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A RE-EXAMINATION OF THE 1928 TRANS-TASMAN DUST TRANSPORT EVENT

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Abstract

This paper presents a re-examination of the meteorology of the largest reported Australian dust fall, when in 1928 up to 206 g m^2 of dust was deposited over a four day period throughout much of New Zealand. Two contrasting explanations of the meteorology of the event have been offered; initially that dust transport took place within a series of extra-tropical cyclones and associated troughs; and the second forty years latter, that the dust was transported across the Tasman Sea in the upper-troposphere and lower stratosphere embedded within a jet stream. Re-analysis of observations made during the event, combined with recent studies of the nature of inter-regional dust transport suggests that the latter explanation of high-level transport is not valid. Examination of synoptic charts show that the deposition of dust in New Zealand in October 1928 resulted from four separate dust storms in eastern Australia. These were the result of the passage of successive cold fronts during a period of drought. It is argued that these fronts transported dust at low levels across the Tasman Sea rather than at high levels in the troposphere.

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1. Introduction

Large episodic outbreaks of Australian dust over the last one hundred years have been reported to periodically affect New Zealand (Table 1). Events have typically been associated with both wet and occasionally dry deposition of dust, coating buildings, cars and vegetation. Moreover, Australian dust is regularly observed deposited upon New Zealand snow fields, where the dust is visible as an orange, red, or brown discolouration of the snow. It has also been linked to other atmospheric phenomena, including dust haze and clouds, 'yellow light', red clouds, spectacular sunsets and thunderstorms. Australian sourced dust forms a significant component of deep sea sediments in the Tasman Sea, while enriching the waters of the Tasman Sea and Southern Ocean with iron and silicon leading to phytoplankton blooms (Windom, 1969; Glasby, 1971; Hesse, 1994; Martin*, et al.*, 1994; Hesse and McTainsh, 1999; Boyd*, et al.*, 2000) (Figure 1).

Internationally, interest in the role of atmospheric dust in climate systems has been growing led by research efforts to resolve the influence of dust on radiation transfers. For example, global mean annual radiative forcing of dust is estimated to range between +0.5 and -0.7 Wm^{-2} (Tegen*, et al.*, 1996). In comparison, annual radiative forcing by greenhouse gases is +2.5 Wm^{-2} (IPCC, 2001). Locally however, such effects may be considerably larger and are of particular importance in regions adjacent to major dust sources (Tegen*, et al.*, 1996) such as Australia, the largest dust source in the Southern Hemisphere.

The impact that dust has on climate depends primarily upon its physical characteristics and the nature of dust transporting weather systems (Charlson*, et al.*, 1992; Tegen*, et al.*, 1996). Size, shape and mineralogy, as well as the volume and concentration of dust in the atmosphere are all critically important (Tegen and Lacis, 1996; Miller and Tegen, 1998; Sokolik and Toon, 1999; Arimoto, 2001). Particularly relevant to this study is the atmospheric residence time of dust and the height at which it is transported within the atmosphere in the mid-latitudes from which there is currently a scarcity of observations.

Table 1. Incidences of Australian dust in New Zealand.

Dates	Year	Observations	Effects	Source
14-Nov	1902	Southland	Dust deposits/thunderstorms	The Southland Daily News 1902
		Otago	Mud showers/Reddish clouds	Marshall, 1903
		Waipawa	Dust storm	
6-10-Oct	1928	Southland/Otago	Dust deposits	The Dominion 1928a
		Christchurch	Visible dust in the air	Marshall and Kidson 1929
		Nelson	Dust in rain water	The Dominion 1928b
		Wellington	Yellow light, dust deposits	
		Taihape/Taranaki	Dust clouds/Dust deposition	
		Napier	Dry dust deposition	
		Northern North Island	Haze	
		Chatham Islands	Haze	
		New Zealand	Violent Thunderstorms	
End of Oct	1928	Queenstown	5" dust layer in snow	Kidson and Gregory, 1930
Jan	1929	Mt Cook, Mt Rolleston	Pink snow, 1928 deposit	Marshall and Kidson 1929
4-Sep	1929	Reefton	Sediment left by rain	Kidson and Gregory, 1930
24-27-Oct	1929	Niue	Smokey haze/Thunderstorms	Kidson, 1930
23-Nov	1929	Tasman Sea	Dust haze/deposits	Kidson, 1930
27-Nov	1929	Marlborough	Dust in rain	Kidson and Gregory, 1930
		Nelson	Thunderstorms	
		Taranaki	Reddish clouds	
		Wellington		
		Central New Zealand		
	1930	Southern Alps	Oct 1928 dust visible in snow	Kidson, 1930
Nov-Dec	1944	New Zealand	Dust Haze	Hawke, 1973
		Fiji	Dust	
10-14-Oct	1948	Tasman Sea	Dust clouds	The Dominion 1948a
		Tasman Sea	Thick dust plume	The Dominion 1948b
		Lord Howe Island	Reduced visibility	The Dominion 1948b
		Auckland/Kaipara	Haze	The Auckland Star, 1948
		Raglan/New Plymouth		
Mar	1965	New Zealand	Spectacular sunsets	Glasby, 1971
			Haze, smoke	
Spring	1966	Southern Alps	Red snow	Windom,1969
		North Island Mts		
	1969	Tasman Glacier	Red snow/Australian pollens	Moar, 1969
	1972	Westland Glaciers	Dust bands in ice	Mokma, *et al.* 1972
24-26-Nov	1982	Hokitika	Dust deposit	Collyer, et al. 1984
9-14-Feb	1983	Northern NZ	Dust plume	TOMS imagery
27-Nov to	1987	Franz Josef Glacier	Red snow	Kiefert and McTainsh, 1995
4-Dec				Knight, *et al.* 1995
28-Apr-	1997	New Zealand	Haze	The Christchurch Press, 1997
2-May				
4-6-Feb	2000	Fox Glacier	Red dust strips in snow	McGowan, *et al.* In press

