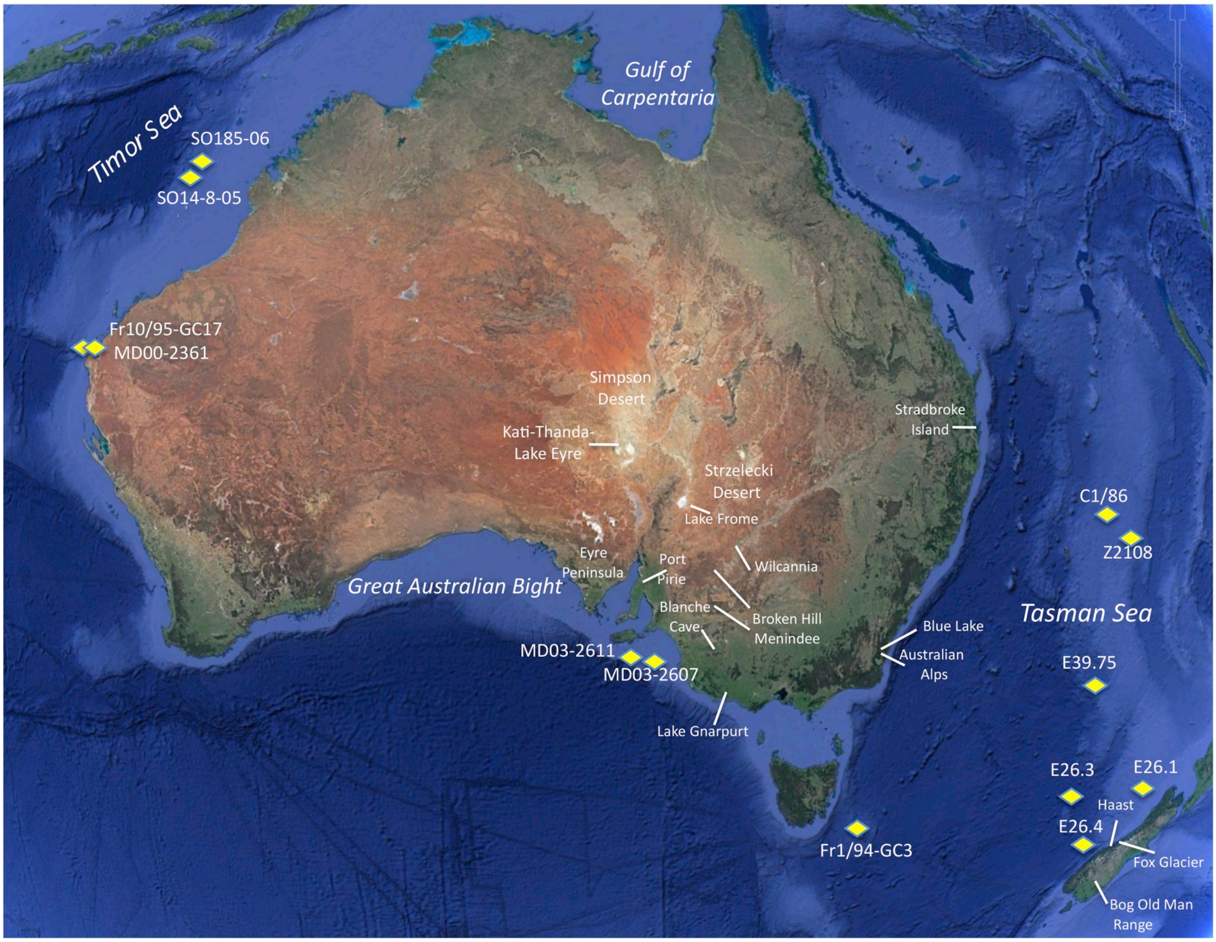

Fig. 1. Satellite map (courtesy of Google Earth©) showing the localities and core sites adjacent to Australia that are mentioned in the text.

(2017) examined the sources and pathways of air parcels using the HYSPLIT model backtracking for eastern Australian coastal cities and found a variety of 'routes' of dust pathways that reached eastern Australian coastal cities. In another study, going further back in time (75 years), O'Loingsigh et al. (2015) found that despite the intensity and extent of the Millennium Drought, wind erosion was much higher overall during the drought that occurred in Australian at the time of World War II. It is clear therefore that we cannot rely on recent events only to characterize dust events and conditions that caused them, especially when postulating for the past.

2.3. Geochemical evidence

McGowan et al. (2005), using a combination of trace and rare earth elements (REE), identified that dust deposited after a cold front in February 2000 on the Fox Glacier (Fig. 1) in the central southern Alps of New Zealand, originated from a variety of Australian locations, 20% from western NSW (Wilcannia and Menindee) and 45% from the Eyre Peninsula, with the remaining 35% from local New Zealand dust. This was further confirmed by Marx et al. (2005a, 2005b) who used a combination of some 25 trace elements not affected by atmospheric pollution, mineral sorting (such as Zr and Hf), and weathering/solubility. The same year, McGowan et al. (2005) showed that the average of atmospheric concentration of Australian dust reaching New Zealand is 5.3 $\mu g.m^3$. Obviously, this amount must vary between events.

Marx et al. (2008), in their examination of the scavenging processes of trace element pollutants that occur by mineral dust, determined for a number of sites in New Zealand, viz. red (6 samples) and grey (4 samples) dusts, plus in three dust traps, that in all cases an Australian origin of the collected dusts could be determined based on trace elements. All the samples had originated y from South Australia, the Murray Darling Basin and the Lake Eyre Basin.

It is noteworthy that Vallelonga et al. (2002) determined a major 'pollution event' at Law Dome in Antarctica (66°43′ 59.99″S 112° 49′ 59.99″E; Fig. 3) between 1884 and 1908 CE, where lead concentration had increased four-fold and the $^{206}Pb/^{207}Pb$ ratios in the ice had changed significantly from ice samples that were older at that site. These authors attributed the 'anomaly' to a direct contribution of aerosols containing Pb particles mined at Broken Hill and smelted at Broken Hill and Port Pirie (located on the coast of South Australia, Fig. 1). The transport of those particles occurred mostly during 'Federation Drought' that affected a large part of Australia. Significant drought conditions interspersed with heavy rainfalls had commenced as far back as 1894. By 1900 and 1901, monsoonal rains had failed in northern Australia, thus resulting from very different atmospheric conditions.

Deposition of Pb particles at Law Dome over the period described by Vallelonga et al. (2002) could not have occurred following the usual pathway of air masses originating from southeastern Australia. Already, using the HYSPLIT backtracking system referred to earlier in the paper, De Deckker et al. (De Deckker et al., 2010; see Fig. 4 and appendices A-E) showed that air masses exiting the southeastern Australian mainland (Fig. 2E) tend to move over the South Island of New Zealand, or south of it, before contouring Antarctica. It appears therefore that meteorological conditions would have been different during the 'Federation Drought' when Broken Hill Pb particles would have been transported to Law Dome. Allan et al. (1995) showed that there was a significant El Niño event in 1896 (with a strongly negative Southern Oscillation Index

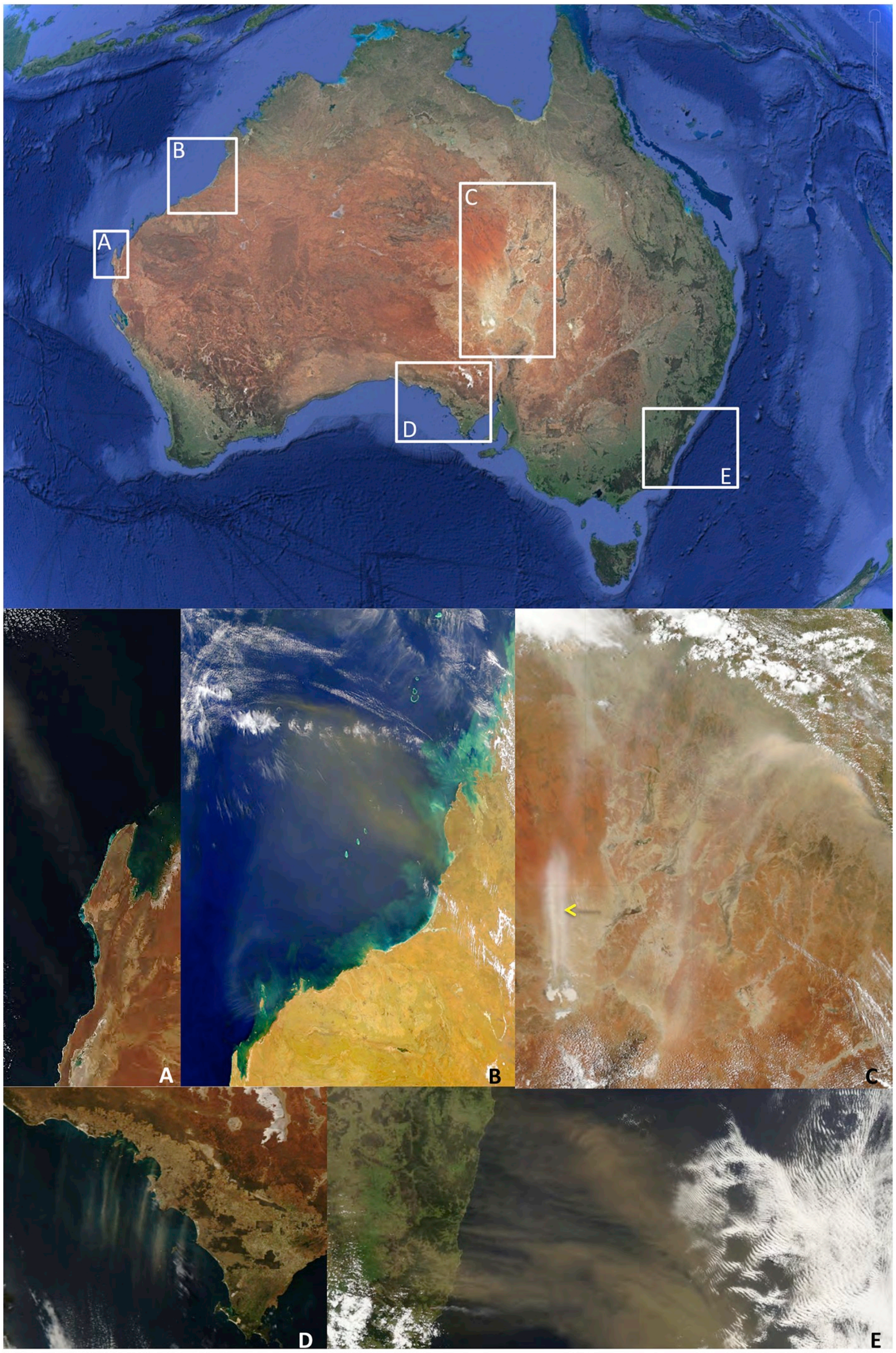

Fig. 2. Top panel: Satellite map of Australia (courtesy of Google Earth©) showing the locations of the enlarged photos illustrated in the lower panel which also shows satellite images (courtesy of NASA) with various dust plumes exiting from Australia (A, B, D, E) and from central Australia. A: photo taken on 1.8.2017 showing dust traversing the eastern Indian Ocean; B: photo processed from SEAWIFS by J. Schmaltz, taken on 29.9.1999 and showing dust traversing over the Timor Sea; C: photo taken on 2.2.2002; note the dust entrainment from the Kati Thanda-Lake Eyre traversing directly north; D: MODIS image obtained on 16.6.2008 showing dust plumes extending over the eastern portion of the Great Australian Bight; E: photo taken on 30.11.2006 showing dust traversing across the Tasman Sea.

(SOI)) followed by a reverse to positive SOI, but immediately there was a return to a negative SOI in 1900 with fluctuations later on, but with a very negative SIO in 1905. More information is also available in Gergis and Fowler (2009) who used the Coupled ENSO Index (CEI), which is a composite index for the identification of a period of 7 years of protracted El Niño events. Allan et al. (1995) identified what conditions operated in the Indian Ocean during these events that perhaps ought to be considered for further climate modelling so as to explain deposition of Australian dust over parts of Antarctica.

