A vertical wind structure that leads to extreme rainfall and major flooding in southeast Australia

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Here we examine winds associated with extreme rainfall and major flooding in coastal catchments and more broadly over southeastern Australia. Both radiosonde and re-analysis data are examined. In every case (i) atmospheric moisture content is high and (ii) the low-level winds are onshore, and in almost every case (iii) the wind-direction turns anti-cyclonically with increasing height up to 500 hPa. Data from Brisbane extending back more than 50 years is consistent with this behavior: winds turn anti-cyclonically with increasing height on days with heavy rainfall, whereas winds turn cyclonically with increasing height on days with light or no rainfall. In the coastal zone, extreme rainfall rarely occurs without (i), (ii) and (iii). In eastern Australia beyond the coastal zone, conditions (i) and (iii) are also associated with extreme rainfall. We found very few cases where such conditions were not associated with extreme rainfall in this broader region. This study extends previous work by showing that the link between turning winds and rainfall exists in both the tropics and subtropics, and the link applies in cases of extreme rainfall and associated major flooding.

1. Introduction

Callaghan and Power (2014, hereafter CP2014) documented major flooding events since the mid-19th century in a coastal strip of catchments in Australia extending from Brisbane (27.5°S, 153.0°E, Queensland), through Sydney, to Eden (37.1°S, 149.9°E, New South Wales (NSW)), approximately 1500 km south of Brisbane (Figure 1, left panel). CP2014 described the structure of weather systems that produce very heavy rainfall. They found that most of the extreme rainfall events in their study region were associated with systems that slope with height, between a surface low or trough near the coast, and a middle level trough inland. This structure results in winds between the two systems changing direction with height between the 850 hPa and 500 hPa levels in an anti-cyclonic sense.

Forecasters in the Severe Weather Section of the Bureau of Meteorology in Brisbane have been using this turning wind signature in forecast output from the European Centre for Medium-Range Weather Forecasts numerical model output (EC) to successfully warn for flash flooding for decades. Despite this success, the documentation of the links between heavy rainfall and turning winds in the scientific literature is limited. The main purpose of this study is to rectify this by documenting the winds associated with a large number weather systems producing extremely heavy rainfall.

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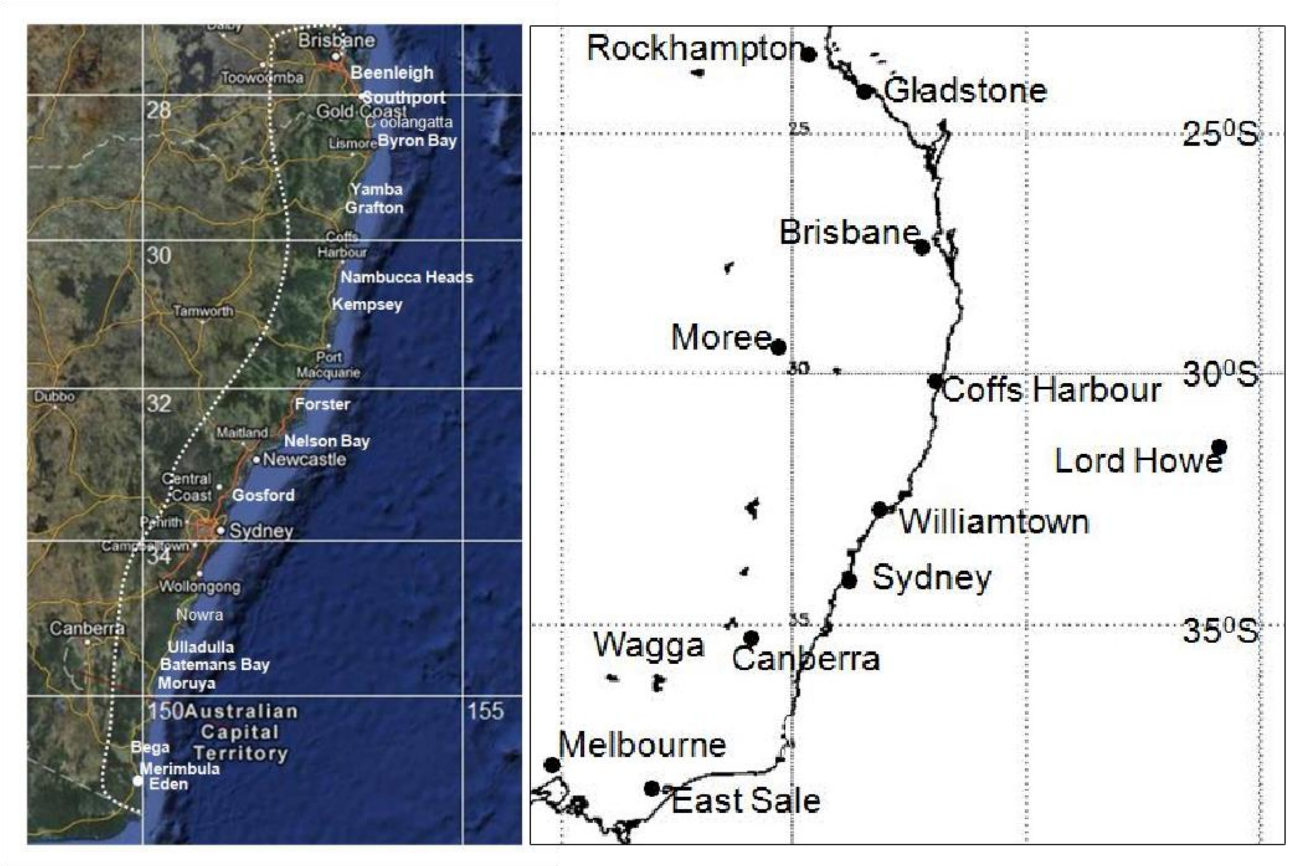

Figure 1 CP2014 study region is shown in the left panel enclosed by the dotted white line and the coastline. The location of radiosonde stations that surround the coastal region is given in the right frame.

This wind structure often coincides with a rapid development of surface lows. Numerical models forecast this turning signature well, but these same models generally underestimate the magnitude of the rainfall (pers. comm. Beth Ebert and Kamal Puri 2014). van den Honert and Mc Aneney (2011), for example, showed that the rainfall forecasts prior to the disastrous 2011 Brisbane River and Lockyer Valley floods in Queensland forecasted rainfall that was approximately one third of that actually received. An underestimation of extremely heavy rainfall also occurred for the disastrous 2005 Mumbai Floods (Sahany et al. 2010), and the severe floods in China in 2006 (Gao et al. 2009). Indeed, often the most intense rainfall in a major flood event is not sampled by even a relatively dense rain gauge network. This was the case leading into the disastrous 2011 Lockyer Valley flash flood (see Bureau of Meteorology report, http://www.bom.gov.au/qld/flood/fld_reports/lockyer_creek_fact_sheet_2011.pdf).

Extreme rainfall sometimes leads to major flooding. Major floods frequently isolate towns, can cause major disruptions to road and rail links, the evacuation of many houses and business premises, and the widespread inundation of farmland (CP2014). Major flooding can also lead to high death tolls. For example, there were at least 90 known deaths caused by floods in June 1852, and 25 deaths during the Brisbane River catchment floods in January 2011 (CP2014). A more recent study (Power and Callaghan 2016) provides evidence that the occurrences of these major flood events has increased since the late 19th century. Given these severe impacts, and the possibility of an increasing trend, it is important that we improve our understanding of the causes of extreme rainfall, and increase the accuracy of forecasts of such events, so that people can better prepare for the impacts.

CP2014 compiled a list of major floods in the study region (Figure 1, left panel). Here we describe the low-to-mid-level (850-500 hPa) winds associated with the floods CP2014 identified, in the cases where such data are available. We also examine wind structures associated with extreme rainfall both within and beyond the study region in CP2014. This broader region (Figure 1, right panel) includes regions in the tropics, sub-tropics and mid-latitudes.

We follow CP2014, and regard flooding as “major” if it caused inundation of a river within approximately 50 km of the coast or flooding overland near the coast from the active part of a weather system that extends at least 20 km along the coast. In the former case extreme rainfall extends well into the hinterland and the upper reaches of the river catchments, causing a flood that drains down the river systems to coastal areas. In the latter case the extreme rainfall is confined to the coast and floods form directly over the coastal area rather than propagating down the river systems.

Many studies have previously looked at the synoptic systems linked to rainfall in south-east Australia (e.g. Hunt 1914; Visher and Hodge 1925; Bond and Wiesner 1955; Brunt 1956, 1958; Public Works Department, NSW 1985; Shepherd and Coloquhoun 1985; Holland et al. 1987; Whetton 1990; Hopkins and Holland 1997; Speer 2008; Speer et al. 2009, 2011; Vernon-Kidd et al. 2010; Wilson et al. 2013; Mackay 2014; Browning and Goodwin 2013; CP2014). However, fewer studies have looked at the detailed structure of the synoptic systems linked to either extreme rainfall or major flooding (Bond and Wiesener 1955; Browning and Goodwin 2013; Wilson et al. 2013; Dowdy et al. 2013). While these studies did not examine winds, they did examine both Mean Sea Level Pressure (MSLP) patterns and the structure of middle to upper-level troughs linked to heavy rainfall. In this study we extend this earlier work by examining many more events and by providing further details on the three-dimensional structure, including winds, of the weather systems triggering extreme rainfall and major floods.

In Section 2 we describe in more detail the mechanisms producing the turning winds with height. The data sources used in this investigation are described in Section 3. In Section 4 we examine long-term average daily wind speed and direction at Brisbane airport, stratified according to the amount of daily rainfall received. In Section 5 we provide a detailed description of wind structure associated with most of the major riverine coastal floods identified by CP2014. This includes three notable events: the Brisbane floods of 2011, the floods triggered by the *Pasher Bulker* Storm in 2007, and the floods associated with the Great Cyclone of 1954. Detailed radiosonde data over a large area of southeast Australia is used to assess wind structures more broadly. In Section 6 we provide details on wind structure associated with some of the major coastal overland (non-riverine) floods identified by CP2014. In Section 7 we examine wind structures associated with record or near-record rainfall at several stations. In Section 8 we provide a brief overview of wind structures for all remaining major flood events identified by CP2014 since 1948 and assess the ability of reanalyses to capture these wind structures. In Section 9 we compare and contrast winds associated with localised flash flooding with winds associated with major (more widespread) flooding. In Section 10 we use and extend the analyses presented in Sections 5-8 to provide a more accurate description of the relationship between turning angle, wind-speed and extreme rainfall, and discuss the importance of atmospheric moisture to extreme rainfall. Results are summarised and discussed in Section 11.