The trans-Tasman dust transport event of the 6-10 October 1928 is the largest ever reported to affect New Zealand. The meteorological controls on dust transport from AAustralia to New Zealand during this event were first outlined by Kidson (1929), who concluded that the transport of dust took place within a series of intense cyclonic systems and associated troughs, which crossed the Australian continent during a four to five day period. Forty years later, Healy (1970) reviewed the event and concluded that the dust must have been transported across the Tasman Sea at 'high levels' within the upper troposphere and lower stratosphere. Furthermore, Healy believed the dust was most likely to have been transported across the Tasman Sea within the 'jet-stream' and was subsequently 'sucked' down to the surface by downdraughts in thunderstorms and/or the exchange of stratospheric air with the troposphere. This paper reviews the meteorological controls on dust during this event based on recent advances in the understanding of atmospheric dust transport from eastern Australia. It is argued that dust transport in early October 1928 took place within a relatively stable west to northwesterly airflow in which cold fronts were embedded as originally described by Kidson (1929), and not within the sub-tropical jet and stratosphere as proposed by Healy (1970).

2. The meteorology of Australian dust storms

Dust storms in eastern Australia typically occur during the passage of cold fronts associated with parent cyclonic systems to the south of the continent. Sprigg (1982) identified three principal dust transporting winds associated with the passage of cold fronts, i) anticyclonic pre-frontal northerlies or north-westerlies associated with strong baroclinic conditions ahead of the approaching front, ii) frontal westerlies during the passage of the front, and iii) post frontal anticyclonic south-easterlies. The first two wind systems can result in the transport of dust out of south-eastern Australia toward New Zealand (McTainsh, 1989). Particularly large dust storms however, are characterised by the entrainment and transport of dust by frontal westerlies. These 'rolling wall' *haboob* type dust storms (Sprigg, 1982) typically have very high dust concentrations as witnessed across much of western New South Wales and Victoria in the 2002/03 summer (McTainsh, *et al.*, 2005).

Haboobs of the type described by Sprigg (1982) are associated with non-precipitating

