Defining the Australian monsoon onset: A systematic review

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Three key findings from this review:

- The north Australian monsoon onset has been defined in at least 25 different ways since the beginning of research on the topic in 1961
- Different methods pin the "onset" to different events throughout the progression of the north Australian wet season—some capture a "wet season onset" while others capture the dynamical overturning of the atmosphere, i.e. "the monsoon".
- Some definitions are more useful than others in real-time assessment of monsoon conditions.

Key words: Monsoon, Onset, Wet Season, Climate Variability, Australia, tropical circulation

ABSTRACT

The annual Australian monsoon pattern includes an onset, or the much anticipated first active monsoon period of the season, but defining the monsoon onset has proven to be problematic. Since the first Australian monsoon onset definition by Troup (1961) there have been many others presented. There appears to be no universally accepted method to define the Australian monsoon onset, and therefore we present here an analysis of the methods that have been proposed.

The aim of this paper is to systematically review the different methods used to define the Australian monsoon onset, adding to the work that has been done by other reviews for monsoon systems around the world. For the first time we identify the 25 different methods that have been published for the Australian monsoon/wet season onset and compare them to identify how well they align. When considering the 57 seasons where more than one onset definition is provided, the range of dates within the season can range over several months with the average range of 44 days and the largest range within a season of 78 days. Thus, we show that different onset definitions are capturing different events altogether and pin the "onset" to different dates throughout the progression of the north Australian wet season. Some capture a "wet season onset" while others capture the dynamical overturning of the atmosphere (i.e. the monsoon). In conclusion, our analysis finds that there is still a lack in real-time monitoring or prognostic capabilities of monsoon onset dates as well as a limited operational applicability despite a plethora of definitions.

1. Introduction

The word "monsoon" has often been applied to the seasonal wind reversal from southwest to northeast along the Arabian Sea (Ramage 1971; Webster 1981). It has been extended to apply to wind reversals over other parts of the planet (e.g., Ramage 1971; Holland 1986; Li and Zeng 2002; Kajikawa et al. 2010). Regional monsoon patterns are evident in Southeast Asia and India, Africa, North and South America and northern Australia (Webster et al. 1998; CLIVAR 2015; Qian et al. 2002).

The northern Australian climate can also be characterized as monsoonal with two distinct seasons. The dry season, usually defined as comprising the months of May through September, is marked by easterly prevailing winds and little or no rainfall. The wet season, usually comprising the months of October to April, receives over 90% of the annual rainfall across tropical northern Australia (Pope et al. 2009; Nicholls et al. 1982), with intermittent westerly winds (Troup 1961). Within the wet season the rainfall patterns can be categorized as either: (1) isolated mesoscale thunderstorms, usually prevalent in the early wet season months, October, November and December, or (2) the Australian monsoon comprising more-widespread rain systems, which usually occurs in January, February and March (Pope et al. 2009). Although a large percentage (about 70%) of wet season rainfall comes from the latter, the former is also very important for agriculture and people (Nicholls et al. 1982; Green et al. 2009), and the distinction between the two is often blurred. The question of whether a single date should be used to characterize this transition from dry to wet, or easterly to westerly, must also be considered. Nevertheless, as we will show, the concept of an onset date has received widespread use and is thus deserving of review.

The monsoon pattern over northern Australian experiences a great-deal of intra-seasonal variability. These were first described by Troup (1961) as "bursts" or active periods and "breaks" or inactive periods (Wheeler and McBride 2012; Troup 1961). With the monsoon following a pattern of bursts and breaks, the "onset" is naturally defined as the first burst, or active monsoon period, of the northern Australian wet season.

Defining exactly when the monsoon has set in has proven difficult, not just for Australia but also for monsoon patterns around the world. While the broad definition of the monsoon is generally accepted, that is, a seasonal change in the direction of the prevailing winds accompanied by an increase in rainfall, the exact criteria used to define the monsoon, and identify when a monsoon pattern is in place, are widely varied. Kim et al. (2006) summarised this well when they wrote, "It is difficult to come up with an accurate definition of the monsoon onset because it is affected by many physical mechanisms". Smith et al. (2008) noted that "It is apparent that there is no globally accepted single index that can be used to completely describe the rainy season, but it is also apparent that most indices are not suitable for simultaneously describing onset and end dates for individual stations for individual years". Wang et al. (2004) noted, "Defining the onset date of the [South China Sea summer monsoon] for an individual year has been noticeably controversial, even though the corresponding climatological mean onset is a notable singular episode…The lack of a universally accepted definition of [South China Sea summer monsoon] onset is a major roadblock for studying interannual variability of the monsoon evolution". In fact, Wang et al. (2004) list 17 different definitions before proposing another based on 850-hPa zonal winds (Smith et al. 2008). Similarly, Fitzpatrick et al. (2015) identified 18 distinct definitions for the West African monsoon onset and noted little agreement between various onset definitions at a regional scale and what is actually experienced at a local scale. Noska and Misra (2016) referenced 16 separate definitions for the Indian summer monsoon, and Wang et al. (2009) highlighted complexity of the Indian summer monsoon and the difficulty in finding an objective definition of its onset. As this literature review will demonstrate, the subject of the Australian monsoon onset and intra-seasonal variability has, likewise, been the topic of many studies, each defining the onset slightly differently.