2. Mechanisms producing the turning wind structure

Turning of the winds with height in an anti-cyclonic sense from Quasi Geostrophic (QG) theory is related to warm air advection and, under certain conditions, ascent (Holton 2004, pp. 73-74). The primary simplification in QG theory is that horizontal advection is accomplished by only the geostrophic winds. The data collected in this study consists of real wind observations and, as such, may differ from QG theory, which does not capture the full complexity of advection in Meteorology. For example, warm air advection can produce ascent, which cools air parcels adiabatically as they ascend. Conversely, cold air advection can produce adiabatic warming on the surface from descending air parcels. Nevertheless, we found that this observed wind structure - with winds turning anti-cyclonically with height and thus resembling QG warm air advection - to be associated with both large-scale ascent and extreme rainfall. Goff and Hanson (2012) found this to be the case in the middle latitudes of the United States. Previous studies (Callaghan and Tory 2014, Tory 2014, Bonell et al. 2005, Bonell and Callaghan 2008) examined winds associated with extreme rainfall in tropical cyclones and other weather systems in the tropics. They found, in the cases they examined, that extreme rainfall was associated with winds turning anti-cyclonically with height, between low levels and 500 hPa. Theoretical arguments (Tory 2014) suggest, assuming gradient wind balance, that isentropic uplift is likely to be associated with winds that turn anti-cyclonically with height in most heavy rain-bearing systems, including the tropics and subtropics. Here we will examine winds triggering extreme rainfall over our study region to determine whether or not these conclusions have broader applicability than the above studies, as anticipated from theory (Tory 2014).

The simplest explanation of the mechanism described in this paper involves warm moist air being lifted as it passes over denser and cooler air. Weather systems in these situations evolve such that large-scale flow patterns change with height to set up a synoptic-scale temperature gradient (or baroclinic zone) in the middle to lower levels of the troposphere. In this study the low level flow in the heavy rainfall area consists of mostly strong onshore (easterly) winds, whereas above this -

around 500 hPa - the flow is generally northerly and associated with a trough system to the west. This sets up the wind structure we observe of typically east northeasterly winds at 850 hPa turning anti-cyclonically with height to northerly winds by 500 hPa. The troughs evident at the 500 hPa level are associated with upper cyclonic potential vorticity anomalies (Hoskins et al 1985) which generate cool anomalies in the lower half of the troposphere and it is the cool zone which the low level onshore flow interacts with to form the baroclinic zone. This flow from warm to cold means that, as the flow is restrained to follow isentropes, it rises vertically. If the system is quasi-stationary, this configuration of vertical motion can be sustained, thus supporting continuous deep convection or stratiform rainfall or both.

This observed wind structure covers a larger area than the heavy rain area and can last several days. For example, during the disastrous Southeast Queensland floods of January 2011 the above wind structure existed at Brisbane Airport from 2300UTC 6 January 2011 to 1700UTC 11 January 2011. The extreme rainfall over this period, in five 24 hour blocks, was located 150 km, 70 km, 65 km, 30 km and 30 km from the radiosonde station.

The extreme rainfall is located in thunderstorms embedded in an area of moderate to heavy rainfall, and to produce major flooding usually has to be sustained for more than 24 hours. For example, in the Brisbane River average catchment rainfalls in excess of 200-300 mm in 48 hours are likely to produce moderate to major flooding.

Other weather systems capable of this heavy rainfall from the same process include the principal rainbands of tropical cyclones. Recent evidence shows that this can extend into the eyewall (see Callaghan and Tory 2014). Somewhat shorter periods of warm air advection are associated with severe convection, which generates major overland flooding (see below).

3. Data sources

The major aim of this investigation is to characterize the wind structure associated with major flooding in southeast Australia. Obtaining low to mid-level (850 to 500 hPa) wind data during heavy rainfall is extremely difficult. Prior to radar the presence of heavy cloud prevented balloon tracking. Even after the emergence of radar in the 1950s the problem was not completely overcome due to the difficulty in tracking balloon radar targets, as they are often difficult to discern from spurious radar returns reflected by heavy rain. The formation of ice on the radar targets carried by the balloons can prevent ascent of the balloon above the freezing level. Fortunately, highly skilled Bureau of Meteorology staff were often able to overcome these difficulties to obtain many reliable low-to-mid-level wind observations during extreme rainfall events. We have analysed this data to determine wind structure during well over 100 major floods over the last 50 years. Representative systems are presented and discussed below. This data is also used to calculate the climatology of winds and vertical differences in winds associated with heavy rainfall at Brisbane airport (Section 4).

To augment the upper wind observations, we will also use data from the National Centers for Environmental Prediction/ National Centre for Atmospheric Research (NCEP/NCAR) Reanalysis Project. This data extends back to 1948 (Kalnay 1996). These data were available at http://nomad3.ncep.noaa.gov/ncep_data/index.html. Recently this site became inoperative but similar charts are still available at http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html but unfortunately there are no vector wind analyses on this latter site.

4. Links between wind and rainfall at Brisbane

In this section we examine long-term average daily wind speed and direction at Brisbane airport, stratified according to the amount of daily rainfall received. The results are given in Table 1. Wind direction and speed are shown for three different vertical levels averaged over days with daily rainfall (i) 0-2 mm and greater than (ii) 2, (iii) 25, (iv) 50, (v) 75, and (vi) 100 mm. Data includes all days from approximately 1950-2007 with sufficient data available to perform the analysis.

The wind averaged over either all dry days or light rainfall days has a westerly component above 850 hPa. The wind averaged over days receiving more than 25 mm of rain, on the other hand, has an easterly component at 850 and 700 hPa, and at 500 hPa on days with rainfall exceeding 100 mm. The winds at 700 and 500 hPa on raindays turn cyclonically as the rainfall increases. On raindays, wind-speeds at 700 and 850 hPa tend to increase as the rainfall increases.

Pressure/Change in Pressure	*0-2 mm*	*> 2 mm*	*> 25 mm*	*> 50 mm*	*> 75 mm*	*>100 mm*
500 hPa	258/12.5	277/08.5	305/08.5	319/08.0	335/08.0	007/06.5
700 hPa	227/05.0	223/01.0	014/02.0	029/04.0	052/05.5	069/09.0
850 hPa	203/03.0	117/03.5	085/05.5	081/07.0	086/09.5	097/13.0
change, 700 to 500 hPa	31	54	-69	-70	-77	-62
change, 850 to 700 hPa	24	106	-71	-52	-34	-28

Table 1 Long-term climatological wind-direction at Brisbane Airport stratified according to daily rainfall received. Cells in the first three rows give the direction in degrees North, followed by the wind speeds in m/s. Angles between 0 and 180 degrees have an easterly component. The wind averaged over either all dry days or all raindays has a westerly component at all three levels (i.e. 850, 700 and 500 hPa). The wind averaged over days receiving more than 25 mm of rain, on the other hand, has an easterly component at 850 and 700 hPa, and at 500 hPa on days with rainfall exceeding 100 mm. The winds at 700 and 500 hPa on raindays turn clockwise as the rainfall increases. The average wind turns clockwise with increasing height on dry days and on days receiving 2 mm or less of rainfall. The average wind during days with rainfall exceeding 25 mm, on the other hand, turns anti-clockwise with increasing height. Anti-clockwise turning with height is indicated by negative changes. Winds measured twelve hours before reading the rain gauge for 24 hour rainfall. Cells in the last two rows give the change in wind direction from 700 to 500 hPa (again in degrees).

On days with light or no rainfall the winds turn cyclonically with increasing height, whereas on days with heavy rainfall the winds turn anti-cyclonically. The fact that the anti-cyclonic turning of winds with an easterly component in the low-to-mid troposphere is so clear in the climatology suggests that this wind structure is very likely of value for diagnosing heavy rainfall in and around Brisbane.

A graphical representation of the data is given in Figure 2. The observed turning in the wind direction with height results in vertical wind shear. To the extent that winds are approximately geostrophic, the shear barbs are approximately parallel to the 700 hPa isotherms with warm air to the left (SH) in the direction of the barb (Holton 2004). The diagram indicates that systems producing rainfall exceeding 25 mm/day are associated with winds at 700 hPa directed from warm areas to cooler areas.

The association between turning winds with height and extreme rainfall seen here at Brisbane is also evident at Cairns in the deep tropics (Callaghan and Tory 2014). Weather forecasters have been using the link between heavy rainfall and winds turning anti-cyclonically with height, particularly in the Queensland regional office, for many decades. A qualitative relationship between turning geostrophic winds with height and thermal advection can be found in most dynamic meteorological texts (e.g., Holton 2004). Upward motion is implied when wind blows from warm areas towards cold areas, indicative of isentropic ascent. This assumes that in dry processes the air is moving along constant potential temperature surfaces. An even stronger relationship between turning winds with height and thermal advection holds for gradient winds (Tory 2014). As almost all extreme rain events documented in this paper would be expected to approximately satisfy gradient wind balance, the turning winds with height is a reliable qualitative indicator of thermal advection and isentropic upslope flow. In a thermodynamically favorable environment (warm, moist lower troposphere) this synoptic scale lifting mechanism (under QG balance) leads to wide-spread, persistent deep convection, and associated extreme rain. Tory’s (2014) theory indicates that this relationship is true for gradient flow, and is independent of latitude. We therefore expect the relationship to hold throughout our study region (Figure 1, right panel). We will test this hypothesis in the following section by examining winds that occur in conjunction with extreme rainfall and major flooding.