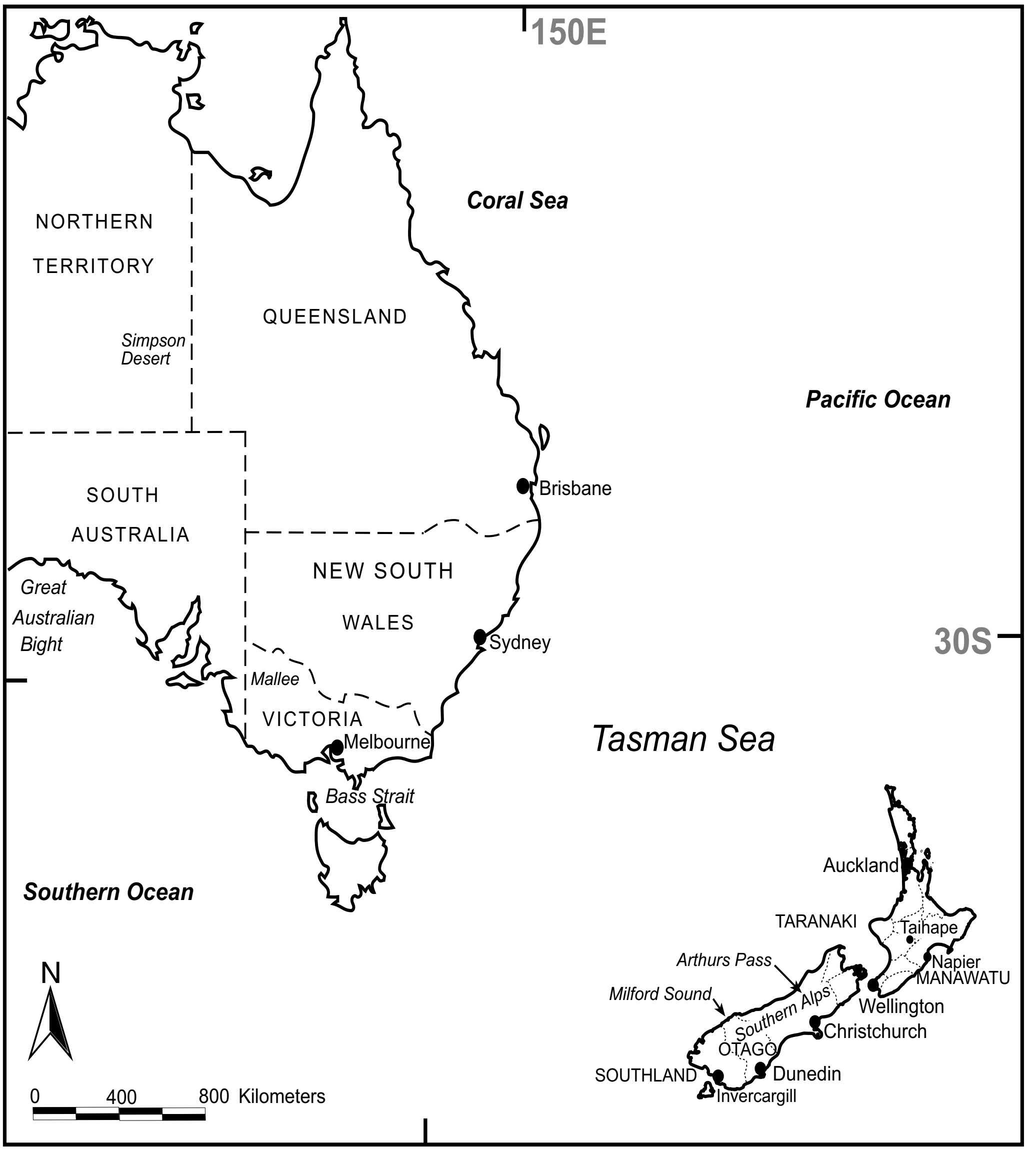

Figure 1. Location map with sites mentioned in the text indicated.

cold fronts. These weather systems are highly effective at entraining and transporting dust as they travel from west to east over southern Australia due to their low humidity, particularly during spring and summer (Clarke, 1961; Ryan and Wilson, 1985; Wilson and Stern, 1985; Garratt, 1988; Garratt, *et al.*, 1989). Those occurring in late spring and early summer are generally associated with synoptic scale southern ocean cold fronts and have a wide prefrontal trough in which complex squall line thunderstorm activity is typical (Garratt*, et al.*, 1985; Ryan and Wilson, 1985). Although prefrontal precipitation is common, the very dry prefrontal air coupled with significant sub-cloud evaporation means the amount of rainfall actually reaching the ground is insignificant, and the passage of the front is typically dry (Ryan and Wilson, 1985; Garratt, 1988). Alternatively, cold fronts between mid-summer and early autumn often occur as dry surface features associated with cut-off lows which develop in the prefrontal trough ahead of a mature synoptic scale southern ocean cold front (Wilson and Stern, 1985; Garratt, 1988). Significantly, prefrontal flow is characterised by temperatures of around 30°C and relative humidity < 30 %. These conditions dry surface sediment predisposing it to entrainment by strong winds at the leading edge of the front, which may reach velocities > 25 ms^{-1} and penetrate > 500 km inland from their parent low resulting in large dust storms (Garratt, 1984).

Frontogenesis may also occur within the west Australian heat trough which can become mobile due to the influence of a mid-latitude trough (Wilson and Stern, 1985; Smith*, et al.*, 1995; Deslandes*, et al.*, 1999). As these fronts are much further north of their parent cyclonic system, central Australian cold fronts are typically shallow features less than 1000 m in height. They are characterised by low relative humidity of approximately 20%, little or no significant cloud and strong squally winds with velocities greater than acknowledged dust threshold entrainment velocities of 7.5 ms^{-1} (Smith and Ridley, 1990; Reeder*, et al.*, 1992; Smith*, et al.*, 1995; Deslandes*, et al.*, 1999). These systems may also result in widespread dust entrainment and transport, particularly in regions such as Lake Eyre and Simpson Desert.