The aim of this paper is to present a systematic scientific literature review on the Australian monsoon onset using the methodological approach detailed by Pickering and Byrne (2014). This study is not only motivated by the importance of the monsoon weather pattern in society, but also the apparent difficulty in defining what it is and when it is in place. Our specific objectives are to identify and compare all the ways that the onset has been defined in the past. Has the understanding of monsoon onset changed over time and to what degree do the different definitions agree? It is important to note that although we lump all the various definitions together in this review, it was not necessarily the intention of the authors of the earlier works to have a consistent definition of onset. For example, in some papers the authors were specifically interested in the change of the winds from easterly to westerly (e.g. Drosdowsky, 1996) whereas in others they were interested in the onset of useful rain (e.g. Drosdowsky and Wheeler, 2014). Here, for the sake of completeness and potentially greater understanding, we include all such definitions in this review.

This paper is organised in the following way. The results of our systematic literature search are provided in section 2. This is followed by an analysis of the different definitions and comparisons of dates are provided in section 3. Section 4 provides a brief overview of climate influences on onset timing, and conclusions in section 5. The scope of this study focuses on the Australian monsoon, although other monsoon systems are referenced occasionally where the research had influenced the understanding of the Australian monsoon. Similar reviews have been done for other monsoon systems by Wang et al. (2004) for the South China Sea monsoon, Fitzpatrick et al. (2015) for the African monsoon, and by Noska and Misra (2016) for the Indian summer monsoon.

2. Literature Summary

Previously published reviews of the Australian monsoon have given special attention to the timing and intra-seasonal variability of the Australian monsoon (Suppiah 1992; Shaik and Cleland 2010; Wheeler and McBride 2012). Suppiah (1992) provided a thorough review on the topic, but this work is now 27 years old and much has been accomplished since its publication. Shaik and Cleland (2010) provided a review that focused on the four techniques that have been developed in the Darwin Regional Specialised Meteorological Centre to monitor the Australian monsoon progress at Darwin. Wheeler and McBride (2012) examined research on the intra-seasonal variability of the bursts and breaks within the monsoon season, but did not include a comprehensive review of monsoon onset. This review is written with the intent to be a more contemporary, exhaustive and systematic summary with a particular focus on the variability of onset timing.

As Wheeler and McBride (2012) point out, the word "monsoon" has been used to describe North Australia's climate since as early as 1814. However, the first published research demonstrating that northern Australia's wet season was monsoonal in nature was done by Troup (1961); this paper marks the beginning of the timeline, shown in Figure 1. Table 1 provides details of the monsoon onset definition provided in each paper.