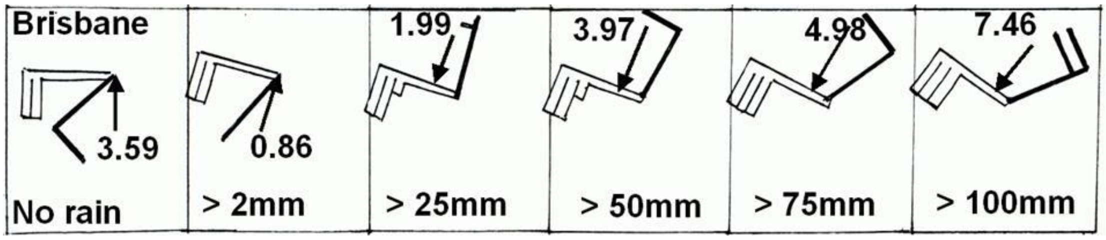

Figure 2 Vector analyses of average winds at Brisbane Airport Meteorological Station (latitude 27.40°S) for various 24-hour rainfall totals showing 850 hPa to 500 hPa shear (unfilled barb) and 700 hPa winds (solid barbs) using standard plotting convention where flag/ barb/half barb represents 50 knots (25 ms^{-1})/10 knots (5 ms^{-1})/5 knots (2.5 ms^{-1}). The component of the 700 hPa wind normal to the shear direction is marked by the arrows, with the speed in ms^{-1} near the arrow tail.

5. Low-to-mid-level wind structure associated with extreme rainfall and major riverine floods

In this section we examine low-to-mid-level winds associated with major riverine flooding. This includes examples of the two weather types responsible for triggering all of the major floods identified by CP2014: East Coast Lows (ECLs) and Tropical Interactions (TIs). CP2014 defined ECLs as (a) low pressure systems (either a closed low or trough) near or on the eastern coast of Australia of non-tropical origin, which are located (b) east of a deep layered trough and (c) north of a high pressure system, with (d) heavy rain in coastal areas generally south or southwest of the low pressure centre. The importance of ECLs and other low pressure systems to heavy rainfall over the eastern seaboard of Australia has been noted previously (e.g. Hopkins and Holland 1997; Pepler and Rakich 2010; Pepler et al. 2013).

CP2014 identified three different types of TIs: (i) Type I: a tropical cyclone (TC) that moves into the study region retaining its TC characteristics (e.g. minimal vertical shear environment); (ii) Type II: a deep layered trough system extends well into the tropics and either interacts with a TC or tropical low (TL), or forms an inland trough with strong north-easterlies on the coast. (iii) Type III: a TC or TL that is re-organised or transformed into a more ECL-like structure while interacting with a deep-layered trough as it moves into the study region. This particular TI is often referred to as an Extratropical Transition or ET (e.g. Callaghan 2005).

5.1 The Pasher Bulker Storm, 2007

A major flood was triggered by an ECL, called the "*Pasha Bulker* Storm", on Friday 8 and Saturday 9 June, 2007 (Verdon-Kidd et al. 2010; CP2014). The storm was named after the ship the storm forced ashore near Newcastle. Low to mid-level wind data is available from Williamtown in the Newcastle region. The Williamtown low to mid-level winds at 2100UTC 7 June 2007 and 0000UTC 8 June (Figure 3a) indicate anti-cyclonically turning winds with height during the period of heaviest rainfall. The heaviest rain at Williamtown fell soon after these radiosonde flights – 27.2 mm in 1 hour to 0230UTC 8 June 2007 and 45.8 mm in 1 hour to 0300UTC 8 June 2007. The *Pasher Bulker* Storm caused both riverine and overland (non-riverine) major flooding.

Note that this and other major floods were assigned reference numbers by CP2014. The *Pasha Bulker* Storm was referred to as Event 238 by CP2014, as it is here.

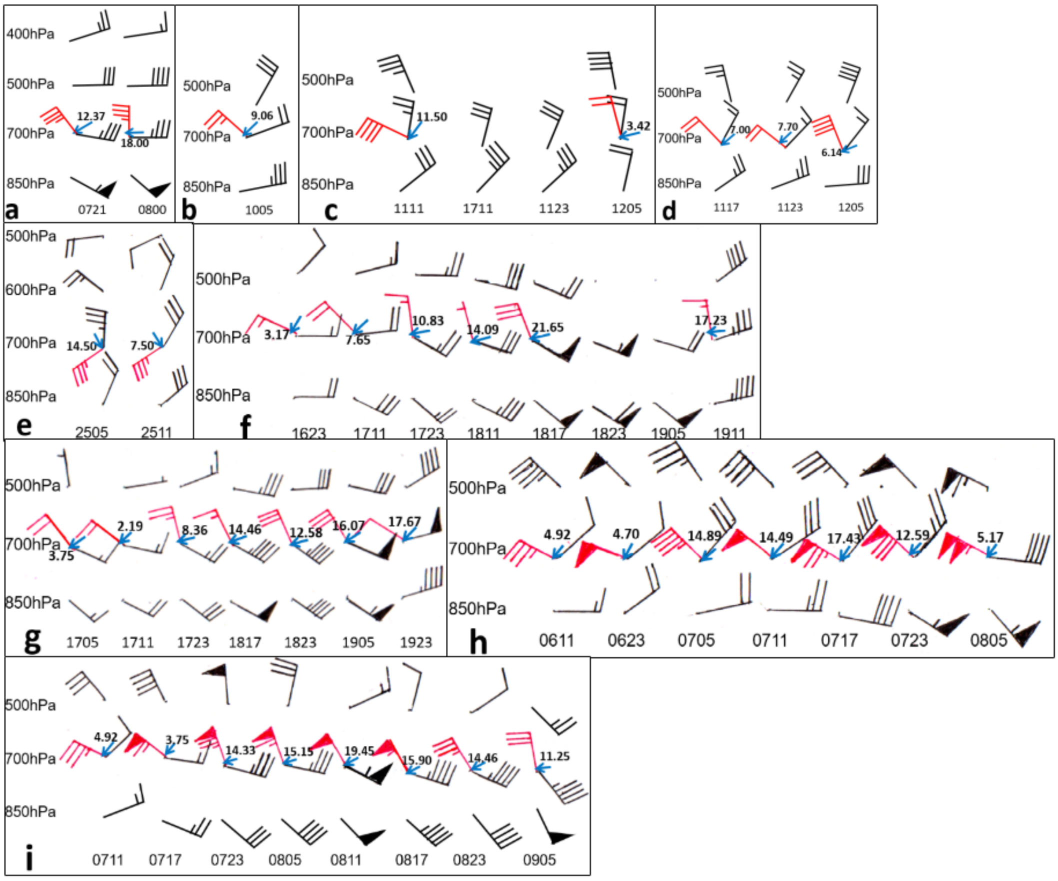

Figure 3 Winds with normal plotting convention are shown for 850 hPa 700 hPa and 500 hPa (and in some cases 600 hPa and 400 hPa) with the 500 hPa- 850hPa (sometimes 600 hPa-850 hPa) vector wind difference in red. The component of the 700 hPa wind normal to the shear direction is marked by the blue arrows, with the speed in ms^{-1} near the arrow. **a.** ECL, Williamtown 2100UTC 7 June 2007 (0721) and 0000UTC 8 June 2007 (0800); **b.** TI II, Lockyer/Toowoomba Floods Brisbane, 0500UTC 10 January2011. **c.** TI II, Brisbane, 1100UTC 11 December 1991 (1111) to 0500UTC 12 December 1991 (1205); **d.** TI II, Coffs Harbour, 1700UTC 11 December 1991 (1117) to 0500UTC 12 December 1991 (1205). **e.** ET arising from TC Wanda, Brisbane 0500UTC 25 January 1974 (2505) to 1100UTC 25 January 1974 (2511); **f.** ET, Event from Tropical Low, Williamtown from 2300UTC 16 March 1978 (1623) to 1100UTC 19 March 1978 (1911). **g.** ET arising from a Tropical Low, Sydney, 0500UTC 17 March 1978 (1705) to 2300UTC 19 March 1978 (1923). **h.** ET, arising from TC *Lance*, Brisbane from 1100UTC 6 April 1984 (0611) to 0500UTC 8 April 1984 (0805). **i.** ET arising from TC *Lance*, Coffs Harbour, from 1100UTC 7 April 1984 (0711) to 0500UTC 9 April 1984 (0905).

5.2 Brisbane floods, 2011

A low in the tropics interacting with a deep-layered trough in the study region (TI Type II, CP2014) triggered major flooding in the Brisbane River Catchment in January 2011. The most extreme rainfall and most disastrous flooding occurred on 10 January leading to the Toowoomba/Lockyer Creek flash-floods with around 25 fatalities. Brisbane Airport winds at 0500 UTC 10 January 2011 (close to the time of the event) showed the anti-cyclonic turning with height structure (Figure 3b).

5.3 Tropical Dip

Another example of TI Type II is often called a "*Tropical Dip*", in which a trough just inland from the coast dominates the synoptic situation. Such a system occurred in December 1991 (Event Number 215). There was very heavy rain reported between Brisbane and Coffs Harbour. Mt Glorious (western Brisbane suburb) recorded 500 mm in 24 hours and 211 mm fell in six hours to 2200UTC 11 December 1991 (9am local daylight saving time on the 12th). Official 24 hour totals to 9am were 319.2 mm on the 12th and 269.0 mm on the 13th. Further south Coffs Harbour recorded 230 mm in the 24 hours to 9am on the 13th (local time) that was a record daily December total. The interaction between a mid-to-upper-level trough with the low-level onshore flow produced the anti-cyclonic turning with height low-to-mid-level wind structure at Brisbane and Coffs Harbour and this is displayed in Figures 3c and 3d.