The subtropical jet has also been linked to the transport of aerosols across the Tasman Sea. This jet and west-east propagating jet streaks are prominent features of the Australian region (Vincent*, et al.*, 1997; Vincent and Silva Dias, 1998) and are important for local cyclogenesis (Uccellini and Johnson, 1979; Velden and Mills, 1990), but are less likely to play a major direct role in dust transport as suggested by Healy (1970). This is because spring and summertime cold fronts in eastern Australia are shallow, stable features in which the surface front remains isolated from upper level features such as the sub-tropical jet, with the dominant processes confined to the lowest 3 km of the atmosphere (Ryan and Wilson, 1985; Wilson and Stern, 1985). Smith and Ridley (1990) similarly found no connection between surface cold fronts and upper level features in central Australia.

3. Observations of the october 1928 event

3.1 Synoptic Setting

In early October 1928 a series of intense mid-latitude depressions and associated troughs crossed south-eastern Australia between the 2 – 7 October. The strong westerly airflow across the Tasman Sea then prevailed through to 9 October as the succession of mid-latitude depressions travelled east, south of the Australian continent. The first of these depressions crossed the Great Australian Bight and Bass Strait on the 2-3 October (Figure 2a), while an associated cold front (A) and trough penetrated well into central Australia. Over the next four days this depression tracked to the south-east beneath a large anticyclone, which remained centred to the north of New Zealand throughout the period.

A second depression entered the Southern Ocean south of the Great Australian Bight on 3 October (Figure 2b and 2c). Cold front (B) extended north from this system into the col over south Western Australia, while a series of trough lines tracked east over southern Australia. On 5 October central Australia was under the influence of a large trough and associated front (B), which extended into central Australia where it appeared to stall. Strong westerly airflow occurred across eastern Australia and into the Tasman Sea at this time.

By 6 October the anticyclone in the Coral Sea had travelled east toward New Caledonia, while a region of low pressure developed in central Australia. This caused winds to ease in Queensland and the Northern Territory, while another front (C) developed in eastern Australian and was located east of the New South Wales coast (Figure 2e). It would seem likely that this front crossed New Zealand sometime between the afternoon of the 7 and the morning of 8 October 1928 (Figure 2f).

On 7 October the second depression had moved from the Great Australian Bight and was centred over Tasmania, while the associated front (B) extended into south-