3. Movement of air masses and airborne dust in the Southern Hemisphere

Li et al. (2008), in their model-based paper for the entire Southern Hemisphere, identified the distribution, transport, and deposition of mineral dust in the Southern Ocean and Antarctica and identify that dust originating from Australia amounts to 120 ± 8.4 Tg a^{-1} [a value lower than postulated by Luo et al., 2003 which was 132 Tg a^{-1}, also model-based], whereas South America amounts to 50 ± 3 Tg a^{-1}, with Patagonia contributing up to 38 Tg a^{-1} annually (no particular season indicated). Third in the list is southern Africa which amounts to 34 Tg a^{-1}, with most of the dust contribution occurring between July and January. Li et al. (2008) indicated that dust emission in Australia peaks from October to March, being the warmest months. In addition, Li et al. (2008)' model identifies a 4th source of dust originating from the northern hemisphere, some 31 ± 4 Tg a^{-1} coming predominantly from North Africa. Importantly, Li et al. (2008) identify that the 'source regions between 15° and 50°S account for nearly all the emissions in the

Table 1
Summary of the seasonal pathways of airmasses originating from the Lake Eyre Basin based on HYSPLIT-reconstructed trajectories calculated by McGowan and Clark (2008) for the 1980–2000 period. ITCZ = Intertropical Convergence Zone; KT-LE = Kati Thanda-Lake Eyre.

Austral season	Months	Height of trajectory density	Reaching
SUMMER	Dec-Feb	< 500 m	1. entire Australian continent 2. extending to southern Tasman Sea, Timor Sea and southern Indonesian Islands
		2000-5000 m	1. east of New Zealand, and to South Pacific and Southern Oceans 2. over Indonesia and New Guinea 3. after 8 days, can pass over the coast of northern Victoria and George V Land and southern Chile
AUTUMN	March–May	< 500 m	1. highest concentrations over the northwest of the Australian continent 2. can reach Indonesia, New Guinea and New Zealand
		500-2000 m 2000-5000 m	Greater meridonal and zonal transport to the south and southeast into the Southern and South Pacific Oceans reaching coastal waters of Antarctica between 120°E and 75°W, as well as northen Victoria and George V Lands
WINTER	June-Aug	< 500 m	1. trajectories of 1–50 per 10 m^2 affect nearly all of Indonesia, +Borneo and Midanao within < 8 days leaving the Lake Eyre Basin and is due to the repositioning of the ITCZ which is north of the equator 2. significant air parcel reaching Southern Ocean south of Australia + New Caledonia
		500-1000 m	Can reach New Caledonia
		All levels	Trajectory densities of > 25 per 10 m^2 affect the Tasman Sea and New Zealand, with densities of 1–25 per 10 m^2 mapped as far as 90°W cover a large part of the Pacific and Southern Oceans
SPRING	Sept-Nov	< 1000 m	Highest concentrations of trajectories centered on Kati Thanda-Lake Eyre and central Australia
		> 1000 m	1. trajectory densisites of 1–25 per 10 m^2 over most of SE Australia and much of Tasman Sea 2. trajectory densisites of 1–25 per 10 m^2 also affect coastal waters of Antarctica between 120°E and 150°W and east to 75°W 3. a significant number of trajectories pass over southern Chile and Argentina with < 8 days of leaving their KT-LE above 500 m 4. other trajectories pass over Wilkes and George V Land.

Southern Hemisphere (199 Tg a^{-1})'. These authors also state that only a minimal fraction (0.06 Tg a^{-1}) reaches inland Antarctica. It is that tiny fraction that concerns the work presented here! In addition, these authors discussed the importance of identifying the vertical distribution of dust in the troposphere in the southern hemisphere, and critical to our investigations here on dust reaching Antarctica is that the highest concentration of dust above Antarctica occurs in the upper troposphere between 400 and 200 mb, whereas in the Southern Ocean it is between 800 and 600 mb, with even lower altitudes for dust originating from South America (being the boundary layer, see Fig. 7 in Li et al. (2008)).

Krinner et al. (2010) conducted another examination of atmospheric transport of dust and concluded that Australian 'tracers' (sensu Krinner et al., 2010) are transported to/over Antarctica at higher altitudes compared to those from South America. This is in line with the findings of Li et al. (2008). Further, this is confirmed by the observations made by De Deckker et al. (2010); (Fig. 4) and maps in appendices, plus check the different coloured dots that relate to different altitudes) who produced HYSPLIT maps for major Australian dust events, and the plots show that it is only through the upper atmosphere that air parcels commonly reached Antarctica. Krinner et al. (2010) further stated that their models showed a more vigorous atmospheric circulation at the LGM and that low-level transport was also stronger at the LGM, a contrasting conclusion from what Krinner and Genthon (2003) had proposed earlier.

Neff and Bertler (2015) conducted an extensive examination of HYSPLIT trajectories spanning the period of 1979 to 2013 and they used 10-day forward trajectories. They point out that dust particles within a range 0.1 to 2.5 µm diameter range can travel up to 10 days. In the case of Australia, their point of origin for air masses was centered on Kati Thanda-Lake Eyre (centred on 29°S, 137.5°E).[1] Nevertheless, the study of Neff and Bertler (2015) convincingly identified that dust from Patagonian and New Zealand, as well as other aerosol emissions, occur during all seasons. In addition, they point out that New Zealand can potentially be a source of PSAs to the Southern Ocean and to West Antarctica in particular (their HYSPLIT point of origin being 43°30′S, 172°E west of Christchurch on the South Island, between two major rivers that drain the Southern Alps, the Waimakariri and Rakaia Rivers) and, in fact, sample NZ7 analysed by Delmonte et al. (2004) originates from the headwaters of the Rakaia River and that is now shown to have a Holocene Sr and Nd isotopes ratio signature for a sample from the EDC core.

Furthermore, Neff and Bertler (2015) provide an important table (Table 1) which compares the PSA contribution of total dust deposition in both the Southern Ocean (SO) and Antarctica [ANT at > 70°S]: it points out that the percentage of Patagonia PSA (with the source point being located at 49°S, 69°W) contributes to 55.8% to SO and 58.5% to ANT, Australia with 36.1% to SO and 32.9% to Antarctica, South Africa (source point located at 28°S, 21°E) with 8.1% to SO and 2.9% to ANT, and finally New Zealand with 6.3 to SO and 13.7 to ANT. These figures vary somewhat with the estimates provided by Li et al. (2008), for Patagonia and Australia, so refer to Table 1 in Neff and Bertler (2015). Pertinent to this study, these authors stated: "although source-weighted trajectories from the Australian dust PSA exhibit some dominance at Vostok, South Pole, and especially the EDC ice core site, Australian trajectories arrive at EDC as soon as 4 days after initiation, while transport to Vostok and South Pole takes more than 8 days". In addition, at coastal Antarctic sites, such as Law Dome the Australian and South African components are large and significant, respectively (Neff and Bertler, 2015). On the other hand, at Talos Dome (Fig. 3), the New Zealand contribution is the most dominant source of unweighted trajectories (Neff and Bertler, 2015). Dust contribution to the West Antarctic Ice Sheet is not discussed here as Neff and Bertler (2015) indicated little contribution of Australian PSA. Australian dust contribution to Antarctic ice will be discussed further in this paper.

Finally, examination of Figs. 1 and 2 j-l in Neff and Bertler (2015), shows that quite a large number of trajectories that commenced at Kati Thanda-Lake Eyre traversed towards the Indian Ocean and were at relatively low elevation (eg. being mostly concentrated below 600 hPa, P. Neff. pers. comm. 2018 to the author).

4. Dust traffic from and within Australia in the past

4.1. Evidence of dust transport within Australia

Stanley and De Deckker (2002) studied a core taken from the Alpine

[1] It is unfortunate that Neff and Bertler (2015) did not centre their examination of HYSPLIT data at 27°30"S because this region is clearly more prone to deflation, being the upper portion of Kati Thanda-Lake Eyre North where fluvial deposition occurs during and after flood events.

Blue Lake in the Snowy Mountains of eastern Australia (Fig. 1) and recorded the deposition of aeolian quartz grains during the Holocene. These authors did not assess the origin of the grains, but postulated that they likely came from the southwest, such as the Mallee region, and that climatic instability was found for the last 3.5 ka, with the largest quartz grains deposited since 1.6 ka, indicating that storminess was more predominant during that period, with stronger storms carrying larger aeolian grains.

Marx et al. (2011) studied the geochemical composition in a Holocene sequence of an Alpine mire in the Australian Alps (36.463°S, 148.299° E, 1940 m asl) that does not deal with Trans-Tasman transport. It is discussed here as it showed that - based on trace elemental composition - the dust was delivered via the westerly wind belt during a low phase of the Southern Annular Mode (Marshall, 2003), resulting in a reduction of precipitation in the southern portion of the Murray Darling Basin, that led to an increase in dust entrainment and transport.

Petherick et al. (2009) studied a core from Companion Lake on Stradbroke Island (Fig. 1) located offshore SE Queensland that spans a 25 ka record and which provides a record of dust deposition. These authors, using a combination of some 16 trace elemental fingerprints from central and eastern Australia, identified not only the provenance sources of the various dust events which varied quite considerably, but also the dust fluxes through time. The sources of dust varied from local ones (mostly during a large part of the Holocene) to central, southern and southeastern Australia (refer to Petherick et al., 2009, Fig. 12). Of particular interest is that the dust flux was > 3 times larger during part of the LGM (~21 ka) than for other periods.

Darrenougue et al. (2009) studied a late Pleistocene deposit from Blanche Cave near Narracoorte in South Australia (Fig. 1) which accumulated as a result of a cave roof collapse. The high-resolution and layered sequence consists in fact of aeolian material that trickled into the cave. These authors examined quartz grain morphology, XRF analyses as well Nd isotopic ratios of the aeolian material recovered from a stratified deposit spanning the period of ~40 to 14.6 ka. Their findings suggested a change a wind direction during this period of time, based on the εNd values recovered from the sediment. Already, Sprigg (1979), who examined the pattern of ancient dune fields in southern and south-central Australia (including northern Tasmania), pointed out these were active during the "glacial' period (*sic* Sprigg, 1979). In addition, the same author identified an equatorward shift of > 5° that is apparent in the southerly stream of dune-forming prevailing winds compared to those of the present 'interglacial' phase (sic)". This will be further discussed later in the paper.

4.2. Trans-Tasman traffic east of Australia

Hesse (1994) was the first to assess the flux of aeolian dust from Australia recorded in core sediments (Fig. 1; green dots) from the Tasman Sea, east of Australia spanning the last 350 ka. He found: (1) an increase during glacial stages; (2) that through a transect of five cores dust fluxes are low north of 33°S, and increasing southward to ~40°S; and (3) that during glacial periods, there had been a 3° (perhaps < 6°) latitudinal shift to the northern boundary of the dust plume which he interpreted to have been dictated by the north boundary of the subtropical ridge (STR). Today the STR, which divides the tropical easterly circulation from the mid-latitude westerlies, is located at 35°S in summer, but it is more northerly at high altitude. Importantly, also, Hesse (1994) established that the dust flux to the Tasman Sea had increased by 1.5 to 3 times resulting from a combination of stronger winds and a greater sediment supply. He also noted that from Marine Isotopic Stage 10 (MIS), there had been an increase in the dust flux from Australia. Earlier, Thiede (1979) examined the percentage of quartz content in some 18 dated cores from the southwest Pacific Ocean, but unfortunately his results were never published, except for one core Z-2108 (Fig. 1). Nevertheless, Thiede (1979) provided a map (his Fig. 3) which clearly identifies an extended zone of high quartz content (> 20%) in the Tasman Sea and that curved around the northern end of New Zealand for the period corresponding to the LGM. In support of Bowler (1976)'s classic map (his Fig. 1) that showed the pathways of Australian dust extending both into the Tasman Sea and the eastern Indian Ocean, Thiede (1979) also found a tongue of equally high quartz concentration extending east of New Zealand. The same author then concluded that the northerly shift of the 'dust/quartz-rich plume' in the Tasman Sea to the north of New Zealand would also imply a shift of the westerlies, that in turn would imply a northerly shift of the subtropical convergence. In fact, such a shift was later confirmed by Martinez (1994) who examined a north-south transect of deep-sea cores in the Tasman Sea that clearly identified a northerly shift of the Tasman Front (= Subtropical Divergence and located ~30°S) by 4° during the LGM; these shifts will be further discussed later in this paper. This was confirmed by Bostock et al. (2006) who, based on core studies in the Tasman Sea, showed that the Tasman Front had shifted from 34°S to 26–23°S during the LGM. This was attributed by these authors to a weakening of the subtropical trade winds and a northward movement of stronger westerlies in the region.