5.4 Brisbane Floods 1974

A (TI) Type III, Event Number 174, involved tropical cyclone Wanda in 1974 and caused record rainfall and major flooding in Brisbane. The heaviest rainfall in Brisbane fell early in the event. In the catchments of the Brisbane Metropolitan creeks heavy rain commenced about 2am on Friday 25 January (1600UTC 24 January) and continued until about 2 pm the same day (0400UTC 25 January). During that 12-hour period, falls ranged from 197 mm at the Bureau to 236 mm at Enoggera Reservoir and 280 mm at Mount Nebo. Another heavy rain period occurred from 0800UTC to 1700UTC 25 January. This record rainfall was shown to be associated with an anti-cyclonic turning with height wind profile at Brisbane Airport (Figure 3e).

5.5 Tropical Low 1978

Another example (Event Number 191) of (TI) Type III was presented by CP2014 in which a tropical low transformed into an ECL. This event caused disastrous flooding in Nepean/Hawkesbury River system in 1978 and many rainfall records were broken. The favorable wind structure for extreme rainfall in this event for both Williamtown (Figure 3f) and Sydney (Figure 3g) are shown.

5.6 Ex-Tropical Cyclone Lance

Event Number 196 was another TI Type III event in this case when Tropical Cyclone *Lance* underwent rapid extra tropical transition near and east of Brisbane resulting in the intensification of a new centre of low pressure south of the cyclone, much like Event Number 49 in 1893 (see CP2014). Heavy rain fell between Brisbane and Coffs Harbour, with the heaviest rainfall on the Gold Coast and in the Lismore area. The evidence of anti-cyclonic turning with height over this region is provided by the Brisbane and Coffs Harbour winds shown in Figures 3h and 3i.

5.7 The Great Cyclone of 1954

The last TI Type I to cause a major flood in the study area was by triggered by the *Great Cyclone* on February 20, 1954. The Great Cyclone was a severe tropical cyclone (Event Number 134 in CP2014). At that time the Bureau's radiosonde network was in its infancy. Only two sites near the cyclone, Charleville and Newcastle, had radiosonde data. As these sites are quite a distance from the main centre of the cyclone, we use the diagnostic technique introduced in Section 3, illustrated in Figure 2, together with reanalysis data (Figure 4). This figure indicates that the structure of the *Great Cyclone* consisted of a cyclonic circulation with ascent on the eastern side of the circulation centre, and descent on the western flank. Figure 4 also indicates a consistency between the reanalysis data and the radiosonde data, with ascent diagnosed in the east and descent diagnosed in the west.

6. Winds associated with coastal overland (non-riverine) major flooding

In this section we determine the wind structure that occurs in association with major coastal overland (i.e. non-riverine) flooding in the CP2014 study region. Low to mid-level wind observations were obtained near and close to the time of the extreme rainfall. Five case studies are described below. The Event Number assigned to them by CP2014 is provided in each case. Further details on the events are available in the Supplementary Material to CP2014.

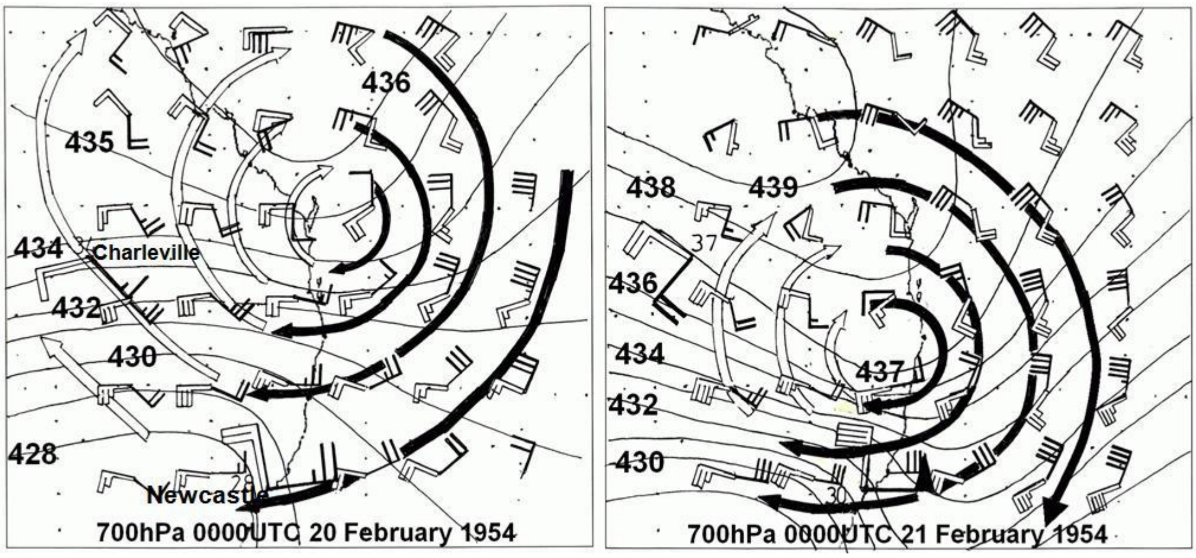

Figure 4 Sequence of isotherms and winds at 700 hPa for 0000UTC 20 February 1954 (left) and 0000UTC 21 February 1954 (right). The charts show 700 hPa wind (solid barbs) and 850 to 500 hPa shear vectors (unfilled barbs). Large barbs are actual observations at Charleville and Newcastle while smaller barbs are from NCEP/NCAR reanalyses. Large black arrows indicate warm air advection and ascent at 700 hPa. Large unfilled arrows indicate areas of descent at 700 hPa. The thin solid curved lines are 850-500 hPa isothickness lines, an indicator of average temperature through the layer (i.e. isotherms).

6.1 Event Number 195

On 18 February 1984 extreme rainfall amounts, exceeding 800 mm in 24 hours, fell on the Illawarra escarpment and similar falls were estimated to have covered about 100 square kilometres. The very heavy rain extended in the Illawarra region from Mount Keira Scout Camp to Foxground, a distance of just over 350 km. The winds for this event, which turn anti-cyclonically with height, are depicted in Figure 5a.

Figure 6 helps describe this event, which produced some of the heaviest rainfall ever recorded in NSW. At Wongawilli on the Illawarra Escarpment west of Dapto, 796.5 mm was recorded in 24 hours and 597 mm of this fell in the 8 hours from 1700UTC 17 February 1984 to 0100UTC 18 February 1984 (Shepherd and Coloquhoun, 1985). In the 2 hours from 1700UTC 17 February covered by Figure 6 when a mesoscale low was evident near Wollongong, 224.5 mm was recorded at Wongawilli, which was the most intense rainfall of the whole event. The winds were very strong and reached storm force at Port Kembla. At 2300UTC 17 February the mesoscale low was still evident but winds at Port Kembla were down to 35 knots. By 0000UTC 1 February the low had dissipated, but 75 to 80 mm were still recorded over this hour. Over the intense rain area, convective thunderstorm cells moved from northeast to southwest through a quasi-stationary rain area. The extreme rainfall formed from storm cells that developed in an environment of turning winds with height.

6.2 Event Number 198

On 5-9 November 1984 a storm affected Sydney. During 8 November extreme rainfall from thunderstorms extended from Turramurra 16 km north-northwest of the City to Randwick Racecourse 5 km SSE of the City and then to Audley Royal National Park 26 km SSW of the City. At Observatory Hill 196 mm fell in the three hours from 1000UTC 8 November 1984. The winds for this event turn anti-cyclonically with height (Figure 5b).

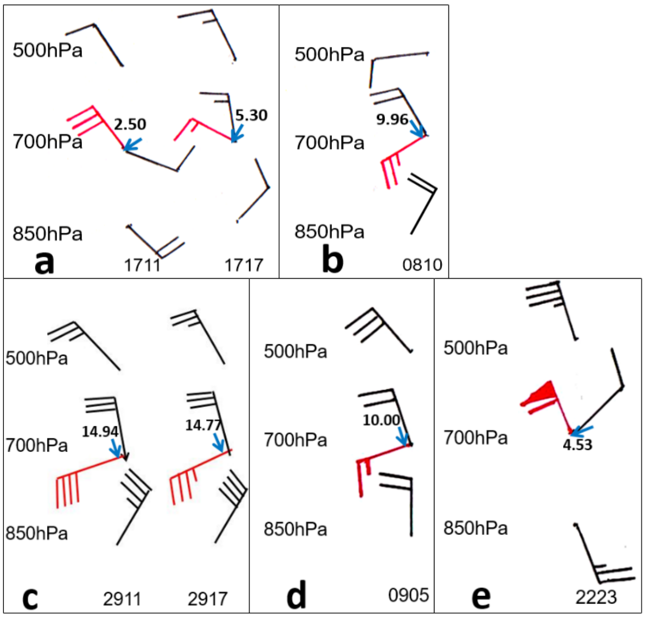

Figure 5 Upper winds (as in Figure 3), except for overland flooding events. **a.** Sydney, 1100UTC 17 February 1984 and 1700 UTC 17 February 1984; **b**. Sydney, 1000UTC 8 November 1984; **c**. Brisbane, 1100UTC 29 June 2005 and 1700UTC 29 June 2005; **d**. Brisbane, 0500UTC 9 March 2001; **e.** Coffs Harbour.

6.3 Event Number 237

On 30 June 2005 (described in Section 8) there was widespread severe flooding along the whole Gold Coast and NSW Tweed Coast strip with hourly rainfall totals up to 145 mm and 12 hour rainfall totals to 0100UTC 30 June 2005 of 503 mm. The winds for this event turn anti-cyclonically with height (Figure 5c).

6.4 Event Number 234

On 9 March 2001 widespread severe flash flooding occurred over southeast Queensland (Malone and Muller 2004) after a TI Type III low system made landfall and two fatalities occurred with these floods. The heavy rainfall extended over a large area of Southeast Queensland extending from the Sunshine Coast through greater Brisbane to the Gold Coast (over 140 km) and it occurred from 0400UTC to 1100UTC 9 March 2001. Some of the heavier hourly rainfalls totals were: Nambour (Sunshine Coast) 152.0 mm in 1 hr to 1000UTC; Everton Hills (NW Brisbane) 106.0 mm in 1 hr to 0900UT; East Brisbane (Inner Brisbane) 102.0 mm in 1 hr to 0800UTC; Greenslopes (S Brisbane) 114.0 mm in 1 hr to 0800UTC; Holland Park (S Brisbane) 111.0 mm in 1 hr to 0800UTC; Mt Gravatt (S Brisbane) 128.0 mm in 1 hr to 0800UTC; Beenleigh (Northern Gold Coast) 114.0 mm in 1 hr to 0700UTC; Wolffdene (Gold Coast Hinterland) 106.0 mm in 1 hr to 0800UT; Carrara (Gold Coast) 108.0 mm in 1 hr to 0700UTC. The winds for this event also turn anti-cyclonically with height (Figure 5d).