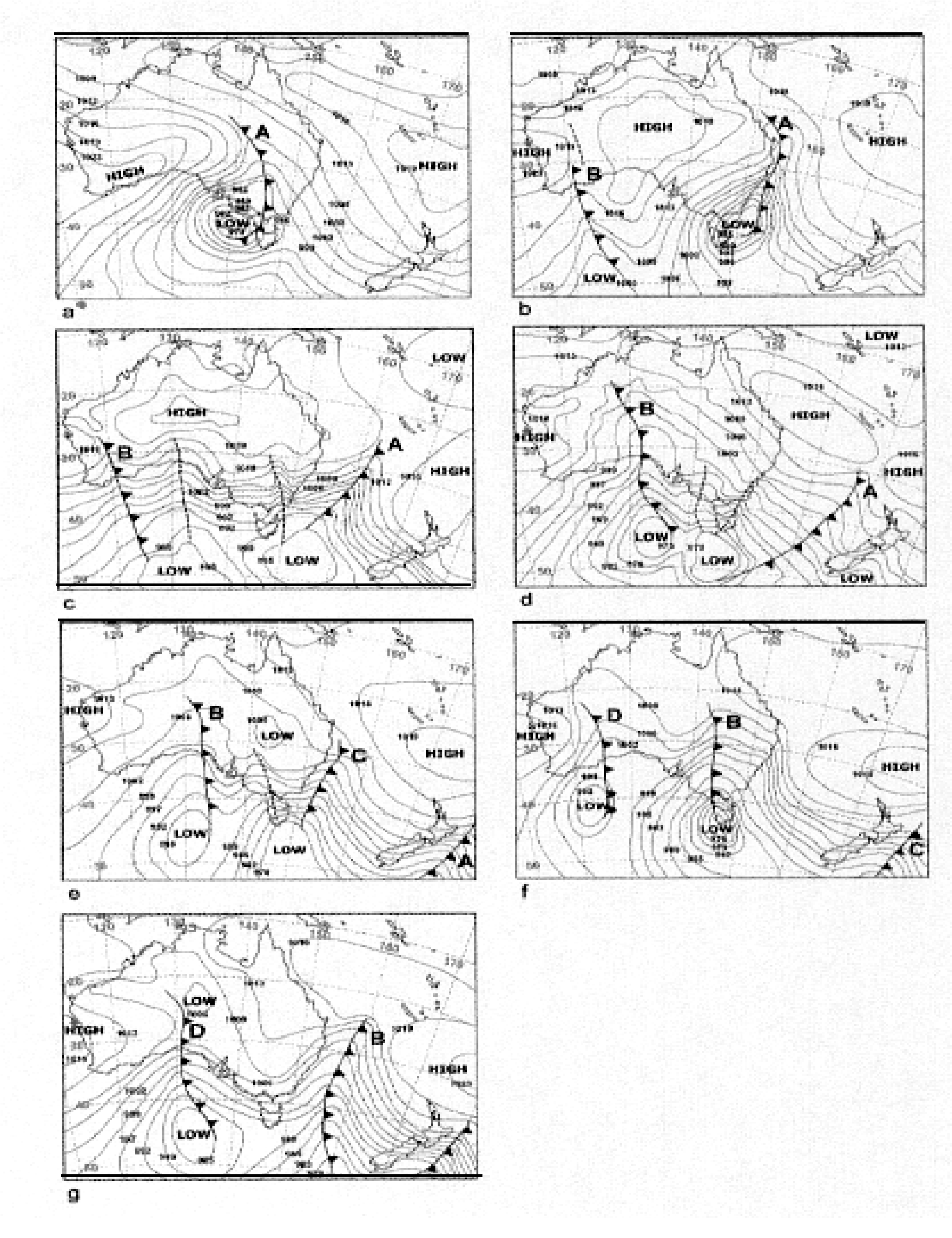

Figure 2. Mean sea level analyses for 1100 NZST, a) 2/10/1928, b) 3/10/1928, c)4/10/1928, d) 5/10/1928, e) 6/10/1928, f) 7/10/1928, g) 8/10/1928.

eastern Australia (Figure 2f). This front then moved into the Tasman Sea on October 8 (Figure, 2g) and is believed to have crossed New Zealand on October 9. A third depression developed on the western side of the Great Australian Bight on 7 October, while an associated trough and front (D) extended north over the continent. However, by 8 October a ridge had developed over eastern Australia and the front weakened as it crossed the continent.

3.2 Trans-Tasman dust transport

Dust storms were first reported in eastern Australia on 2 October 1928 during the passage of the first cold front (A) (Figure 2a) (The Melbourne Age, 1928). This same system produced heavy rain in South Australia and Victoria, while further north little precipitation fell (Kidson, 1929). In southern central Queensland a line of thunder-storms was reported associated with the prefrontal trough, while the frontal change was marked by strong westerly winds reaching between 40 and 100 km h^{-1} and severe dust storms (The Sydney Morning Herald, 1928a; The Courier Mail, 1928). The line of thunderstorms was reported crossing Brisbane shortly before midnight on 2 October, and was followed by strong frontal westerlies that enveloped the city in thick dust (The Courier Mail, 1928; Kidson, 1929). Similar reports of dust occurred from throughout south-east Queensland and northern New South Wales (The Sydney Morning Herald, 1928a; The Courier Mail, 1928) (Figure 1). Healy (1970) did not report this event and therefore rejected the possibility of dust entrained on the 3 October being transported to New Zealand. Instead he makes reference to low concentrations of dust “wafting” in over Brisbane on the afternoon of October 3, noting the dust was transported by lighter post frontal south-westerlies and was unlikely to have been transported to New Zealand. He also notes that dust deposited in Brisbane in the afternoon was a yellow-grey colour, whereas dust deposited during the morning associated with the front was reported as being red to pink in colour, similar to the dust deposited in New Zealand 3 days later. Figure 2b shows the position of front A at 1100 NZST 3 October east of the Queeensland coast having previously enveloped Brisbane with dust earlier in the morning. Over the next two days the front travelled in a south-easterly direction due to the blocking anticyclone over northern New Zealand. As a result, the section of the front that had entrained dust over southern Queensland on 2 October crossed over the southern South Island sometime on the afternoon of 6 October. This coincides with the first reports of Australian dust in Southland.

On 4 October a second series of dust storms were reported over southern Australia, but were not particularly severe and were probably generated by the trough lines in the disturbed westerly flow (Figure 2c). Dust storms were reported on October 5 in southern Queensland in strong hot, dry northwesterly airflow ahead of the approaching front (B). Dust storms were again reported widely on 6 October in New South Wales with a large dust plume passing over Sydney at 2 pm (Kidson, 1929). This plume is likely to have been associated with the passage of front C, located just east of the Australian coastline (Figure 2e). This front is believed to have crossed New Zealand sometime on the 7 or 8 October causing widespread dust deposition.