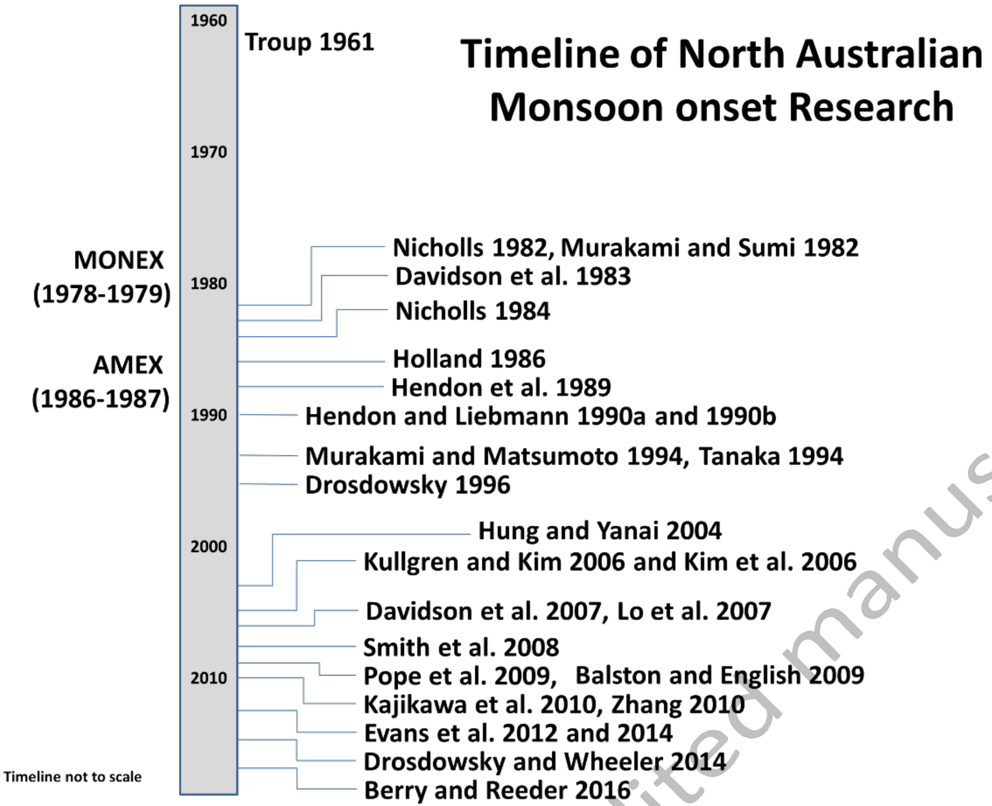

Figure 1 Timeline of Australian monsoon research. [MONEX (MONsoon EXperiment, sometimes called W-MONEX, the Winter MONsoon EXperement) and AMEX (Australian Monsoon EXperiment) were two major field research experiments based in northern Australia with a focus on (Holland 1986; Earth Observing Laboratory).**]**

In the two decades that followed Troup (1961), the scientific literature was relatively quiet regarding the Australian monsoon and the subject is mostly neglected until the Global Weather Experiment which included the Winter Monsoon Experiment (WMONEX). The experiment gathered a wealth of data on the Australian monsoon during the 1978–79 wet season and results were documented by Murakami and Sumi (1982), Davidson et al. (1983), Davidson (1984), Davidson et al. (1984).

Nichols et al. (1982) was the first of several papers to use a rainfall-only criterion. It is important to distinguish, however, that these rainfall-only criteria were not used to identify the onset of the monsoon per se, but rather the onset of the northern wet season (Nicholls et al. 1982). Holland (1986) built upon the wealth of research that was done from the WMONEX field study during the 1978–79 wet season to describe not just the onset, but also the inter-annual variability of the monsoon. Holland (1986) explicitly rejected using a rainfall based monsoon definition due to the large and variable proportion of rain that falls in the early wet season leading up to the monsoon and before a change in the large-scale circulation. Instead, Holland (1986) proposed a wind-only monsoon index. Hendon and Liebmann (1990b) defined the monsoon onset using both wind and rainfall in an idea they called “wet westerlies”, similar to Troup (1961). In the mid-1990’s, with the development of reanalysis data, other criteria were used to examine the monsoon onset, such as Outgoing Longwave Radiation (OLR; Murakami and Matsumoto 1994; Tanaka 1994). In the early 2000’s many new criteria and onset definitions were proposed. To compare these, and to see how definitions have changed over time, we have included a short description of all the onset definitions in Table 1.