6.5 Event Number 223

This storm devastated Coffs Harbour region on 23-24 November 1996 with South Boambee recording 446.5 mm in 6 hours from 0400UTC 23 November. The very heavy rain in the Coffs Harbour region extended from extended from Upper Orara to Bellbrook a distance of around 55 km. The winds for this event are depicted in Figure 5e. As for the previous events, the winds turn anti-cyclonically with height.

6.6 Overview and Summary

As noted above, all of the main results from these five events are depicted in Figure 5. Winds turning anti-cyclonically with height are again evident. However, there tends to be a reduced or zero easterly component in the 700 hPa and 500 hPa winds. This difference in wind structure, as compared to winds that occur during major riverine flooding, tends to keep the

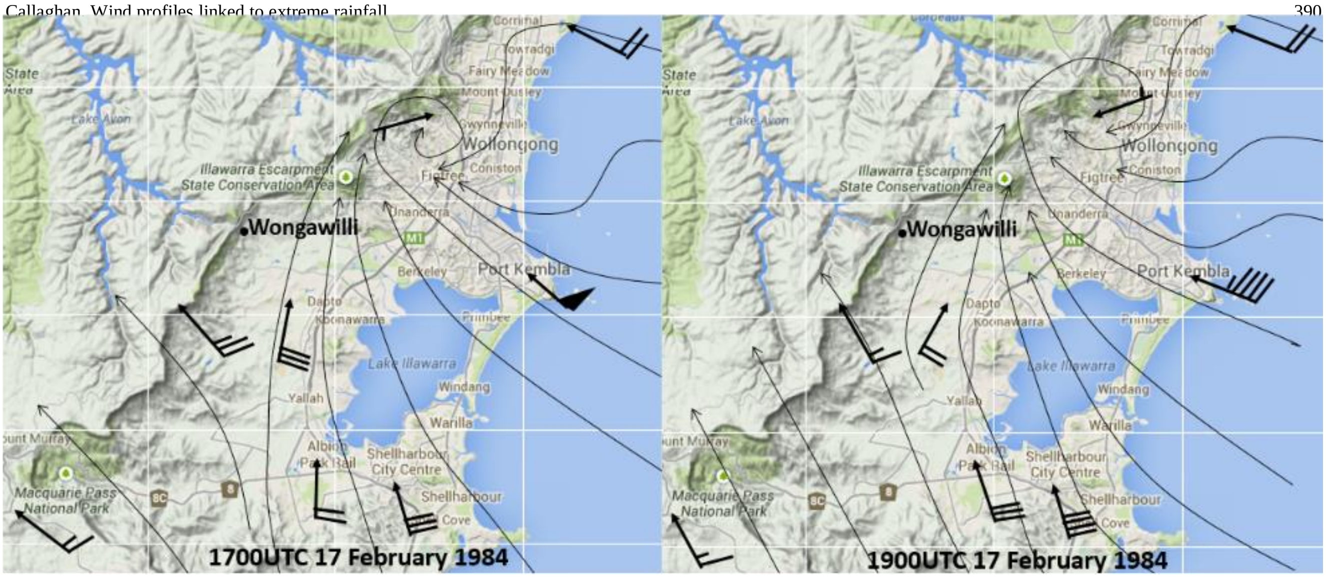

Figure 6 Surface wind analyses during the heaviest rainfall of the event between 1700UTC and 1900UTC 17 February. Wind data from Woelfle anemometers owned by Macquarie University.

intense convective rain near the coast. This is because convective systems that develop are not steered inland by the middle level winds with an easterly component.

7. Wind structure associated with record or near-record rainfall

In this section we will determine whether or not the association between extreme rainfall and wind structure applies in cases where record rainfall occurs. To do this we examine data at twelve stations that have both rainfall and low-to-mid-level wind data. Some of these stations are within the CP2014 study region, some well beyond (Figure 1, right panel). In eleven of the twelve sites we determine the low-to-mid-level wind structure associated with the highest rainfall evident in each of station's record. Winds are not available at one station for the period when the station's record rain fell. For this station we examine winds that occurred during the period when the second highest rainfall on record occurred. Details on rainfall and other features of the events are given in Appendix A. The low-to-mid-level wind data associated with these events are shown in Figure 7**.** All locations have winds turning anti-cyclonic with height during the record rainfall event. This indicates that the link between extreme rainfall and turning winds is evident well beyond the study region used by CP2014 (Figure 1, left panel).

8. A summary of winds associated with additional major floods since 1948

In previous sections we provided details and presented data on winds associated with rainfall at Brisbane (Section 3), major riverine floods (Section 4), some major overland (non-riverine) floods (Section 5), and record or near-record rainfall at additional sites (Section 6). We found in each case that that low-to-mid-level winds turned anti-cyclonically with height in association with extreme rainfall. As noted in Section 3, this wind structure is associated with warm air advection at the 700 hPa level, i.e., with winds blowing from warmer to cooler regions (Tory 2014).

In this section we examine winds in additional events to first provide an example of the small number of cases in which winds do not turn anti-cyclonically with height, and second, to assess the ability of the NCEP/NCAR reanalysis to capture synoptic structures associated with extreme rainfall events.

It is not possible to provide this level of detail for all of the remaining events. Instead, in this Section we provide a very short summary of remaining events, focusing on whether or not the winds turned anti-cyclonically or, equivalently, whether there is warm air advection evident from reanalysis data (see Section 3).

We examined the low-to-mid-level wind structure for all major flood events from Numbers 119 to 240 (1948-2012, see CP2014 for further details), events for which information on the low-to-mid-level wind structure is available. From Event 158 (29-30 August 1963) to Event 240 (22-27 January 2012) only one heavy rainfall event did not display the anti-cyclonically turning wind pattern or 700 hPa winds flowing from warm to cool regions associated.

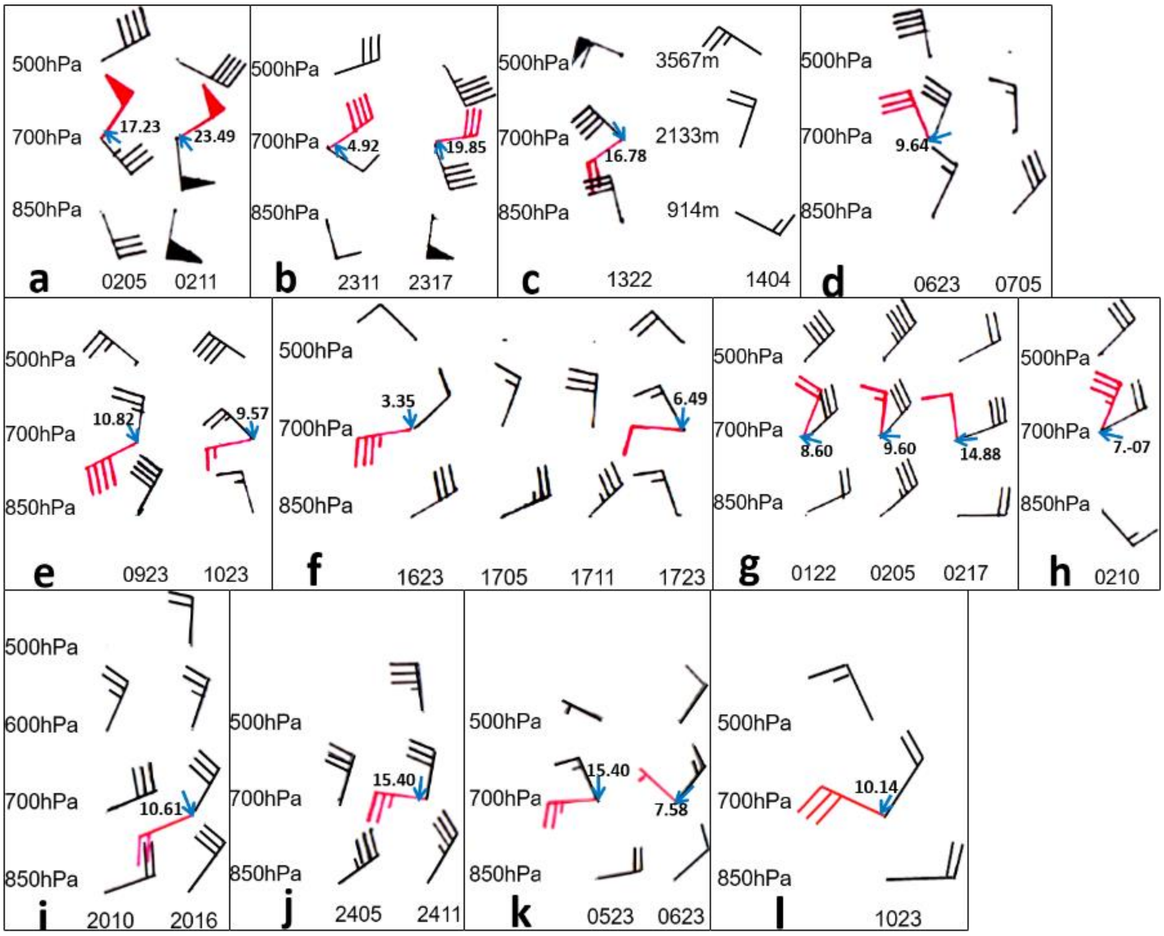

Figure 7 Upper winds (as in Figure 3), for record rainfall events at radiosonde stations. **a**. Melbourne, 0500UTC 2 February 2005 and 1100UTC 2 February 2005. **b**. East Sale, 1100UTC 23 April 2004 and 1700 UTC 23 April 2004. **c**. Canberra, 2200UTC 13 March 1989 (winds at pressure levels) and 0400UTC 14 March 1989 winds at elevation in metres. **d**. Wagga Wagga, 2300UTC 6 March 2010 and 0500UTC 7 March 2010. **e**. Moree, 2300UTC 9 February 1976 and 2300UTC 10 February 1976. **f**. Lord Howe Island, winds from 2300UTC 16 June 1996 to 2300UTC 17 June 1996. **g**. Williamtown, 2200UTC 1 February 1990 to 1700UTC 2 February 1990. **h.** Sydney Airport, 1000UTC 2 February 1990. **i**. Gladstone, 1000UTC 20 February 1992 and 1600UTC 20 February 1992. **j**. Rockhampton, 0500UTC 24 January 2013 and 1100UTC 24 January 2013. **k.** Coffs Harbour, 2300UTC 5 November 2009 and 2300UTC 6 November 2009. **l.** Nowra, 2300UTC 10 March 1075. Recorded rain in the Nowra region over the 10-11 March 1975 during an ECL, Event No 180.