On 7 October the most severe dust storms of the entire period were reported affecting Queensland, and in particular New South Wales and Victoria. Red rain was reported east of Melbourne, while "*great volumes of dust*" were reported affecting Sydney (The Sydney Morning Herald, 1928b; Kidson, 1929). In addition, wind damage occurred throughout Sydney, with roofs blown off buildings, windows blown in, and ships breaking their moorings and dragging their anchors (The Sydney Morning Herald, 1928b). The storm was noted for its rapid movement across New South Wales, as well as its short duration and was associated with the passage of frontal system B. In Sydney, the wind speed and direction was reported to change rapidly as the front and associated dust storm approached. In the morning ahead of the front a light north-easterly was recorded, which backed to the north-west ahead of the surface trough and front. As the front passed the wind direction changed rapidly to the west and winds speeds exceeded 100 km h^{-1} as the front and dust plume hit (The Sydney Morning Herald, 1928b).

Conditions improved in eastern Australia from 8 October, and no further dust storms were reported during the passage of front D. The parent low associated with front B that raised dust on 7 October travelled north-east into the south Tasman Sea, and it is likely that the front crossed New Zealand on the afternoon of 9 October. Although rain fell over the South Island and lower North Island at this time, conditions remained dry over northern New Zealand and dust remained suspended in the atmosphere leading to reports of dust haze, which continued through to the 10 October 1928.

3.3 Australian dust deposition in New Zealand

Initial reports of Australian dust deposition in New Zealand were from Southland and Otago (Figure 1) on 6 October 1928. Reports of dust deposition from sites further north were recorded over the following four days. During the event dust was reported being washed from the atmosphere as showers of mud fell at Winton in Southland (Kidson, 1929), while in Invercargill homes, footpaths, cars and roads were found to be covered with mud following rain (The Dominion, 1928a). Dust deposition occurred throughout the South Island and was noted as being "*extraordinarily heavy*" in Southland and Central Otago, with the Southland Times reporting ….. "*A peculiar dull-red glow was observed in the sky to the west of Gore on Saturday afternoon, and on Sunday morning many parts of the town bore the appearance of having been dusted with brick dust*" (Kidson, 1929). Dust deposition was also recorded throughout the central and lower North Island, with Wellington being enveloped by a "*dull sickly yellow light"* (The Dominion, 1928b). Further north at Taihape, "*thick dust clouds were seen in the valleys below the meteorological station*" (Kidson, 1929). Dust deposition also occurred throughout the Manawatu and in southern Taranaki. In Napier, unusually the deposition of dry dust occurred (Kidson, 1929) and reports of dust haze were even made as far east as the Chatham Islands (Kidson, 1929).

Following the event dust remained visible in the snow pack of the Southern Alps for more than 12 months. Kidson (1929) reported a 13 cm thick dust layer within the snow at Ben Lemond near Queenstown at the end of October 1928, while "*pink*" snow was observed in January 1929 at Milford Sound and Mt. Rolleston near Arthur's Pass. Furthermore, red dust in the snow attributed to the 1928 event was still visible in parts of the Southern Alps in 1930 (Kidson, 1930), although this is likely to have been augmented by additional trans-Tasman dust transport events which occurred during 1929 (Table 1).

Overall dust deposition was reported widely across New Zealand, with dust falls occurring over much of the South Island, as well as the lower half of the North Island from Taranaki south (Figure 1). Given deposition rates reported by Marshall of 3.59 to 206 g m^2 (Marshall, 1929), a conservative estimate is that 1 x 10^6 t of dust was deposited in New Zealand over the period assuming a mean deposition flux of 5 g m^2.

This value is considerably more than the 2 x 10^5 t estimate by Kidson (1930), who was unaware of the full aerial extent of deposition. The actual mass of dust transported across New Zealand was likely to have been even higher, as although dust was reported as haze over the upper North Island and Chatham Islands, no deposition was reported at these locations.

4. Meteorological controls on trans-Tasman dust transport

Two contrasting explanations have been offered to explain the deposition of Australian dust in New Zealand in October 1928. Kidson (1929) believed that dust transport between Australia and New Zealand took place within the series of intense mid-latitude depressions and associated troughs that crossed south-eastern Australia between 4 - 7 October 1928. Conversely, Healy (1970) in his reappraisal of Kidson's original description of the event argued that dust transport occurred at much higher levels in the atmosphere including within the stratosphere and the subtropical jet stream. He concluded that only dust entrained from southern Queensland on the 5 October was transported to New Zealand. This dust was raised by winds associated with the passage of a deep trough which crossed south-eastern Australia on the afternoon of 5 October, from where it was transported to New Zealand and deposited from the afternoon of 6 October 1928. In order for dust to traverse the Tasman Sea within this time frame Healy (1970) believed that it must have been transported within jet streams, where velocities may reach speeds of 185-280 km h^{-1}. It was suggested by Healy that dust could have been raised into the upper level jet stream by strong vertical velocities associated with the cold front, while deposition over New Zealand occurred due to dust being "sucked" from the mid-troposphere by down-draughts within towering cumulonimbus. Accordingly, dust reported in New Zealand after 6 October was envisaged to be travelling *"at slower average speeds than the maximum jet-stream rates*" (Healy, 1970).