Returning to Hesse's (1994) study, confirmation of the aeolian nature of the fine fraction recovered from his core E26.1 located on the eastern side of the Tasman Sea close to New Zealand (Fig. 1) was provided by Revel-Rolland et al. (2006) who measured the Sr and Nd isotopic composition of 2 samples from the core (E1 dated at ~4.5 ka and E-8 at < 18.8 ka)) which have isotopic signatures very similar to those obtained from the Lake Eyre Basin. Note that Hesse in Fitzsimmons et al. (2013; see supplement Tables S4, 5) revised the chronology and the dust mass accumulation rates for core E26.1 extending ~back to 44 ka (18 samples).

Hesse and McTainsh (1999), re-visited Hesse (1994) study and concluded that there were not necessarily stronger winds during the LGM, but instead that the activation of the deserts over 40% of Australia was the result more arid conditions and that sand movement was activated by the absence of vegetation in dune fields.

McTainsh and Lynch (1996) further examined conditions that occurred during the LGM and identified that dust activity had increased by some 57% in the northeastern Australia and 52% in southeastern Australia compared to the present day. They also concluded that the dust storm seasons were lengthened and dust paths modified. This further confirms the earlier finding of Hesse (1994).

Ash and Wasson (1983), who assessed today's presence of vegetation and sand mobility in Australian desert dunefields, postulated during the last glacial period windiness in the arid zone must have increased by some 20 to 30%. This, with an increase in evapo-transpiration - that would have prevented vegetation growth on the dunes - would have caused large dune fields to become mobile.

Marx et al. (2009) assessed long-range transport of Australian dust over the last 8 ka in a peat bog (Fig. 1) in the south-central part of the South Island of New Zealand and found four distinct Australian-sourced dust periods during the Holocene, with varying composition. Finally, these authors estimated that Australia contributed > 5 kg m^{-2} over the Holocene, and that during the middle Holocene 1.4 g m^{-2} yr^{-1} reached New Zealand. These are quite substantial figures, although much lower than what comes out of western Africa.

Finally, Marx et al. (2009) used trace-element chemistry to identify the timing of dust deposition in a New Zealand peat bog over the last ~8 ka. They confirmed that there are significant climatic controls on dust entrainment at the source (in this case, it was Australia) and during periods of increased ENSO variability (wet periods (La Niña) assumed here for fine particles deposition in PSAs and dry periods (El Niño) facilitating the dust entrainment). These authors suggested that dust deposition in New Zealand increased > 4-fold after 4.8 ka when Australia became prone to aridity and climate variability (note: their chronology is only based on three ^{14}C dates, with only one (5.16 ka) close to the event of interest).

Revel-Rolland et al. (2006), using a combination of Sr and Nd isotopes, studied a great variety of dust samples from central and eastern Australia, as well two samples from one of the cores (E26.1) from the Tasman Sea (see discussion above). This seminal paper discussed the possible occurrence of Australian dust recorded in Antarctic ice cores.

4.3. Dust traffic offshore southern Australia

Gingele et al. (2007) studied in detail the last 17 ka record of a deep-sea core (MD03–2611, see Fig. 1) located offshore of Kangaroo Island, east of the Great Australian Bight that is considered still to be bathed by the southeastern Indian Ocean. A series of proxies were used, including clay mineralogy, XRF analyses of the clay fraction and the Sr and Nd isotopic composition of the same fraction. The outcome has been the discovery of a delivery of aeolian dust material to the core site from 5 ka, but dust was also recovered from the core before that time. Gingele et al. (2007) showed also that the evidence of aridity follows the trend already recognised at Blue Lake (Fig. 1) by Stanley and De Deckker (2002), confirming therefore that the Holocene, regarded as a much warmer phase than the previous glacial phase, and that the second half of the Holocene saw much dust entrainment that coincided with a progressive decrease of some 2 °C in sea-surface temperature (Calvo et al., 2007; Lopes dos Santos et al., 2013). In addition, Gingele et al. (2007) sourced the dust that was deposited above the core site and it was from the southwestern portion of South Australia, not the MDB.

De Deckker (2014) complemented these findings by using the increase of yttrium in the same core to confirm the supply of airborne dust to the core site. In addition, he was able to determine the provenance of the dust deposited over the core site, using a combination of Sr and Nd isotopic ratios, for before and after 11 ka.

For another deep-sea core MD03–2607 (Fig. 1), located some 60 km from core MD03–2611 mentioned above, De Deckker et al. (2012) reported a significant deposition of dust at the core site as recognised by two proxies: (1) continuous XRF analyses of the core detailing the total counts per second of titanium as well as iron and (2) the percentage of quartz obtained by X-ray diffraction. The deposition of aeolian material at sea commenced ~28 ka and was completed by 18 ka. That period also saw much fluctuation, with a drop in dust deposition peaking at 24 and 21 ka, and very high values continuously for the 20 to 18 ka period, and another peak at ~22 ka. These authors did not specify the original source of the dust, but importantly identified that both the Subantarctic Front (SAF) and Polar (PF) Fronts had significantly shifted northward towards the Australian continent. This will be further discussed in the paper.

De Deckker et al. (2019a,b) studied in great detail a short deep-sea core (Fr1/94-GC3; see Fig. 1) obtained offshore eastern Tasmania. This core spans the last four glacial/interglacial cycles, and goes back to 450 ka. The aeolian component deposited at sea was established, once again through XRF scanning as well as by the presencte of quartz grains (> 60 μm). The surprise was to discover that most of the aeolian material deposited over the East Tasman Plateau, from where the core was obtained, occurred during the interglacials and the interpretation here is that airborne material was deposited when the intertropical convergence was located at quite some distance from southern Australia. During glacials, this oceanic front and others such as the SAF and PF were all compressed against the southern margin of Australia and Australian dust plumes could not travel in a southerly direction as the westerlies were very strong. Dust plumes travelled more in an easterly direction, as well as in a northeasterly direction as documented by Hesse (1994) and Thiede (1979). This will be discussed further in the paper. De Deckker et al. (2019a, 2019b) interpreted the larger quartz grains to indicate stronger winds and their findings are that winds on average were stronger during glacial periods, and interestingly the LGM was found to have the lowest grain sizes for any of the last four glacials.

4.4. Evidence of dust transport into the eastern Indian Ocean, NW of Australia

Stuut et al. (2014) studied the 550 ka record of core MD00–2361 located in the eastern Indian Ocean (Fig. 1), offshore Exmouth in NW Western Australia. They used two proxies to determine aeolian input offshore: (1) the presence of wind-blown terrigenous quartz in 438 samples, and (2) the log (Zr/Fe) determined by XRF scanning of the upper 13.5 m of the core (covering 550 ka). The findings are that especially during glacial periods, back to MIS 14, a vast amount of aeolian material was deposited at sea at quite some distance from land. A new record spanning the last 1 Ma for the same core has recently been submitted for publication, and further confirms the export of aeolian material offshore NW Western Australia. Ehlert et al. (2011) who examined the radiogenic component using a combination of Nd, Pb and Sr isotopes of clay-sized detrital samples obtained from core Fr10/95-GC17, located close to the site of core MD00–2361, spanning the last 25 ka of deposition showed a broad change of isotopic composition for all 3 isotopic ratios during the LGM (compared to the Late Holocene) which were attributed to oceanic changes offshore the northwest shelf of Western Australia. *Re*-examination of the data could possibly show an input of aeolian material from the Australian dune fields located close to the Australian coast (see figs. 22–24 in De Deckker, 2019) or perhaps even further inland. This will require further investigation.

Kuhnt et al. (2015) examined a set of cores located further to the east in the Timor Sea with a record of deposition spanning the last 25 ka and, again using XRF scans, these authors showed broad fluctuations of a dust input to the Timor Sea using ln((Zr + Ti + Fe)/(Al + K)) as a proxy for airborne dust. The detected patterns point to much variation in a broad period of dust deposition during the 25 to 15 ka period, and also a broad and substantial dust input to the ocean between 7 and 4 ka. This phase coincides with the onset of ENSO recognised by Perner et al. (2018) in a high-resolution core south of Australia. Hopefully, radiogenic isotopic analyses in the key core (SO185–18506; see Fig. 3 in Kuhnt et al., 2015; Fig. 1) in the Timor Sea will one day enable us to identify the source areas of the dust recovered in that core. Already, Hesse in Fitzsimmons et al. (2013; see supplement Tables S2, 3) detailed the dust mass accumulation rates for an adjacent core (SO14–08-05; Fig. 1) spanning the last 42 ka covered by only 16 samples.

5. Previous work examining sources of dust in Antarctic ice cores

Delmonte et al. (2004) were the first to examine in great detail the source of dust in the two principal Antarctic ice cores from Vostok and EPICA-Dome C (referred to from now as Dome C (Fig. 3). They concentrated on a combination of two isotopic ratios, that of Sr and Nd. Their conclusion was that: *"South Africa and Australia can be excluded as dominant sources, but a partial overlap arises among southern South America, New Zealand and the Antarctic Dry Valleys isotopic fields"*. To come to that conclusion that was already stated for Australia by Basile et al. (1997), it is necessary to point out that the comparison with the Australian PSAs, only the very few analyses of Grousset et al. (1992) and Basile et al. (1997) were available at that time.

In 2008, Delmonte and co-authors re-examined the record of both ice cores mentioned above for glacial periods, this time having access to the analyses for eastern Australian dusts presented in Revel-Rolland et al. (2006), and concluded that for glacial periods, a mixture between South American and Australian PSAs could be considered, with still a dominance from Patagonia. For elsewhere in Antarctica, Delmonte et al. (2010; 2013) examined the composition of the dust recovered from the Talos Dome ice core (TALDICE) (Fig. 3) and concluded that Australian PSAs ought to be excluded from the core, based on Sr and Nd analyses published by Revel-Rolland et al. (2006). In the meantime, Marino et al. (2008) examined the major elemental composition of dust in the Dome C ice core for the last glacial/interglacial cycle. They concluded, based on the analyses of some major elements for the glacial period, that there is a close correspondence between South American and Antarctic dust composition. However, for the Holocene, the dusts recovered from the ice core display high variability and that Australia could have been a source of the dust, based on analyses made by Gingele and De Deckker (2005) from some 26 samples obtained from the Murray Darling Basin. In fact, based on Sr and Nd isotopes, Revel-Rolland et al. (2006) had foreshadowed this possibility.

Further, Gabrielli et al. (2010) examined the REE composition of dust analysed from the Dome C ice core covering the 33.7 to 2.9 ka period. These authors noted a significant change of dust composition that commenced at 15 kyr BP that persisted in composition throughout the Holocene; this was attributed to a change in atmospheric trajectories. Gabrielli et al. (2010) also pointed out that for a period of some 600 years around 8 kyr BP, dust composition returned to that found for the glacial dusts. In addition, these authors determined that the Holocene REE signatures were indicative of Australian, New Zealand and South American signatures.

Wegner et al. (2012) further discussed the presence of REE in the EPICA Dronning Maud Land (EDML) core in the Atlantic sector Antarctica (Fig. 3) at decadal to centennial resolution, from 6.5 to 7.5 ka. Again, they found that from 26.5 to ~15 ka, the REE composition of the ice show a provenance from a South American source, but after that, Australian and New Zealand signatures are recognised, but that South America remains a the major dust source. Of interest is that compared to the dust record of Dome C (Gabrielli et al., 2010, *op. cit.),* no change is recorded during the return of glacial conditions around 8 ka.