8.1 An Event which does not display anti-cyclonically turning winds

Of all the events examined only one event did not clearly display anti-cyclonically turning winds or warm air advection. This is Event Number 218, which affected the Brisbane area on 19-20 January 1994. Rainfall intensities were around 100 mm per hour with total falls up to 277.6 mm over a wide area around Brisbane. Three people died in traffic accidents and a boy was swept down a drain. A man was also rescued by a State Emergency Service helicopter when his car was swept into a flooded creek. One hundred homes were damaged by the floodwaters.

During the day a series of very heavy thunderstorms affected the Brisbane area causing widespread flash flooding. The atmosphere was very humid with dewpoints up to 25°C under the influence of major tropical cyclone *Rewa* located off the Central Queensland coast. The radiosonde observed winds at 0000UTC 19 January1994 from the surface to 500 hPa came from the northeast with little consistent turning with height. The NCEP winds (not shown) were similar with a mixture of winds turning cyclonically and anti-cyclonically while the 700 hPa NCEP charts indicated weak flow from cool to warm regions. The lack of large-scale ascent helped produce these exceptional storms, as clear skies before and between the storms made the air extremely hot and humid. Aloft (500 hPa), there was a relatively cool environment due to an upper trough system producing an extremely buoyant atmosphere.

The major flooding in this case, which did not have anti-cyclonically turning winds or warm air advection, was caused by persistent, extreme localized thunderstorm activity, helped by a deep-layered trough system extending up to a Severe TC (TI Type II).

8.2 Ability of the NCEP/NCAR reanalysis to simulate wind structures of deep, small-scale lows

NCEP/NCAR reanalyses appeared to be less accurate on several occasions prior to the event described in Section 8.1 (e.g., Event Number 154). This was a tropical cyclone that triggered a major flood at Grafton on 4 January 1963. This weather system exhibited anti-cyclonic turning winds associated with heavy rain at landfall on 1 January 1963, both in the radio-sonde winds and NCEP charts. However, after this, during periods of extreme rainfall, the NCEP charts indicated a cool to warm 700 hPa flow – opposite to the direction of flow typically seen. This was due to a failure to simulate a small-scale, low pressure system at sea level, and therefore not a true depiction of what actually occurred.

Two additional previous events occurred for which the NCEP reanalyses failed to resolve small intense low pressure systems evident in surface data: Event Numbers 147 (3-5 March 1961) and 144 (20-22 October 1959). This inaccuracy resulted in spurious cyclonically turning winds over the heavy rain areas.

No.	*Location*	*Date*	*Type*	*Freshwater flooding fatalities*
119	Lismore, Murwillumbah and Grafton	14-16 June 1948	TI3	
120	Georges River; Lake Macquarie; Maitland, Wyong	19 June 1949	ECL NC	7
122	Brisbane to Sydney	16-19 Jan 1950	TI3	7
123	Bega & Hunter River at Maitland	6–8 Feb 1950	ECL NC	
128	Northern Rivers	20-26 Jan 1951	TI3	
137	Murwillumbah, Lismore and Grafton	26-29 March 1955	TI2	1
142	Major floods Grafton & Lake Illawarra	16-19 Feb 1959	TI3	
144	Widespread very severe floods Illawarra	20-22 Oct 1959	ECL C	
147	Bega	3–5 March 1961	ECL C	
154	Grafton	1 Jan 1963	TI3	
218	Brisbane	19-20 Jan 1994	TI 2	4

Table 2 Subset of major flood events without direct evidence of winds turning in an anti-cyclonic sense between 850 hPa and 500 hPa. From Table 1 in CP2014 found at http://www.bom.gov.au/amm/docs/2014/callaghan_hres.pdf.

Two earlier events, 142 (16-19 February 1959) and 137 (26-29 March 1955), were associated with warm air advection patterns at 700 hPa near, but not exactly over, the heavy rain areas. However, this is likely to be a simulation shortcoming associated with the small-scale nature of the low, rather than what actually occurred in nature.

A simulation failure also occurred with Event Number 128 (20-26 January 1951). In this case NCEP/NCAR winds looked unrealistic, showing a cyclonically turning wind pattern with a 700 hPa cool advection pattern over the heavy rain areas. This also occurred in Events 122 and 123 (during January and February 1950). In the two earliest events, 119 (14-16 June 1948) and 120 (19 June 1949), the reanalyses charts failed to resolve small intense low-pressure systems, and this resulted in spurious cool air advection at 700 hPa above the heavy rain areas.

An outstanding example of the difficulty of using NCEP/NCAR (2.5° by 2.5°) reanalyses is tropical cyclone Tracy, which devastated Darwin on December 25 1974. This was a very intense, relatively small-scale event that was very poorly depicted by the reanalyses (Appendix B).

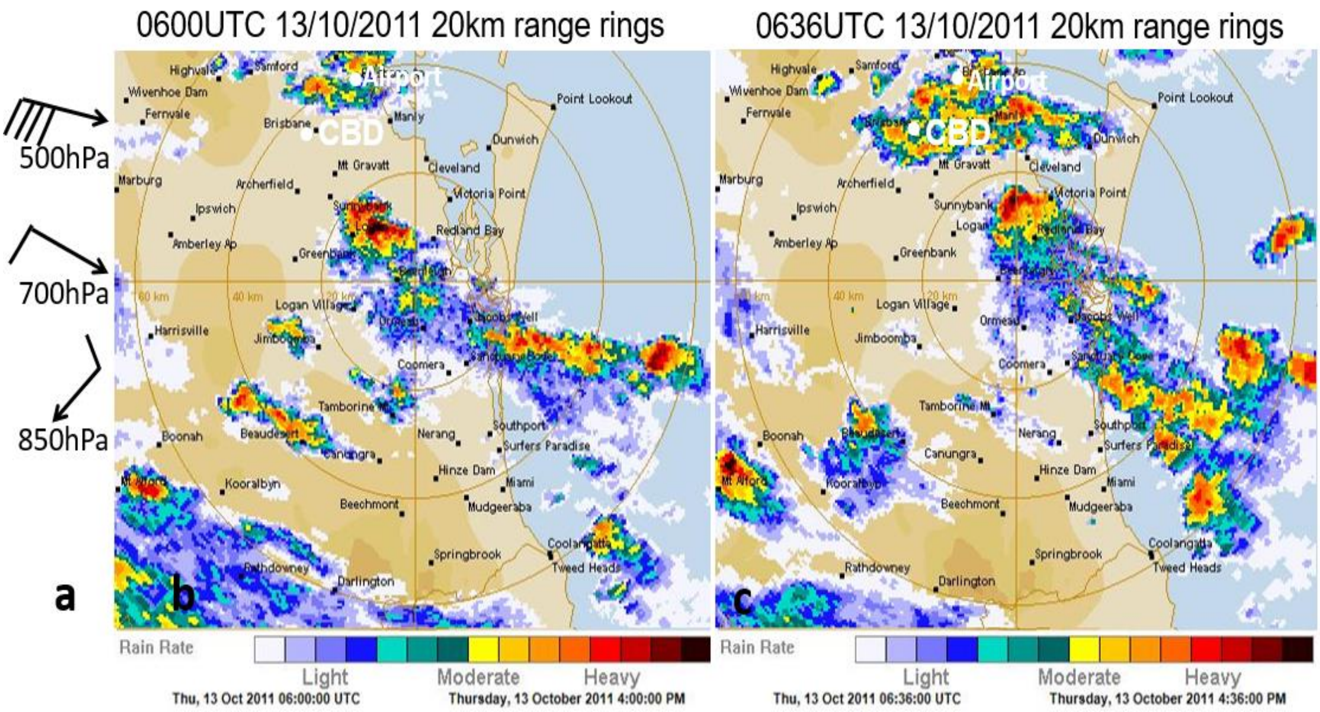

Figure 8 **a.** Brisbane Airport 850 hPa, 700 hPa and 500 hPa winds at 0500UTC 13 October 2011 near the time of the storms with plotting convention as in Figure 2. **b.** Radar image Brisbane radar at 0600UTC 13 October 2011. **c.** Radar image 0636UTC 13 October 2011. The heavy echo which passed between the radar centre and the CBD caused 58mm to be recorded in the hour to 0700UTC 13 October 2011 beneath it and this was the heaviest rainfall registration in the passage of the storms through the Brisbane region on 13 October 2011.

8.3 Overview and implications

Overall, from 1949 to 1963, there were 20 events out of 35 in which the NCEP/NCAR reanalyses exhibited anti-cyclonic turning and warm air advection. The remaining ten cases (see Table 2) appear to be due to simulation shortcomings rather than a true reflection of what actually occurred. For comparison the full list of major flood events can be obtained from the link http://www.bom.gov.au/amm/docs/2014/callaghan_hres.pdf to CP2014. In most of the remaining cases, this occurred when the low pressure system was intense and particularly small in horizontal scale. Since 1963 the warm air advection diagnostic (as depicted in Figure 2) has been an extremely robust indicator of extreme rainfall in the reanalyses.