Recent studies of major dust export events from eastern Australia which have included the application of air parcel trajectory models show that dust plume transport across the Tasman Sea is typically confined to levels below 700 hPa (~3000 m) (McGowan, *et al.* In press). For example, the 22 October 2002 event which crossed eastern Australia as discussed by McTainsh et al. (2005), was confined to between 1.5 and 2.2 km in height.

Air-mass trajectory studies also show that the transport of dust plumes across the Tasman Sea takes between 1-4 days (Collyer*, et al.*, 1984; McGowan*, et al.*, 2000; McGowan*, et al.*, In press). Healy (1970) who considered that only dust entrained on 5 October was deposited in New Zealand, used jet streams to explain its deposition on 6 October. However, despite observations suggesting that dust deposited in New Zealand on 6 October may have been entrained as early as 2 October, frontal speeds of 35-50 km h^{-1} would mean dust could traverse the Tasman Sea in approximately 40 hours even at low levels.

If dust is to be carried to high levels and potentially into jet streams, as suggested by Healy (1970) a mechanism is needed to lift the dust to such levels. The most probable way in which this would occur is by ascent of prefrontal northerlies over and ahead of the front as the 'warm conveyor belt' (Wilson and Stern, 1985). The air mass trajectories conducted by McGowan et al. (2000) corresponding to the 24 May 1994 dust event are an example of this process, where dust entrained by prefrontal northerlies ascended along the leading edge of the front reaching 450 hPa before curving cyclonically around the front's parent cyclone south of Tasmania. Trans-Tasman dust transport by pre-frontal northerly winds appears, however, to be relatively rare in comparison with dust transport by frontal westerlies. Only one such event has been recorded (April-May 1997) (Table 1) and in this case air parcel trajectory modelling (not shown) confirmed that dust transport occurred at low levels within anticyclonic westerlies. Dust entrained by these winds may also be transported to the south-west of Australian and away from New Zealand as shown by McGowan et al. (2000). This occurs as the most western sector of pre-frontal flow typically ascends over the front before subsiding and curving cyclonically (Wilson and Stern, 1985) resulting in a south-westerly trajectory. Prefrontal precipitation, which is common (Ryan and Wilson, 1985; Garratt, 1988), may also serve to inhibit long distance dust transport by washing dust entrained by prefrontal northerlies from the atmosphere relatively close to its source.

The record of trans-Tasman dust events recorded in Table 1 is essentially a record of high magnitude events which have resulted in the transport of dust to New Zealand. In the majority of these events dust was entrained by both hot prefrontal-northerlies followed by a rapid change to gusty frontal westerlies. As previously discussed, widespread precipitation is unlikely during the passage of cold fronts over eastern Australia due to their dry shallow nature. These conditions have been shown to continue off the coast, with relative humidity in the prefrontal airmass below 30% up to 200 km offshore (Ryan and Wilson, 1985). Such conditions allow dust to be transported vast distances at low levels, which was thought unlikely by Healy (1970). This hypothesis is evidenced by a number of observations. During the 1928 event two ships; the Margaret W and the Hatkhola both reported encountering a dust cloud when 640 km from the Australian coast and 320 km from Melbourne respectively (Kidson, 1929; Healy, 1970). Moreover, during the October 1948 event (Table 1), Auckland to Sydney flying boat captains reported flying through a dust plume at heights as low as 900 m asl., when 400 km west of Auckland, and flying above the dust plume at an altitude of 3000 m asl. (The New Zealand Herald, 1948a; 1948b). Dust was observed being held in suspension by strong turbulent winds associated with a cold front, with the dust plume being described as a "*belt*", about 240 km wide and 1000 km long (The New Zealand Herald, 1948b), marking the position of the front. Dust concentrations were observed to be highest along the leading (eastern) edge of the plume (The New Zealand Herald, 1948b). Similar conditions were monitored during more recent events such as the 23 October 2002 dust storm which affected eastern Australia (McTainsh, *et al.*, In press), 8 February 1983 Melbourne dust storm (Lourensz and Abe, 1983; Garratt, 1984), and 1 December 1987 event (Knight, *et al.*, 1995), which resulted in dust being deposited in the Southern Alps.