Delmonte et al. (2017), in their argument that South American PSAs principally contributed to dust at Dome B, mentioned the presence of aragonitic particles as well as diatoms in association with the Dome B dust samples. These authors argued that the latter two indicated a contribution from the exposed Patagonian continental shelf and glacial outwash plains of southern Patagonia during periods of low sea level. After examination of the SEM photographs of the diatom frustules shown in Delmonte et al. (2017), the Australian diatomist expert Professor Peter Gell provided the following statement: "*Halamphora* spp. (syn. *Amphora*) is the new name for a benthic genus that exists in nearly all shallow salt lakes in south-eastern Australia. *Halamphora* would not usually be classified as 'freshwater'. The *Halamphora* in Fig. 6a of Delmonte et al. (2017) looks like *H. coffeaeformis* which is brackish to hypersaline" He also added: "I can certainly say that *Halamphora coffeaeformis*, *H. holsatica* and *H. veneta* are all extremely common in Australia (refer to Gell, 1997), and so these taxa cannot be used as evidence for an exclusively South American source".

In addition, although there is no illustration available of the aragonitic particles mentioned by Delmonte et al. (2017) (B. Delmonte, *pers. comm.*), I suppose here that they very likely pertain to the ubiquitous aragonitic spicules produced by ascidians (also called tunicates) that abound on the sea floor of all the continental shelves around the world, including Antarctica. Note also that a large part of the shelf facing the Great Australian Bight (Fig. 1) was also exposed during periods of low sea levels; amounting to ~4.8 10^6 km^2. In conclusion, the palaeontological information linked to the Dome B samples cannot be conclusively linked to a Patagonian Shelf origin. Interestingly, the single-grain mineralogical investigations by Raman spectroscopy performed by Delmonte et al. (2017) on four samples selected from the Dome B ice core and that are dated between between ~21.7 and 24.7 ka do not contain kaolinite, but very low percentages of chlorite clays. Nevertheless, muscovite was found in high % (12 to 21) in all four samples.

In favour of Delmonte et al. (2017)'s argument for negating a contribution of Australian PSAs for the four glacial samples is that the samples from the Murray Darling Basin analysed by Gingele and De Deckker, 2004, 2005 contained a high proportion of kaolinite, on average for the MDB 37.9% of the total clays. For the Darling sub-basin, this amounts to 41.2 ± 10.6% of the total clays. Magee et al. (1995) and Magee (1997) identified the presence of kaolinite in cores taken at the southern end of Lake Eyre at Williams Point as well as with sediments recovered from a cliff section, stated the following: 'all depositional environments around Lake Eyre, the clay is a variable mixture of kaolinite, illite, montmorillonite and inter layered montmorillonite/kaolinite. Kaolinite is always present, but rarely dominant, and the other clay species are much more variable and occasionally absent.'. Examination of Magee's various core sections show that the % of kaolinite is most often > 20% and may even reach values of > 70%. The sediments studied by John Magee were deposited during the last glacial/interglacial cycle, some of which would have been deflated later, and perhaps transported as far as Antarctica.

Delmonte et al. (2017) refer to the clay analyses performed by Gaudichet et al. (1986, 1988) on a few samples from the Dome C and Vostok ice cores. We note that in those publications, only 3 levels were analysed from the Dome C core and 6 from the Vostok core. In contrast with the work of Gingele et al. (2005), Delmonte et al. (2017) list the percentage of kaolinite of the total clays for the MDB, whereas the percentage of the clay species identified by Gaudichet et al. (1986, 1988), is that the percentages for the clays relate to the entire mineralogical suite. Of the 6 samples examined by Gaudichet et al. (1986) for the EDC core, three do not have kaolinite, whereas % of the total clays are: 10.5, 8.8 and 4.2. Those three samples span MIS1 and 3. None was taken from the LGM. For the 5 Vostok samples, Gaudichet et al. (1988) reported having not found any kaolinite. In the same paper, they reported on three additional Dome C samples and the kaolinite % of the total clays were 10.5, 8.8, and 0 respectively. The first two samples are aged 6 and 16 ka, respectively. In both papers, these authors reflected on the fact that Australia could not have contributed dust to the core sites, at least for the sampled horizons. These observations on so few samples call for additional investigations. At present, we have to agree with those analysed samples that an Australian source is not warranted, at least from the MDB, nor the Lake Eyre Basin. Of interest is that the samples referred to above from Dome B related to the LGM.

6. Comparison of isotopic fingerprints of Australian PSAs with those from Antarctic ice core dust layers

De Deckker (2019) documented the location of all the samples examined in Australia from regions considered to be Potential Source Areas (PSA) of airborne sediments and with geochemical characteristics worthy of comparison with analysed Antarctic ice core samples. Because, on average, the dust particles that are recovered from Antarctic ice cores are extremely fine (< 2 μm), it is necessary to be aware that the investigations carried out by other groups of researchers on Australian samples, their analyses bear less interest for comparison with ice cores geochemical analyses for several reasons: (1) the fine fractions (< 2 μm) were not analysed; (2) the relevant isotopes of Sr, Nd and Pb have not been reported. Nevertheless, it is still necessary to consult the contributions by Kamber et al. (2005), Marx et al. (Marx et al., 2005a, 2005b; Marx et al., 2009; Marx et al., 2011; Marx et al., 2014), Petherick et al. (2009) and Marx and Kamber (2010) for a vast number of Australian PSAs. In addition, the paper by Martin and McCulloch (1999), that examined the Sr and Nd isotopic composition of soils in the catchment of the Namoi River (located in the upper part of the Darling sub-basin), identified the possible 'contamination/contribution' by fertilizers which have their unique chemical composition, some of which bear Tertiary oceanic signals since some phosphate fertilizers originate from oceanic islands in the Pacific and Indian Oceans and/or Florida. Obviously, anthropogenic contamination needs to be considered when assesssing PSAs.

In addition, figs. 27–30 presented in De Deckker et al. (2019a, 2019b) which show the geochemical characteristics of the Australian PSA samples that will be used here for comparison against South American PSAs and dust samples recovered from Antarctic ice cores.

Fig. 3 shows the location of all the ice core sites in Antarctica, plus the majority of the Australian and South American PSA sites of relevance to the discussion below.

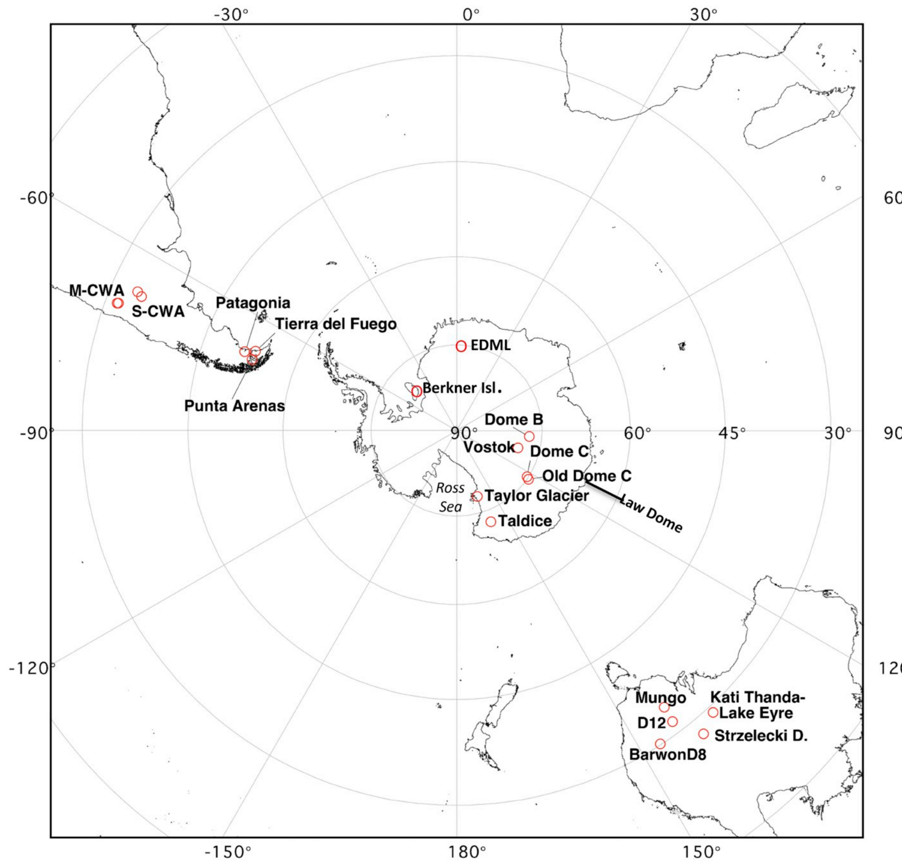

Fig. 3. Map showing in a polar projection the location of the sites in Antarctica discussed in this paper as well as those sites both in Australia and South America that share similar isotopic ratio values. This is to aid in visualizing the pathways of dust towards Antarctica. See discussion in the text and Fig. 13.

6.1. *Comparison of Australian and South American PSAs concerning Sr and Nd isotopes*

Fig. 4 provides a plot of εNd versus $^{87}Sr/^{86}Sr$ signatures for Australian samples from the Lake Eyre Basin and Darling sub-basin which share affinities with those described by Delmonte et al. (2004) and Gili et al. (2017) from South American PSAs. Here, those samples from the < 5 µm fraction for South America are plotted here [unfortunately, no data on the < 2 µm fraction was available]. The salient feature displayed in this figure is that few Australian and South American PSA samples plot close together. It will be necessary to plot individual measurements from the PSAs from the two continents so as to clearly identify individual analyses in contrast to what was done by Gili et al. (2016; Fig. 3C) who, for example, assembled all the Australian PSA

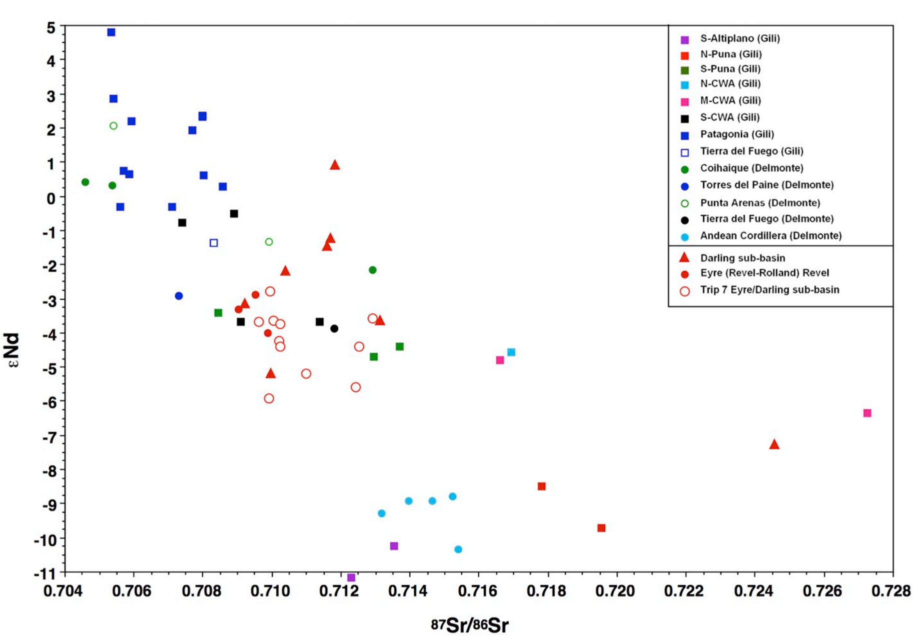

Fig. 4. Plot of eNd versus $^{87}Sr/^{86}Sr$ for all the Australian samples discussed in this paper, for all the South American samples with size fractions < 5 µm discussed in this paper, plus the Australian samples from around Kati Thanda-Lake Eyre, the Darling sub-basin of Gingele and De Deckker (2005) and those collected during trip 7. Abbreviations for the South American samples are: 'Gili' for Gili et al. (2017), and 'Delmonte' for Delmonte et al. (2004).