We identified one case only, Event Number 218 (19-20 January 1994), that we confirmed did not exhibit anti-cyclonically turning winds or warm air advection. The major flooding in this case was caused by extreme localized thunderstorm activity triggered by TI Type II event.

The wind-structures are related to the synoptic scale system surrounding the extreme rainfall. As such they typically extend over a much greater horizontal area than the extreme rainfall. This suggests that the wind structures could be modelled using the relatively coarse resolution employed in the current generation of climate models (typically 180 km, see Hennessy et al. 2015). It might therefore be possible to infer extreme rainfall in many situations, even if models are not able to simulate the extreme rainfall embedded in the typically broader-scale winds. If this is the case, there is potential to use simulated wind structures as a diagnostic for extreme rainfall and major flooding in climate change projection studies.

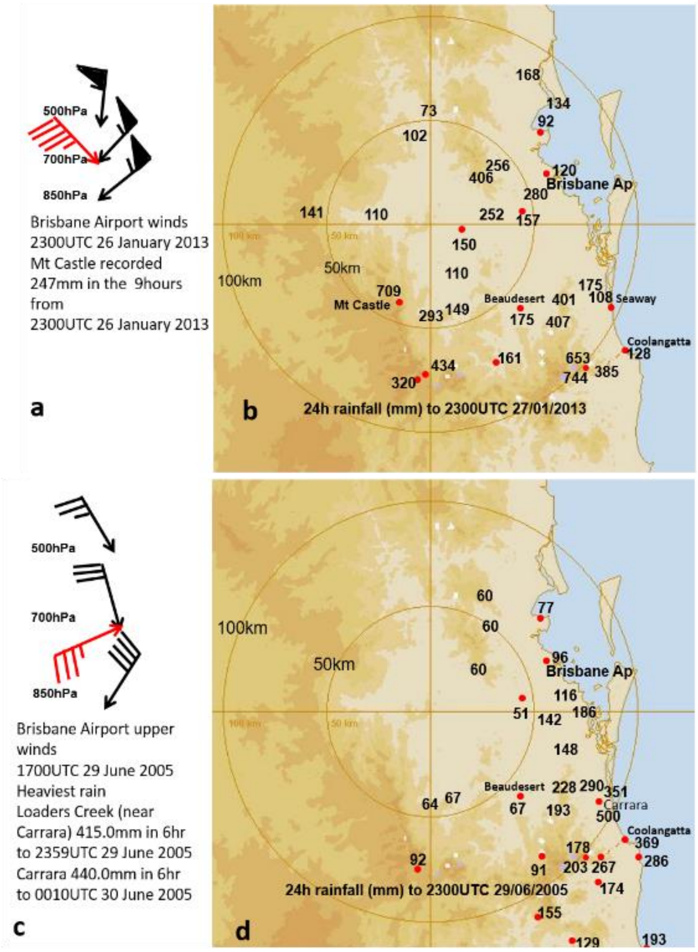

Figure 9 **a.** Brisbane Airport, 850 hPa 700 hPa and 500 hPa winds (plotting convention as in Figure 2) for 2300UTC 26 January 2013. **b.** 24 hour rainfall totals shown on topography (darker brown is higher elevation to approximately 1180 m) for 2300UTC 27 January 2013. **c.** Brisbane Airport, 850 hPa 700 hPa and 500 hPa winds for 1700UTC 29 June 2005. **d.** 24 hour rainfall totals shown with heaviest falls on the coastal plains for 2300UTC 29 June 2005.

9. Winds associated with localised flooding

In this Section we examine the wind structure associated with (i) a localised severe thunderstorm that caused flash flooding and hail. We will compare and contrast these winds with winds associated with major (ii) riverine and (iii) overland flooding. We will see that wind structures associated with (i) are very different to those associated with both (ii) and (iii).

As noted previously by CP2014, thunderstorms are often embedded in large-scale wind structures and frequently contribute to major flooding. Such thunderstorms should be contrasted with more typical thunderstorms that occur in winds with a westerly component above the atmospheric boundary layer during summer. These more typical thunderstorms can also cause flooding. However, the associated flooding is almost always much less extensive than flooding that occurs in association with large-scale onshore winds identified in this study.

A typical example of the wind structure and rain distribution for a thunderstorm during the Brisbane severe thunderstorm season (typically October to January) is shown in Figure 8. The particular event shown caused rain and hail damage to several homes in Brisbane's southern suburbs. The largest hourly rainfall total was 67 mm and the highest total rainfall from the passage of the storm was 112 mm.

This event is compared with the scale and wind structures associated with a major riverine flooding event (Ex-Tropical Cyclone *Oswald* 2013), and a major coastal plains overland event (Event Number 237 in CP2014). The winds and rainfall associated with these events are depicted in Figure 9.

Brisbane low-to-mid-level winds during the riverine flooding event exhibited anti-cyclonic turning winds with an easterly component between 850 hPa and 500 hPa, in association with heavy rainfall (exceeding 700 mm) on the ranges inland from the coast. The coastal flooding event, however, had the anti-cyclonic turning winds with no or little easterly component above 850 hPa, and the heaviest rainfall (500 mm in 12 hours) right on the coast. Strong 700 hPa winds flowing almost at right angles across the similarly strong 850 hPa to 500 hPa shears imply large-scale ascent in both the riverine and overland flooding events with the riverine event having the stronger ascent.

In contrast the severe thunderstorm event had lighter low level winds which quickly turned westerly and increased in speed with height, with the heavy rain very isolated in both space and time compared with the major flooding events.

10. Further investigation of turning angles and wind-speeds associated with extreme rainfall

In this section we use and extend the analyses presented in Sections 3-6, to provide a more accurate description of the relationship between turning angle, wind-speed and extreme rainfall. We also touch on the importance of atmospheric moisture to extreme rainfall.

10.1 Link between the magnitude of the turning angle and rainfall amount

A rule of thumb for extreme rainfall by forecasters in the Queensland Regional Office of the Bureau of Meteorology is

(i) anti-cyclonic turning of the winds between 850 hPa and 500 hPa
(ii) low level winds directly onshore
(iii) and a turning angle of approximately 90° or less.

If we examine individual events in Figures 3, 7 and 9, we find that there is a tendency for the turning angle to be smaller than 90° for high rainfall amounts.

10.2 Extreme rainfall in the presence of lighter onshore winds

Lighter wind speeds between 850 hPa and 500 hPa are associated with extreme rainfall when the atmosphere is buoyant and encourages deep mesoscale convection. For example, on 10 May 1987 (Event Number 202, CP2014) a reliable unofficial total of 280 mm fell in one hour while average winds between 850 hPa and 500 hPa were less than 10 ms^{-1}.

10.3 Effect of dewpoints on extreme rainfall

The focus in this paper is on links between winds and both extreme rainfall and major flooding. Note, however, that the amount of moisture (dewpoint) is also important. This is borne out in a comparing data from Cairns (latitude 16.87° S, see Callaghan and Tory 2014) with data from Brisbane (Section 3) approximately 1500 km further south. Dew points in onshore flows at Cairns are always much higher than in onshore flow at Brisbane. As a result, a given wind in Cairns produces greater rainfall than the same wind strength does in Brisbane. Note also the record rainfall in Melbourne (Figure 7a) where the average winds in the layer were very strong but only produced 138.8 mm of rain in 24 hours as the dewpoints were only 11.2C.

11. Summary and Discussion

The primary aim of this investigation is to determine the extent to which winds associated with extreme rainfall and major flooding in coastal catchments over southeast Australia exhibit common features. To this end we examined both radiosonde and reanalysis data. We analysed long-term average daily wind speed and direction at Brisbane airport, stratified according to the amount of daily rainfall received. We also provided a detailed description of wind structure associated with some of the major coastal floods (both riverine and non-riverine) identified by CP2014, including the Brisbane floods of 2011, the floods triggered by The Great Cyclone of 1954, and the *Pasher Bulker* Storm in 2007. We also examined wind structures associated with record or near-record rainfall at several stations, and we provided a brief overview of wind structures for all remaining major flood events identified by CP2014 since 1948. The ability of NCAR/NCEP reanalyses to capture the wind structure was also assessed.

In almost every case and every location the low-level winds tend to be onshore, and the wind-direction tends to turn anti-cyclonically with increasing height up to 500 hPa. This wind structure is evident over hundreds of kilometres.

Winds associated with major coastal non-riverine flooding also turned anti-cyclonically, however, the easterly component of their 700 hPa and 500 hPa winds tended to be reduced (relative to winds associated with major riverine flooding) or zero. This feature tends to keep the intense convective rain near the coast, because convective systems that develop are not steered inland by the mid-level winds.

We found that from 1949 to 1963, there were 20 events out of 35 in which the NCEP/NCAR reanalyses exhibit anti-cyclonic turning and warm air advection. The remaining cases appear to be due to simulation shortcomings rather than a true reflection of what actually occurred. In most of the remaining cases this occurred when the low pressure system was intense and particularly small in horizontal scale. Since 1963 the diagnostic has been an extremely robust indicator of extreme rainfall in the reanalyses.

We identified one case only, Event Number 218 (CP2014, 19-20 January 1994), that we confirmed did not exhibit anti-cyclonic turning winds or warm air advection. The major flooding in this case was caused by severe thunderstorm activity in deep northeasterly uni-directional flow associated with a TI Type II event (see CP2014 for further discussion of such storm systems). This differed from isolated thunderstorm cases associated with lighter low level winds which quickly turned westerly and increased in speed with height.

In this paper, we focussed on winds associated with major flooding or extreme rainfall. We have also extensively examined winds in situations not resulting in extreme rainfall or major flooding. We were only able to detect a small number of cases in which turning winds (with turning angle less than 90°) were evident in association with onshore low-level winds, in the absence of extreme rainfall or major flooding. All of these cases occurred in the tropics during winter. Heavy rain did not occur in the cases because the air was either too dry at mid-level or too stable in the lower levels. While we hope to report on the details of this additional analysis in a future study, we can already conclude that these null events are rare.