The deposition of long travelled dust occurs primarily due to precipitation scavenging (Pye, 1987), which is much more effective at removing particles from the atmosphere compared to dry deposition (Duce, *et al.*, 1980; Arimoto, *et al.*, 1985). Large particles will drop out of suspension relatively close to their source area, whereas particles smaller than 10 µm may be transported thousands of kilometres (Tsoar and Pye, 1987). For example, suspended dust collected during the December 1987 event (Table 1) in Brisbane averaged 8.87 µm in diameter (Knight, *et al.*, 1995), while the same dust collected as a deposit from the Franz Josef Glacier in New Zealand was 10 µm (McGowan, *et al.*, In press). As a consequence by the time major dust plumes

such as that of October 2002 (as discussed by McTainsh*, et al.*, 2005) reach the east coast of Australia having been entrained ~1-2000 km to the west, grain sizes are such that they are observed to pass without significant deposition in the absence of rainfall. There is no data supporting the assertion that dust transport may occur at upper levels with jets in either the 1928 event or any more recent events. The December 1987 dust storm, previously discussed by Knight et al. (1995) (Table 1) was similar to the first dust-transporting front of the 1928 event when the parent cyclone took an unusually northerly track. The meteorology of the December 1987 event was examined by Velden and Mills (1990) who concluded that upper level jet streaks played a major role in intensification of the cyclone, however there was no evidence that these influenced dust transport with ascending air ahead of the front associated with precipitation.
Jets are typically confined to heights between 500 and 100 hPa (Bals-Elsholz*, et al.*, 2001), so do not influence the shallow surface cold fronts known to cause major dust outbreaks from eastern Australia. In addition, during spring the Sub-Tropical Jet (STJ) weakens, and the mean position of the jet lies well north of New Zealand (Weinert, 1968; Eastin and Vincent, 1998), while in October the STJ remains between 21 and 33°S 80% of the time (Weinert, 1968; Eastin and Vincent, 1998) making it unlikely to influence dust transport.

5. Summary

Large trans-Tasman dust transport events are not uncommon, but the October 1928 event stands alone in the historical record because of its duration and the enormous volume of dust that was deposited on New Zealand. It is often referred to in the international literature on dust storms as an example of long distance inter-regional dust transport (Kidson, 1930; Kidson and Gregory, 1930; Moar, 1969; Windom, 1969; Glasby, 1971; Mokma*, et al.*, 1972; Close*, et al.*, 1978; Goudie, 1978, 1983; Collyer*, et al.*, 1984; McTainsh and Pitblado, 1987; Pye, 1987; McTainsh, 1989; Knight*, et al.*, 1995; McGowan, 1996; McGowan*, et al.*, 2000; McGowan*, et al.*, In press). Despite this, the actual mechanism by which dust transport took place has not been established unequivocally. Initially, Kidson (1929) argued that dust was entrained and transported by the passage of a series of mid-latitude troughs, while Healy (1970) believed that the dust was entrained during the passage of a single cold front and lifted into a jet stream of the upper troposphere and lower stratosphere. Moreover, this latter explanation of events has been cited in the literature as one of the few examples of dust transport within upper-level jet streams, and has also be taken to account for the rapid transport of dust over large distances (Pye, 1987).

Based on the detailed review of this event and a growing understanding of the influence of meso and synoptic scale weather systems on dust transport from eastern Australia we believe that dust transport occurred in early October 1928 at relatively low-levels during the passage of cold fronts, similar to the explanation of events presented originally by Kidson (1929). The cold fronts that cross south-eastern Australia during spring and summer are characterised by strong and often dry winds capable of entraining dust at their leading edge. They are shallow stable features, which are typically confined below 3 km and cut off from upper levels. Therefore, they are unable to raise dust to the top of the troposphere and into jet streams. Although prefrontal air may ascend to higher levels, there are few observations of trans-Tasman dust transport in this manor, owing to precipitation scavenging close to source areas, or trajectories taking a south-westerly trajectory from Australia. Furthermore, observations from Australia during the event suggest the vast majority of dust was transported by the passage of fronts and not in prefrontal winds.

The very dry air and strong winds associated with the passage of cold fronts over eastern Australia in conjunction with the fine grain size of the dust mean it is possible for dust to remain in suspension at low levels during trans-Tasman transport. This is supported by observations of dust transport at low levels during several events, most notably by ships during the event described here. Consequently, it is believed that this event serves as a case study for the way Australian dust is transported across the Tasman Sea, which is typically at low-levels associated with the passage of vigorous cold fronts. Despite this, the October 1928 event is atypical due to the persistent dry and windy conditions that prevailed over dust source areas in central and eastern Australia for 6 days, interrupted only by brief lulls between eastward travelling fronts and trough-lines. This compares to more typical trans-Tasman dust transport events that occur during the passage of a single front, as reported on 1 December 1987 (Knight, *et al.*, 1995). This explains why the event had such a pronounced impact on New Zealand, both in terms of the mass of dust deposited and the aerial extent over which dust was reported.

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