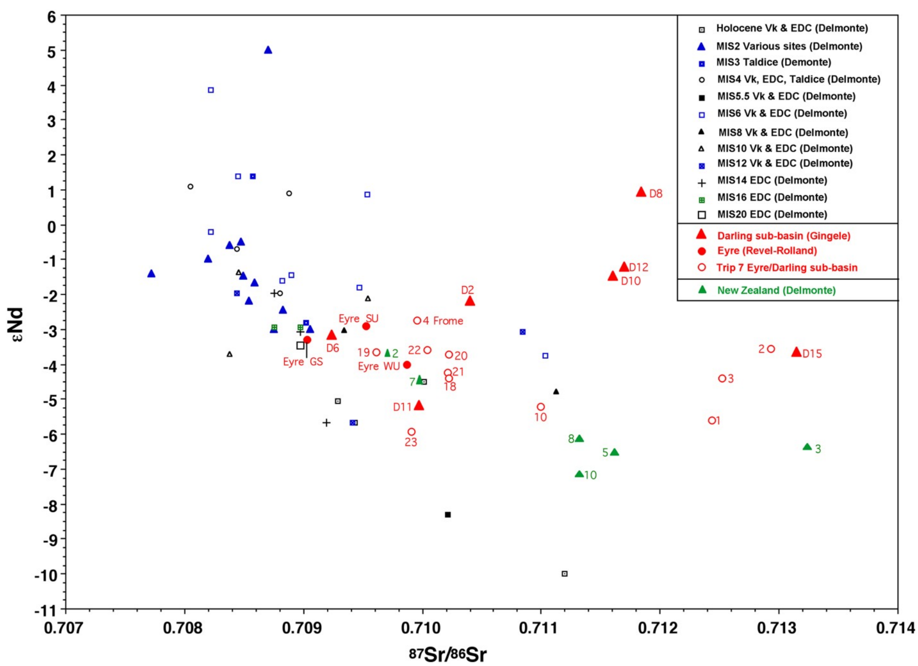

Fig. 5. Comparative plot of εNd versus $^{87}Sr/^{86}Sr$ for the Australian samples from around Kati Thanda-Lake Eyre, the Darling sub-basin of Gingele and De Deckker (2005) and those collected during trip 7, against the samples analysed by Delmonte et al. (2004) for Vostok (labeled as 'Vk'), Epica Dome C ('EDC') and Taldice ice core. Many of the New Zealand samples analysed by Delmonte et al. (2004) are also displayed on this figure. Those omitted did not plot within the boundaries of this diagram.

analyses into a single dot accompanied with large error bars that helped negate the geochemical affinity of Australian dust samples when comparing them with dust analyses from Antarctic ice cores.

6.2. Comparison of Australian Sr and Nd signals with those from Antarctic ice cores

Despite the fact that Bory et al. (2010), who had examined the Sr and Nd isotopic composition of snow layers at the top of Berkner Island ice sheet located at the southern end of the Weddell Sea, had claimed that possible input of dust in Spring snow could have originated from Australia, examination of Supplementary Fig. 1 shows this to be unlikely (except perhaps for one single sample from central South Australia), and this would also make sense in light of the position of Berkner Island ice sheet with respect to the Australian landmass and current atmospheric circulation.

Fig. 5 shows a plot of the εNd versus $^{87}Sr/^{86}Sr$ values for the Australian PSAs from the Darling sub-basin (from Gingele and De Deckker (2005)) and the Kati Thanda-Lake Eyre region (that includes the samples analysed by Revel-Rolland et al. (2006) and those from trip 7 discussed in De Deckker (2019)). The data published by Delmonte et al. (2004) also appear on that figure. The ice core samples span a variety of ages as shown by the figure legend which has different symbols for the different ages for the analysed core sections (MIS stands for Marine Isotopic Stages). Of interest also is that as a result of trips 2 and 7 in Australia, microbiological work was conducted in association with dust samples from a variety of PSAs (refer to Abed et al. (2012; trip 2), De Deckker et al. (2014) and Munday et al. (2016; trip 2 and 7)).

Delmonte et al. 's (2004) analyses of New Zealand samples are also plotted on Fig. 5. It is clear that only one sample (NZ7) plots close to a Holocene sample form Antarctica, whereas two samples Eyre GS and SU of Revel-Rolland et al. (2006) plot close to several Antarctic samples of different ages. In addition, sample D10, collected near Bourke in the Darling Riverine Plain (see De Deckker, 2019, figs. 19, 25) plot close to a glacial sample (MIS8) in Antarctica.

Fig. 6 shows another plot for the εNd versus $^{87}Sr/^{86}Sr$ values for the same list of Australian PSAs discussed above and these are compared with the data [for the same isotope ratios] for analyses of ice core levels from Dome B (Delmonte et al., 2017) and others from various locations on Taylor Glacier (Aarons et al., 2017). The samples concerning Dome B relate to the LGM, whereas the Taylor Glacier samples range from 4 distinct periods: Holocene, the deglaciation, the LGM and marine isotope stage 3 (< 44 ka to 24.4 ka). Note that the range of εNd values on this plot is smaller than in Fig. 4 due to the narrower spread of ice values. Of interest is that analyses from the ice cores plot closely to some of the Australian analyses. Concerning Dome B, which all have an MIS2 age, three samples share the same Australian PSAs based on the isotopic similarities. Despite the fact that Delmonte et al. (2017) point out that the absence of kaolinite in the Dome B LGM samples exclude Australia as a source of dust. This is despite the fact that quite a few samples from the Darling sub-basin, including from the Kati Thanda-Lake Eyre region, share similar ratios as for the Taylor Glacier samples. Nevertheless, we need to ignore this tentative isotopic 'link' as Aarons et al. (2016) argued that, for the Hococene sequence at the Taylor Glacier, the local source of dust is predominant, based on the radiogenic isotopic composition, as well as an increase in dust size particles.

6.3. Comparison of South American Sr and Nd signals with those from Antarctic ice cores

Fig. 7 shows a plot of the εNd versus $^{87}Sr/^{86}Sr$ values for the South American PSAs tabled in Gili et al. (2017) and which are reproduced here in Supplementary Table 1 which only lists those samples from the < 5 μm fractions. There are several samples from South American PSAs that have similar Sr and Nd isotope signals to those from ice cores analysed by Delmonte et al. (2004) for the Vostok, Dome C and Taldice ice cores. Two South American PSA regions analysed by Gili et al. (2017) stand out: the southern part of central-western Argentina (S-CWA) and Tierra del Fuego, with one additional sample from Punta Arenas that had been analysed by Delmonte et al. (2004). It is also obvious also that many other South American PSAs plot away from the Antarctic samples.

Fig. 8 provides a similar comparison as for the previous figure concerning Sr and Nd isotopes for South American PSAs plotted against the ice core data for Dome B (Delmonte et al., 2017) and the Taylor Glacier (Aarons et al., 2017), but a close up shows that only one sample from central-western Argentina (S-CWA) plots near one of the Dome B samples. All the other samples spread out away from the Antarctic samples.

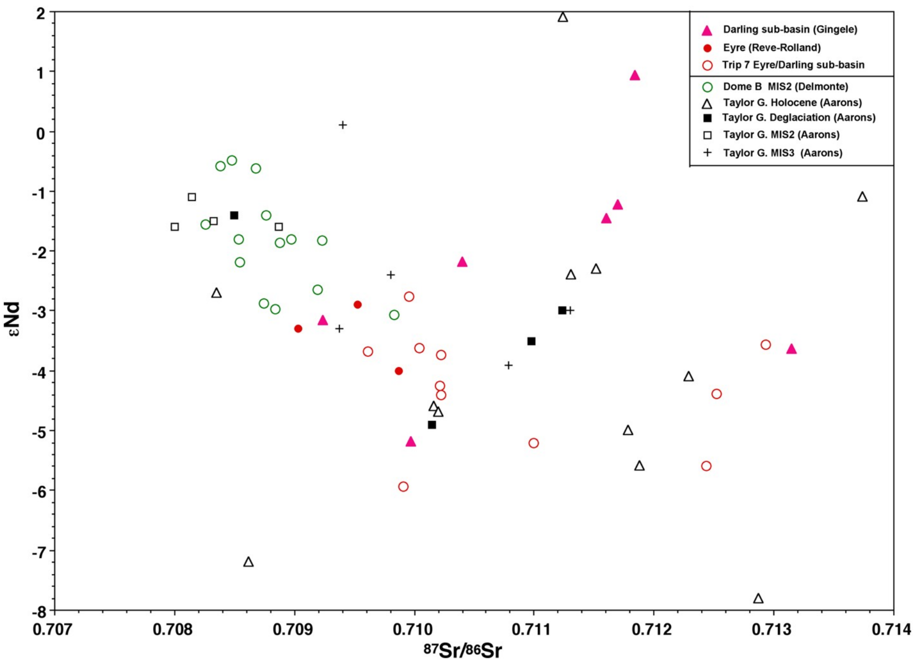

Fig. 6. Comparative plot of εNd versus $^{87}Sr/^{86}Sr$ for the Australian samples from around Kati Thanda-Lake Eyre, the Darling sub-basin of Gingele and De Deckker (2005) and those collected during trip 7, against the samples analysed by Delmonte et al. (2017) for Dome B, and for Taylor Glacier by Aarons et al. (2017).

6.4. Pb isotope signals - comparison between Australian and South American PSAs

In Fig. 9, it has been possible to update the comparison of Australian and South America PSAs with respect to Pb isotopes since the publication by Gili et al. (2016) which provides information on surficial samples. De Deckker et al. (2010), when comparing Pb isotope data between the two continents, had used information for South America from geochemical analyses done on outcrops, not 'dust' per se. In this figure, the Dome C samples analysed by Vallelonga et al. (2010) are also shown. Further examination of these data will be enhanced in the following figures in order to determine the differences between the Australian and South American samples.

In Fig. 10, the results for all the samples obtained by Vallelonga et al. (2010) as well as for the Darling sub-basin are shown. The values presented in De Deckker et al. (2010) for the Murray sub-basin are ignored here because - as shown in Figs. 7 and 8 of De Deckker et al. (2010) - none of the samples from that latter sub-basin plot close to values obtained from the various ice cores of Vallelonga et al. (2010), as well as from Coats Land by Planchon et al. (2003) - that span an age range of 1990 until 1840 y AD -, and Taylor Dome ice by Matsumoto and Hinkley (2001).

Once again, as for the comparison of Sr versus Nd isotopes between the two continents, there are a number of samples that share similar Pb

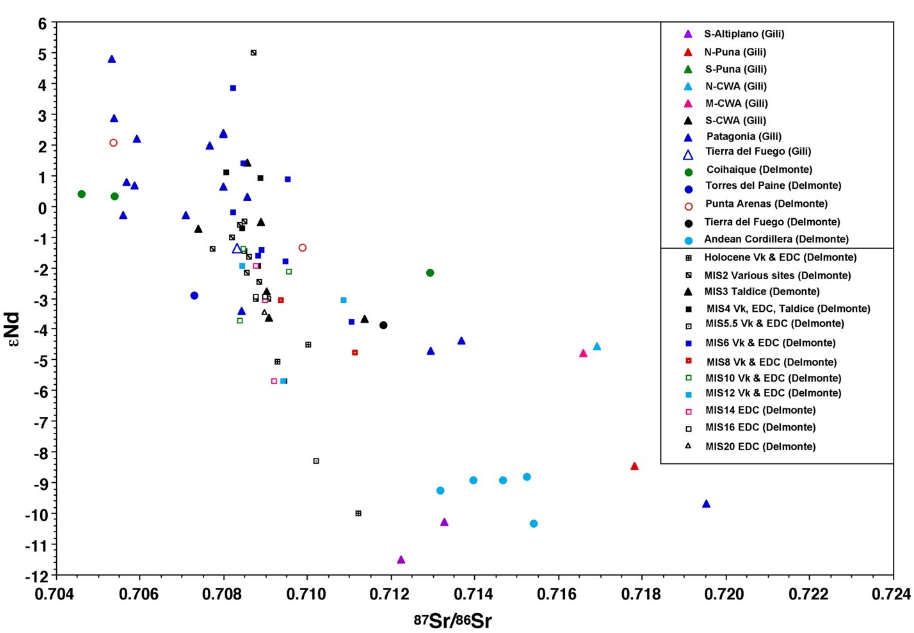

Fig. 7. Comparative plot of εNd versus $^{87}Sr/^{86}Sr$ for the South American samples analysed by Gili et al. (2017; refer to abbreviations in the text and that publication) and Delmonte et al. (2004) against the samples analysed by Delmonte et al. (2004) for Vostok (labeled as 'Vk'), Epica Dome C ('EDC') and Taldice ice core.