As the study region considered incorporates tropical and sub-tropical locations, this study indicates that the relationship between turning winds and rainfall at mid-latitudes (e.g. Holton 2004), and in tropical cyclones (Callaghan and Tory 2014), has broader applicability, and is evident in situations that cause extreme rainfall and major flooding.

Direct model forecasts frequently underestimate the magnitude of maximum rainfall associated with convective processes (van den Honert and McAneney 2011; Gao et al. 2009; Sandeep Sahany et al. 2010). This was the case for direct model forecasts leading up to the disastrous 2011 Brisbane River and Lockyer Valley floods, which were a third of the amount actually received (van den Honert and McAneney 2011). A similar situation occurred in the disastrous 2005 Mumbai Floods (Sahany et al. 2010), and in 2006 associated with one of the worst floods to affect China since 1983 (Gao et al. 2009).

Forecasters in the Australian Bureau of Meteorology's Brisbane office have been using the presence of turning winds to improve the quality of their warming services for many years. In the 1990s severe weather forecasters located regions exhibiting anti-cyclonically turning winds with height in the model forecast fields, and they used this as an indicator of increased risk of imminent heavy rainfall. Since approximately 2000, forecasters have been using rainfall predicted directly from the model. However, they have found that if a model forecasts heavy rainfall in the vicinity of turning winds, then the maximum rainfall actually received is almost always much greater than the maximum rainfall directly forecasted by the model.

The wind structures associated with extreme rainfall and major flooding identified here extend well beyond the region of extreme rainfall, and are properties of the broader synoptic-scale weather system. The large-scale wind structures described almost always occur simultaneously with extreme rainfall, and one rarely occurs without the other. Fortunately, such large-scale winds are expected to be well-simulated using numerical weather and climate modelling systems. So, even though extreme rainfall itself can be difficult to simulate, the relationship between large-scale winds and extreme rainfall described here points to an exciting tool to assist forecasting the location and intensity of extreme rainfall in south-eastern Australia more broadly, and for projecting changes in the intensity and frequency of extreme rainfall and major flooding over coming decades.

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We are indebted to Samantha Taylor for her work on the relationship between rainfall and archived low to middle level wind data at Cairns and Brisbane. We thank NCAR and NCEP for making available their joint reanalysis of past weather, and Google for Figure 1. Radiosonde wind data was obtained from the Bureau of Meteorology's archives and additional wind data was obtained from the University of Wyoming site http://weather.uwyo.edu/upperair/sounding.html. We also thank Kevin Tory, Will Thurston, Beth Lavery and anonymous reviewers for careful and very helpful reviews of earlier drafts, and Madelaine Gamble Rosevear for carefully copyediting the paper.

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Appendix A: Details on events occurring in association with record or near-record rainfall presented in Figure 7.

In Figure 7 The upper winds coinciding with record rainfall events at Radiosonde Stations in and surrounding the study area are presented.

Figure 7a: Melbourne upper winds 0500UTC 2 February 2005 and 1100UTC 2 February 2005 while the Melbourne rainfall was recorded as55.8mm in 12 hours to 1000UTC 2 February, 59.0mmn in 9hours to 1900UTC 2 February and 24.0mm in 3hours to 2200UTC 2 February.

Figure 7b: East Sale upper winds 1100UTC 23 April 2004 and 1700 UTC 23 April 2004 with 24hour rainfall to 2300UTC 23 April 2004 is 108.8mm.

Figure 7c: Canberra upper winds 2200UTC 13 March 1989 (winds at pressure levels) and 0400UTC 14 March 1989 winds at elevation in metres with 107mm in 12 hours to 1000UTC 14 March 1989.

Figure 7d: Wagga Wagga upper winds 2300UTC 6 March 2010 and 0500UTC 7 March 2010 with 24 hour rainfall record to 2300UTC 7 March 2010 110.8mm and 96mm in 14 hours to 1100UTC 7 March 2010.

Figure 7e: Moree upper winds 2300UTC 9 February 1976 and 2300UTC 10 February 1976 with 24hour rainfall to 2300UTC 10 February 1976 of 134.6mm.

Figure 7f: Lord Howe Island from 2300UTC 16 June 1996 to 2300UTC 17 June 1996 and 24hour rainfall to 2300UTC 17 June 1996 was 449.0mm.

Figure 7g: Williamtown upper winds 2200UTC 1 February 1990 to 1700UTC 2 February 1990 and 24hour rainfall to 2300UTC 2 February1990 of 276.0mm.

Figure 7h: Sydney Airport 1000UTC 2 February 1990-and 24hour rainfall to 2300UTC 2 February1990 was 216.2mm.

Figure 7i: Gladstone upper winds 1000UTC 20 February 1992 and 1600UTC 20 February 1992 with 229.4mm to 2300UTC 20 February 1992.

Figure 7j: ET of TC Oswald Event Rockhampton upper winds 0500UTC 24 January 2013 and 1100UTC 24 January 2013. At Gladstone 254.4mm in the 24hours to 2300UTC 24th January2013 and at Rockhampton 349.0mm in the 24hours to 2300UTC 24 January 2013.

Figure 7k: ECL Event Coffs Harbour 2300UTC 5 November 2009 and 2300UTC 6 November 2009 and 371.0mm in 24h to 2300UTC 6th November 2009 (second highest).

Figure 7l: ECL Event Nowra upper winds 2300UTC 10 March 1075. To represent the South Coast of NSW only sporadic radiosonde data is received from the Nowra Royal Australian Navy Meteorological Office. However, there was radiosonde data in the middle of a 48hour period with some of the heaviest recorded rain in the Nowra region over the 10-11 March 1975 during an ECL, Event No 180.

Appendix B: Tropical Cyclone Tracy in observations and reanalysis

Below in Figure B1 we compare mean sea level pressure analysis (constructed from Bureau of Meteorology 1977) with that from the Reanalysis chart.

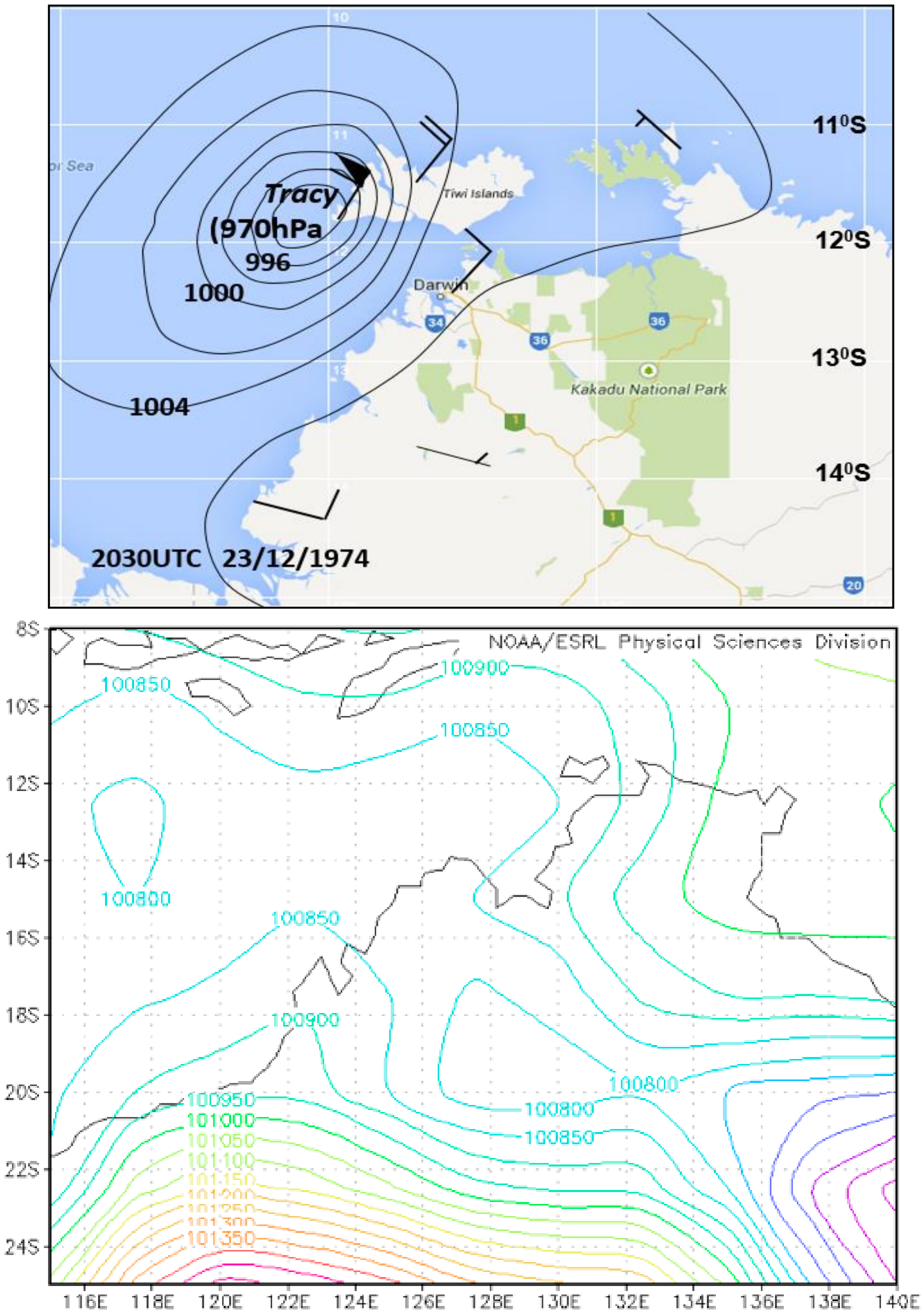

Figure B1 a. MSLP distribution with isobars to 964 hPa, together with mean wind observations for 2030UTC 23 December 1974. Redrawn from Bureau of Meteorology 1977. b. NCEP/NCAR reanalysis MSLP distribution with isobars every 1.5 Pascals for 0000UTC 24 December 1974.