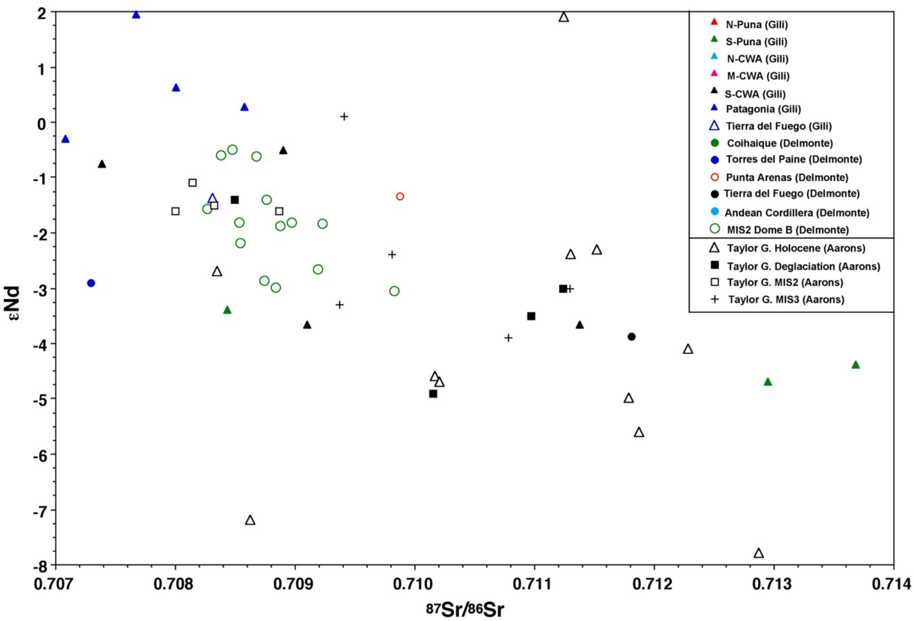

Fig. 8. Comparative plot of εNd versus $^{87}Sr/^{86}Sr$ for the South American samples analysed by Gili et al. (2017; refer to abbreviations in the text and that publication) and Delmonte et al. (2004) against the samples analysed by Delmonte et al. (2017) for Dome B, and for Taylor Glacier by Aarons et al. (2017).

isotopic ratios, some of which also share similar ratios with those obtained by Vallelonga et al. (2010). In Fig. 10, all the data from Vallelonga et al. (2010) are plotted except for those from Brachina Gorge in the Flinders Ranges that obviously relate to local Neoproterozoic lithologies (see De Deckker, 2019, fig. 21). Similarly, the other sample from Tilcha Waterhole along Cooper Creek relates to an aeolian unit, some 55 ka old (Paul Vallelonga, *pers. comm.)* and is ignored here because it is not a PSA per se. Finally, Vallelonga et al. (2010) discussed at length how they processed the samples for Pb isotope analyses using two distinct methods: extraction and digestion. Vallelonga et al. (2010) later on stated that they only used the 'extracted' Pb isotope values for comparison against the ice core samples because 'they correspond to coarse-grained particles (predominantly silicates) which are unlikely to be successfully transported to Antarctica'. Recently, Delmonte et al. (2017) applied single-particle Raman mineralogical investigation to four samples (with a total of 632 spectra conducted) from the Dome B ice core and it showed that all of them contained fine-grained quartz ranging from 13 to 21%. Hence, it may be necessary not to exclude the

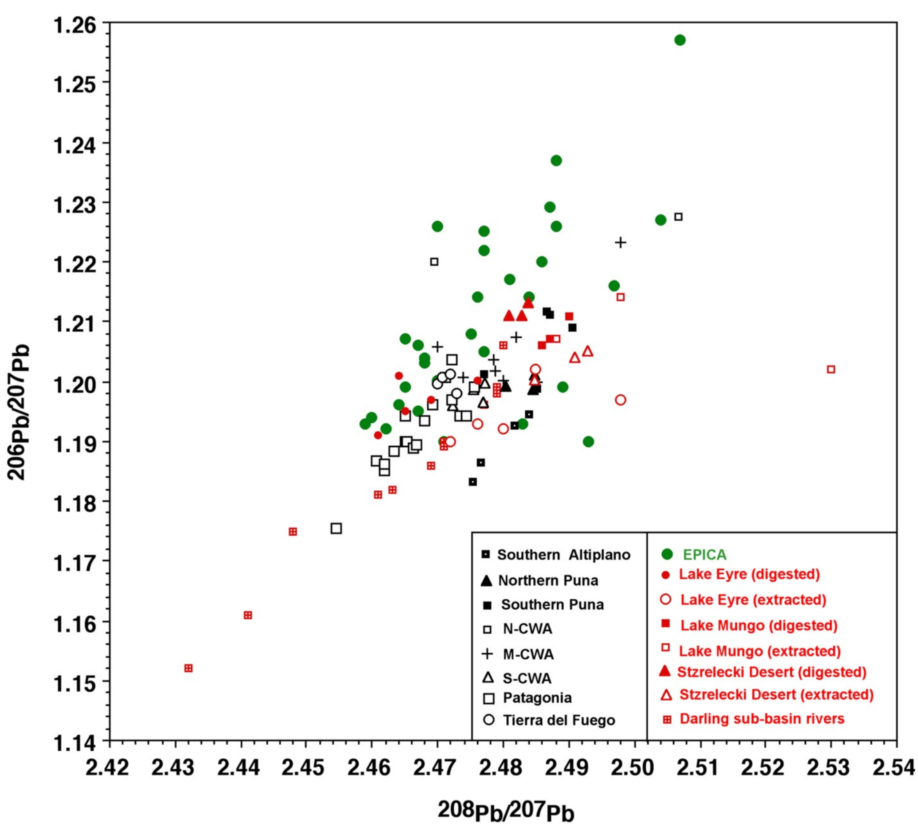

Fig. 9. Comparative plot of $^{206}Pb/^{207}Pb$ versus $^{208}Pb/^{207}Pb$ for all the samples from South America analysed by Gili et al. (2016; see abbreviation in text of that publication), and those from Australia analysed by Vallelonga et al. (2010) and from the Darling sub-basin, against Dome C core samples analysed by Vallelonga et al. (2010).

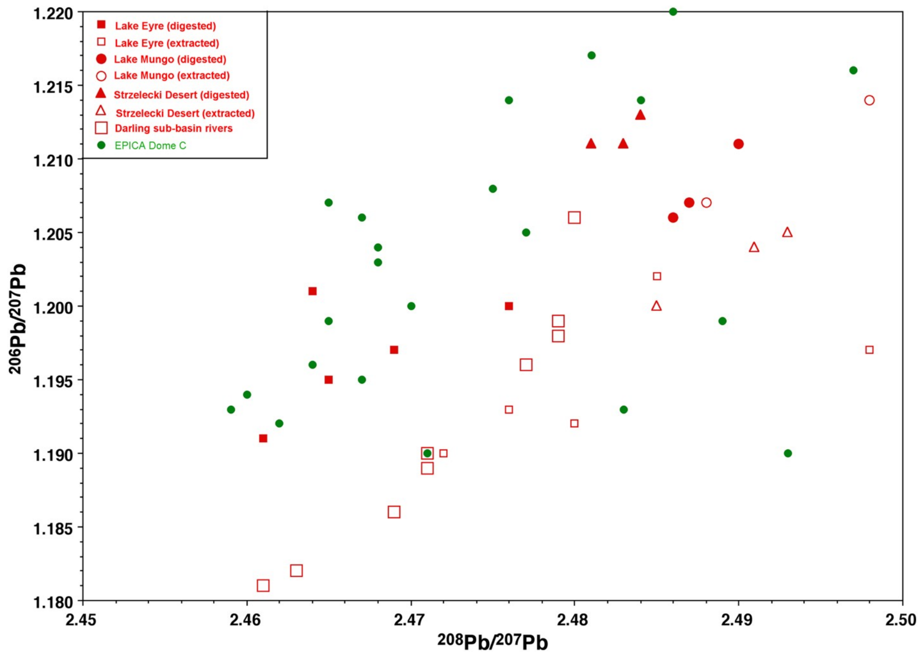

Fig. 10. Comparative plot of $^{206}Pb/^{207}Pb$ versus $^{208}Pb/^{207}Pb$ for all the samples from Australia analysed by Vallelonga et al. (2010) and from the Darling sub-basin against and those from Dome C also analysed by Vallelonga et al. (2010).

samples of Vallelonga et al. (2010) on the basis that they have been 'digested' before conducting Pb isotope analyses. Comparison with Gili et al. (2016)'s extraction method with that of Vallelonga et al. (2010) will require further comparison.

The Australian PSA samples from the Darling sub-basin, previously tabled by De Deckker et al. (2010) pertain to the < 2 µm size fraction that was digested in a HF-HNO_3 solution in screw-cap Teflon vials. It must be assumed that quartz may have been present in those samples but this was not reported as Franz Gingele who performed the mineralogical observations by XRD on all samples did not search for quartz spectra. Similarly, Gili et al. (2016) dissolved their samples in a HF + HNO_3 + $HClO_4$ mixture in tightly closed Teflon Savillex® beakers. Consequently, it is not necessary to ignore the data from Vallelonga et al. (2010) for the samples that had been 'digested'. In fact, it is preferable to compare those results with the other Australian (De Deckker et al., 2010) and South American (Gili et al., 2016) PSAs as all had undergone digestion in HF and HNO_3. Examination of Fig. 10 shows close similarity for several samples from the Kati-Thanda Lake Eyre, plus one from the Darling sub-basin and those from Dome C.

Fig. 11 is an enlargement of the Fig. 9 to help better visualize the comparison between the Australian and South American PSA samples. It transpires that there are quite a few samples that share similar Pb isotopic ratios, three of which concern samples from the surroundings of Kati Thanda-Lake Eyre that are similar to Patagonian PSAs, as well as a few from the Darling sub-basin and one form Lake Mungo that show close values to several samples from Patagonia and central-western Argentina (S-CWA), plus one from northern Puna.

6.5. Comparison of South American PSAs Pb isotope signals with those from the Dome C ice core

Fig. 12 shows that several South American PSA regions share similar Pb isotope ratios with the Dome C samples analysed by Vallelonga et al. (2010). These regions are Patagonia, Tierra del Fuego and possibly the middle Central-western Argentinian region. Many other regions of South America are distinctly different.

6.6. Comparison of all ice core results with fingerprints from Australian and South American PSAs

Examination of the South American PSAs for the same isotopic ratios listed above, and comparison with the Antarctic ice signals show that the number of 'correspondences' is slightly higher (24) than for the Australian PSAs. Concerning the ice cores from Dome C, Vostok and Taldice, the predominant South American PSA regions are the southern part of central-western Argentina (S-CWA) with a number of ratios shared between Antarctic ice core samples, plus with Patagonia as well. In addition, Tierra del Fuego and Punta Arenas score 2 'links' each. Examination of the records from Dome C and the Taylor Glacier samples shows the 'links' to the South American PSA regions differ: Tierra del Fuego has four scores with one for Dome B (MIS2) and one each for the deglaciation, MIS2 and MIS3 ice on the Taylor Glacier. In addition, there is one 'link' between Dome B and the central part of central-western Argentina (M-CWA).

It now becomes clear that there are differences in the continental PSAs from the Australian and South American supply of dust to Antarctica based on the εNd versus $^{87}Sr/^{86}Sr$ ratios. On the other hand, the southern part of central-western Argentina (S-CWA) was a more significant contributor to EDC, Vostok and Taldice sites, and in particular during MIS2 and MIS3. This will be further discussed below.

In summary, based on the geochemical fingerprints, it is clear that some Australian dust did reach Antarctica in the past along with South American dust.

6.7. New Zealand as a potential PSA of dust in Antarctic ice cores

Delmonte et al. (2004) using the combination of Sr and Nd isotopes and Vallelonga et al. (2010) using Pb isotopic ratios are the only source of data on PSAs from New Zealand and these authors discussed their data against the dust records in Antarctic ice cores. Only sample NZ7 (Fig. 5), located in the alluvial Canterbury Plains of the South Island of New Zealand, was defined as 'loess' by Delmonte et al. (2004) and its analysis plots very close to ice core samples with a Holocene age from Taylor Glacier (Aarons et al., 2017), as well as another one dated from the 'deglaciation'. Similarly the same NZ7 sample plots close to Holocene sample of EDC analysed by Delmonte et al. (2007). Of interest is

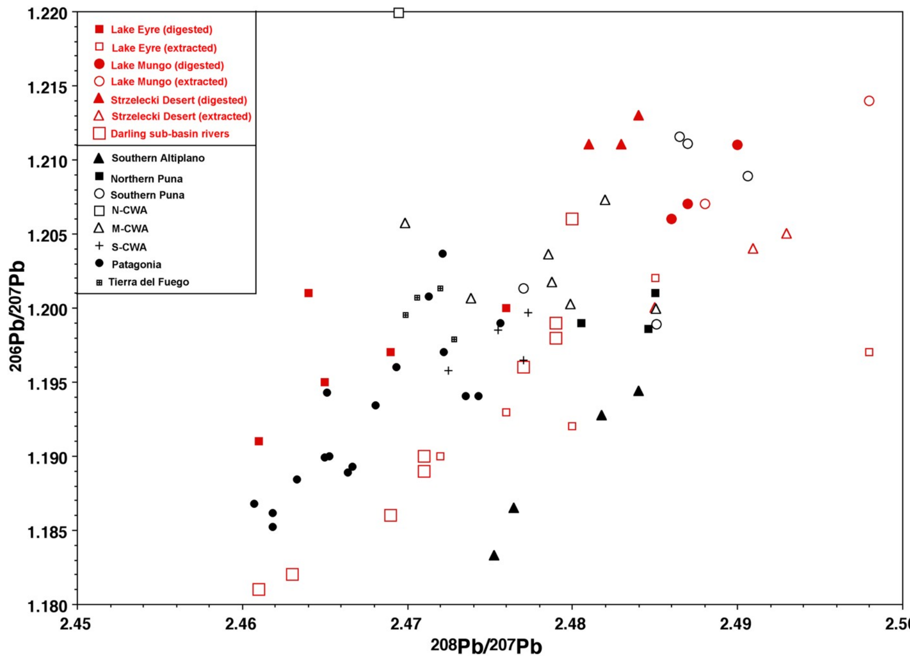

Fig. 11. Comparative plot of $^{206}Pb/^{207}Pb$ versus $^{208}Pb/^{207}Pb$ for all the samples from South America analysed by Gili et al. (2016; see abbreviation in text from that publication), against those from Australia analysed by Vallelonga et al. (2010) and from the Darling sub-basin.

that the location of this sample is very close to the New Zealand station chosen by Neff and Bertler (2015) for their HYSPLIT track studies.

Note also that Vallelonga et al. (2010)'s data for New Zealand are not plotted on Figs. 10-12 as none fitted close to the Antarctic ice core samples analysed by the Delmonte et al. (2004). This disparity perhaps reflects the fact that the ice core samples analysed by Vallelonga et al. (2005) have different ages as the samples analysed by Delmonte et al. (2004).

7. Discussion on the contribution of PSAs from both Australia and South America to Antarctica

It is unfortunate that the samples from Antarctic ice contained too little dust to conduct parallel analyses for the three sets of isotopes of concern here, otherwise it would have been possible to gain more certainty on the links between atmospheric conditions and dust deposition through time in the Antarctic region. In addition, a single analysis of an ice core sample, sometimes covering 60 to 90 cm ice accumulation, in the case of the Dome B core (Delmonte et al., 2017), would naturally relate to more than one dust depositional event. If two consecutive depositional events come from different PSA regions, it would be hard to come to a positive conclusion as to the real origin of any sample. The additional difficulty is that the isotopic fingerprint of several PSA regions in both Australia and South America share similar values. So, how to differentiate between the various sources based on these isotope ratios has proven difficult, almost impossible at this stage

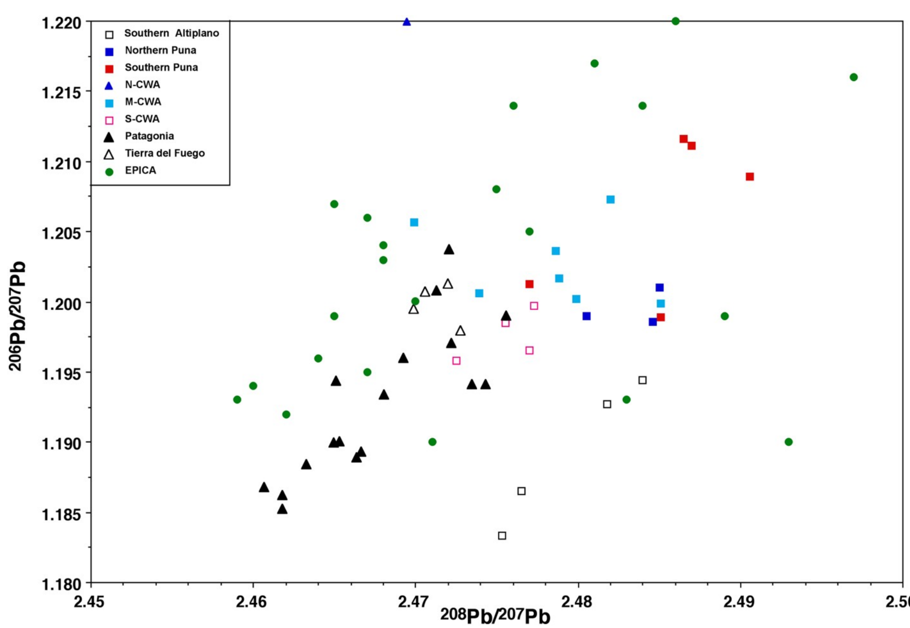

Fig. 12. Comparative plot of $^{206}Pb/^{207}Pb$ versus $^{208}Pb/^{207}Pb$ for all the samples from South America analysed by Gili et al. (2016; see abbreviation in text that that publication) and those from Dome C analysed by Vallelonga et al. (2010).

unless we use additional chemical ‘fingerprints’ such as Hf isotopes in combination with other isotopes, as done by Pourmand et al. (2014) who combined Sr-Nd-Hf isotopes and rare earth element (REE) for tracing the origin of Africa dust as collected on the Caribbean island of Barbados. Already, Gabrielli et al. (2010) and subsequently Wegner et al. (2012) have examined the REE composition from Antarctic ice in the hope of identifying dust sources which they carried out quite successfully, and Marino et al. (2008) used the major elemental fingerprints of southern hemisphere sources to identify the source of dust in Antarctic ice cores.

Eventually, it may be that a combination of all these analytical techniques on a single sample that will allow a better definition of dust sources and their contribution to Antarctic dust deposition. This will then become important to better define atmospheric circulation in the Southern Hemisphere during different climatic episodes of Quaternary. The role of the westerlies in contributing to dust uplift and transport in the Southern Hemisphere would then become better understood.

8. Conditions that operated in the past based on Australian dust fingerprints

Today, atmospheric circulation at sea level in the Southern Hemisphere in the vicinity of Antarctica follows a standard, clear pattern: winds and fronts move in a clockwise direction and this is also maintained at higher altitudes (Fig. 13). Thus, examination of Fig. 3 provides some perspective on the positioning of the various Antarctic ice core sites with respect to Australian and South American PSA regions. The Antarctic sites such as Taldice and the Taylor Glacier appear to be within easy [and rapid: within a matter of just a few days] reach of the Australian PSA region that is the Kati Thanda-Lake Eyre region as well as the Darling sub-basin. For example, examination of some of the satellite imageries on which HYSPLIT tracks have been placed as shown in De Deckker et al. (2010; Fig. 4 C) took 5 days to reach east Antarctica in the Ross Sea region (see also Appendix B, fig. C with 4 days to reach the same region; and Appendix E, fig. E with 5 days to reach the Ross Sea region). Part of this figure is reproduced in the middle panel of Fig. 14, above which synoptic charts for the same period (3–5 April 2008) are displayed. The lower panel in this Fig. 14 displays composite satellite images showing clouds and associated fronts that are clearly visible. The band of dust identified by Alan Wain in De Deckker et al. (2010) using a multilayered HYSPLIT trajectory. The band of dust visible in the middle panel for April 3 occurs ahead of the cold front (red arrow in the upper panel for that day, and the yellow arrow in the bottom panel for that day. Note the progressive shift of the cloud and associated dust band over the following two day.

It is easily envisaged that cloud bands and atmospheric fronts would have looked very different during the LGM as already summarised for the LGM by de Boer et al. (2013) and Kohfeld et al. (2013) who also discussed westerly wind changes. In addition, De Deckker et al. (2012), as mentioned above, identified that the position of the oceanic fronts south of Australia had shifted equatorward during the LGM. This would have been engendered or caused by a strengthening of the westerlies. Toggweiler et al. (Toggweiler et al., 2006; Fig. 11) in their model showed a significant equatorward shift of the westerlies belt during the LGM, being located between the Australian mainland and Tasmania at that time, thus implying a northern shift of > 10°. The atmospheric fronts that traverse the Southern Ocean and at times Australia bring with them a substantial amount of rain. In contrast, it is well known that a large part of Australia was very dry during the LGM (see Sniderman et al., 2019 for a review) and, therefore, these atmospheric fronts would not have transgressed over Australia. Equally, Perner et al. (2018) demonstrated that oceanic front changes occurred even during the Holocene with their poleward shift. As a consequence, the dust plumes that traversed across Australia during the LGM would also have shifted eastward instead as discussed by Thiede (1979) and Hesse (1994). This would explain also why dust plumes did not reach the core site (Fr1/94-GC3) located on the East Tasman Plateau (see discussion in De Deckker et al., 2019a, 2019b). Nevertheless, in core MD03-2607, located near Kangaroo Island (Fig. 1), some aeolian dust signals (Ti identified by XRF scanning and quartz by XRD) are found (see De Deckker et al., 2012), but the delivery of dust to the core site ought to be considered as very local as the core is located close to the Australian continental margin. Sprigg (1979) had also shown a change of wind patterns during the last glacial, and this was also discussed by Darrenougue et al. (2009) based on the origin of dust deposited in a cave in South Australia during the LGM. A close look at the animation available at the following web site can provide some insights as to airflow fluctuations over the Southern Ocean:

https://oceanitesfeed.files.wordpress.com/2014/09/gavinschmidtgif1.gif.

Hesse (1994) showed that not only the dust plume that traversed the Tasman Sea had shifted equatorward, but also that the dust flux during the last four glacials was much higher compared to the interglacials.

It appears therefore that relaxation of the westerlies shifting poleward during interglacial times would allow Australian dust plumes to transgress southward over Tasmania and the South Island of New Zealand and to eventually reach Antarctica as shown in the HYSPLIT reconstructions in De Deckker et al. (2010, Appendix B). In addition, we also need to consider the interpretation of Krinner and Genthon (2003) who identified that transport of dust towards Antarctica during the LGM had been faster from Patagonian PSAs compared to Australian and Southern African PSAs. This would explain the paucity of Australian signals in glacial intervals in Antarctic ice cores. Hence, it will be necessary in the future to examine other evidence to support this assumption. For example, Albani et al. (2016) further developed this concept but showed that even the extent of sea ice around Antarctica can act as a time buffer, something not examined by Krinner and Genthon (2003).

Concerning the dust plume that exits from northwestern Western Australia into the eastern Indian Ocean (and Timor Sea) today, there is no evidence for a change of direction during the LGM, but instead there was an accrued deposition of dust at sea as already shown by Stuut et al. (2014) and Kuhnt et al. (2015).

9. Conclusions

The detailed examination of geochemical fingerprints from both Australia and South America based on the comparison between Sr and Nd isotopes on one end and Pb isotope ratios in the other, hopefully will help convince the “airborne dust research community” that Australia was a source of dust deposited at various sites in Antarctica, predominently during interglacials. This was already shown by Marino et al. (2008) using major elements, Gabrielli et al. (2010) as well as Wegner et al. (2012) using REE. Concerning the Australian sites, the Kati Thanda-Lake Eyre region is the prime PSA for dust deposited in Antarctica. Nevertheless, some Australian dust appears to have been deposited at various locations in Antarctica during glacial periods, but this was definitely less frequent. This suggests that different atmospheric circulation patterns must have operated during different periods of the geological record on the Australian mainland.

The southern part of the central-western region of Argentina was definitely the biggest dust-producing region to Antarctica based on Sr and Nd isotopes, but this is not confirmed by the Pb isotopic ratios and therefore requires further investigation. The fact that quite a few samples from both Australian and South American PSAs share very similar geochemical fingerprints with respect to the isotopes discussed in this paper does not help in clarifying the issue of the provenance of dust in Antarctic ice cores. Therefore, a new procedure is required so as to obtain larger samples from Antarctic ice to perform a complete combination of geochemical fingerprinting analysis that hopefully will provide once and for all the answer as to where dust particles that reached Antarctica came from. Once this is done, we will be able to

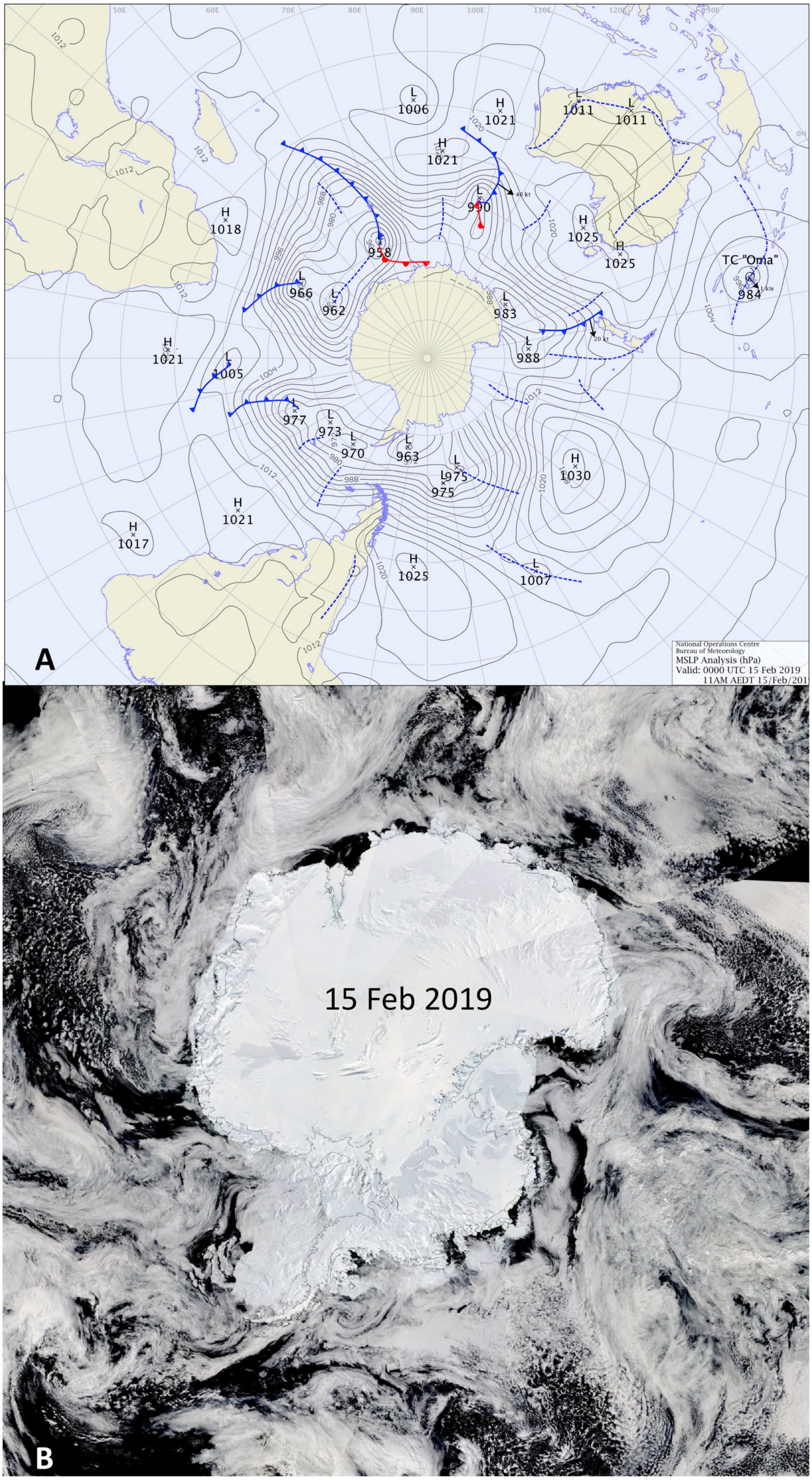

Fig. 13. A. Map of the Southern Hemisphere showing the analysis of mean sea level pressure (hPa) performed by the Australian Bureau of Meteorology for February 15, 2019 to illustrate the numerous cold fronts and the pre-frontal troughs (which often develop ahead of a front and which can be associated with an upswing in pressure and shift in wind direction) that continuously circumnavigate Antarctica in a clockwise fashion. B. Composite satellite imagery for the same day obtained from the NASA's EOSDIS website https://worldview.earthdata.nasa.gov/. The band of clouds are associated with cold fronts and it is those that could potentially entrain dust plumes that would originate from Australia.

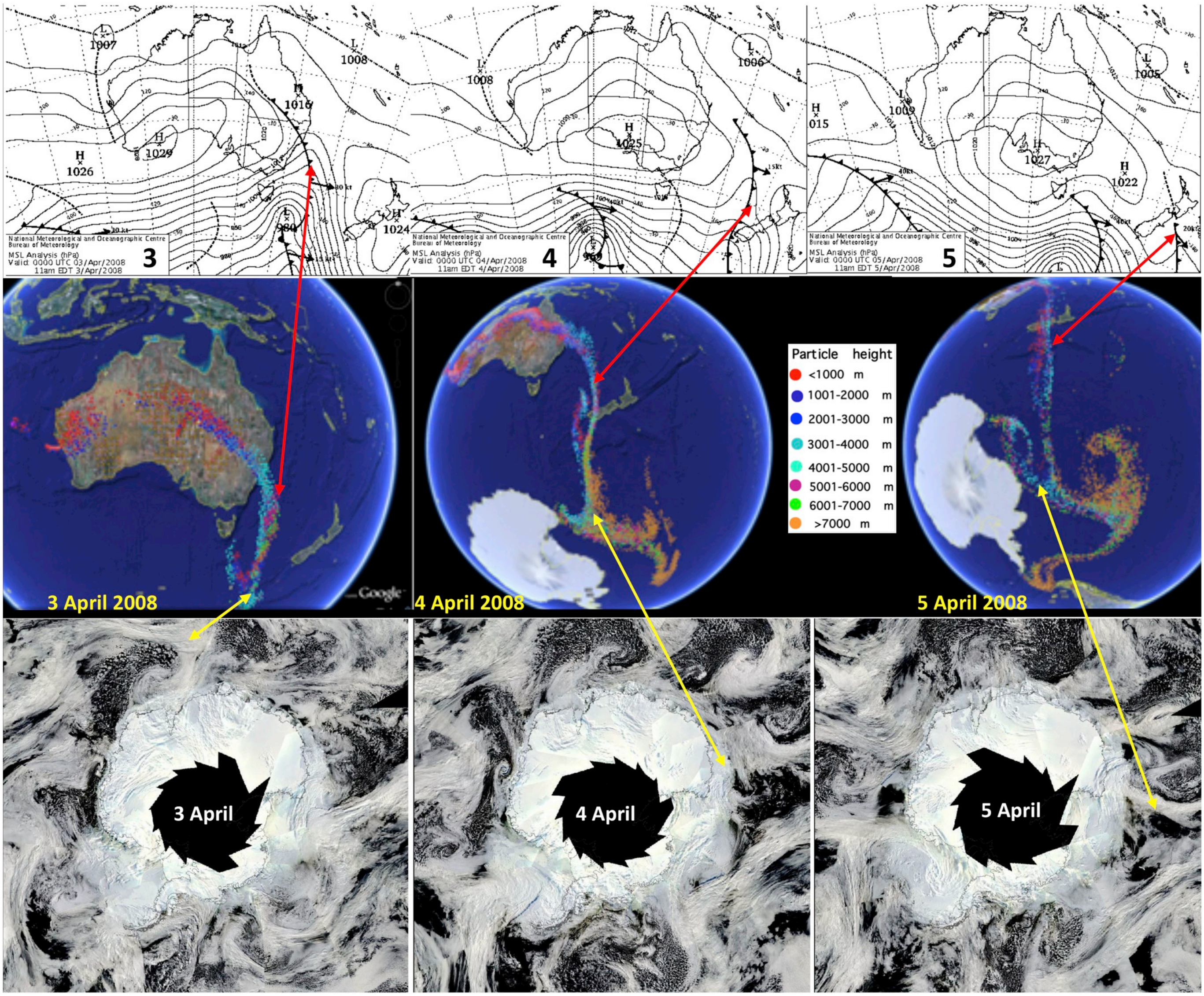

Fig. 14. Comparison between synoptic charts, reconstructed HYSPLIT trajectories and composite satellite images for around Antarctica for the period of April 3–5, 2008.

Top panel: Maps showing the mean sea level pressure (MSLP) for the period of 3–5 April 2008 taken from the Australian Bureau of Meteorology (http://www.bom.gov.au/cgi-bin/charts/charts.view.pl?idcode=IDX0102&file=IDX0102.200804130000.gif). Middle panel: Images of dust plumes that originated from Australia and which were obtained by A. Wain and displayed in Fig. 4 in De Deckker et al. (2010). Bottom panel: Composite satellite images for the same day obtained from the NASA's EOSDIS website. The band of dust visible in the middle panel for April 3 occurs ahead of the cold front (red arrow in the upper panel for that day, and the yellow arrow in the bottom panel for that day). For additional explanation, see text.

identify the atmospheric conditions that prevailed in the Southern Hemisphere during various part of the Quaternary. Examination of today's conditions is not the only way to address this question. The world was certainly different during the Last Glacial Maximum, but also before that time. The role of the westerlies, their 'strength' and latitudinal position during glacial periods need to better confined as it is clear from the comparison between glacial and interglacial aerosols deposited in Antarctica presented here that significant differences occurred through time. It may be worth also identifying the role played by the uplift of airmasses that carry aerosols over different parts of Antarctica so as to better understand the dust signatures in ice cores from the southern continents and their exposed shelves.

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I am also very grateful to Dr. M. Kaplan for his pertinent review that helped improve the text and its clarity.

Data repository

All the chemical data concerning Australian PSA used in this paper, plus trace elemental analyses for the same samples (some not discussed here) have been deposited at the Pangaea database with the following reference: https://doi.pangaea.de/10.1594/PANGAEA.907577

Declaration of Competing Interest

No.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloplacha.2019.103056.

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