149 Table 1 List of 25 Australian wet season or monsoon onset definitions ordered by publication date.

Author(s) / Onset definitions	Description of data used (location/region, resolution, seasons)
(Troup 1961): Defined to occur when 4 out of 6 rainfall stations near Darwin, Australia, experience their first rainfall event simultaneously after 1 November and the area-averaged rainfall over N days exceeded 0.75 (N + 1) inches (19 mm/day) and low level winds 914 m at Darwin are westerly at 10(N+1) knots.	Darwin sounding and rainfall; rainfall at surrounding locations; 1955-1959
(Nicholls et al. 1982): Wet season onset was measured using varying accumulated rainfall thresholds. The wet season onset dates that most closely matched a monsoon onset was 500 mm accumulated after 1 August.	Darwin Airport rainfall, 1952-1980
(M**urakami and Sumi 1982)**: Defined by using the mean 850 hPa zonal wind averaged along 10^{o} S from 100^{o} to 180^{o} E; onset occurs at the first appearance of mean westerlies along this line.	Used WMONEX data; gridded tropospheric wind, pressure and temperature 100^{o}-180^{o} E along 10^{o} S; 1978-79
(Davidson et al. 1983): Defined as the first large-scale blow-up of tropical convection over Australian longitudes that spans more than 10 degrees latitude and 30 degrees longitude.	Used WMONEX data; satellite imagery for northern Australia (5-15^{o} S 110-170^{o} E); 1972-1979
(Nicholls 1984): Wet season onset occurred at a station in northern Australia when 15% of the mean annual rainfall was accumulated after 1 September.	Rainfall at 10 point locations across northern Australia; 1950-1981
(Holland 1986): Onsets occurred with the passing of the first westerly winds at the 850 hPa level.	Used WMONEX data; daily averaged Darwin Airport sounding; 1952-1983
(Hendon et al. 1989): During the AMEX campaign, on 14 January, 1987, the zonal winds changed from easterly to westerly, the area averaged rainfall "increased dramatically", and the cloud top temperatures "became significantly colder"—this was marked as the actual and unambiguous onset date of the monsoon in that season.	Used AMEX data; gridded 850 hPa zonal winds, rainfall, and cloud top temperature. Each of these was taken as an average over the AMEX region (10°–12.5° S, 130°–145° E). Also considered soundings at Darwin, Gove, "the Chinese ship", Weipa, Thursday Island; 1986-87
(Hendon and Liebmann, 1990a, 1990b): Wind definition as per Holland (1986) with the added criteria of area-averaged rainfall rate of at least 7.5 mm/day	Winds from Darwin Airport sounding; Area averaged daily rainfall for Australia north of 15° S; 1957-1987
(Tanaka 1994): Defined in two ways: (1) Cloud: the first pentad (5-day period) with more than 30% of the mean high cloud amount in the 1-2-1 filtered data. (2) Wind: westerly wind at 850 hPa and easterly wind at 200 hPa in 5-day mean at any point.	Java Sea and Northern Australia. 5-day mean 1^{o} resolution gridded data of the geostationary satellite. Wind is the 5-day averaged 2.5^{o} resolution ECMWF 850hPa and 200hPa wind; 1978-1992
(Murakami and Matsumoto 1994): Defined the monsoon as when the OLR drops below 240 W/m^2, with the additional criteria that the annual mean OLR range [OLR(max)-OLR(min)] is greater than or equal to 60 W/m^2 to denote places where there is a clear seasonal alternation.	Three monsoon regions: South East Asian Monsoon, Western North Pacific Monsoon and Northern Australian Indonesian Monsoon. OLR from NOAA satellite and wind from ECMWF gridded global reanalysis; 1975-1988
(Drosdowsky 1996): Defined as a deep layer mean westerly flow in the lower atmosphere (surface to 500 hPa) overlain by strong upper-level easterlies. These westerly winds had to be in place for at least two consecutive days to be considered an active monsoon period. The monsoon onset was defined as the first day of the first active monsoon period within the season.	Darwin airport sounding; 1957-1992

Author(s) / Onset definitions	Description of data used (location/region, resolution, seasons)
(Cook and Heerdegen 2001): The *rainy season* is "the period when the probability of 10-day dry spells was less than 0.5. Within the rainy season, [they] defined the period of monsoon influence (or 'the wet') as the period between the first and last dates that the probability of 10-day dry spells fell below 0.1"	Station rainfall data for the Northern Territory, Australia
(Hung and Yanai 2004): Onset is defined as the first day with average 850 hPa zonal wind exceeding 2 m/s over north Australian/Arafura sea when the westerly wind is sustained for longer than 10 days and the OLR is lower than 210 W/m^2 for at least several days during the 10-day period.	Northern Australia/Arafura Sea (2–15° S, 115–150° E); use OLR and wind data from the ECMWF ERA; rain data from CPC Merged Analysis of Precipitation (CMAP) gridded pentad climatology (Xie and Arkin 1997); 1979-1993
(Kim et al. 2006; Kullgren and Kim 2006): Calculate seasonal (December-March) precipitation mean in mm/day. When the pentad anomaly is positive then the onset has occurred.	Northern Australia (10S-20S), CMAP rainfall data, 1979-2002
(Robertson et al. 2006): Identified 5 rainfall "states" over northern Queensland, each identifies a different rainfall pattern. Authors explain "the first persistent spell of states 1 and 5 could be identified with [monsoon] onset." However, the onset date would be highly variable from year to year and the intermittent nature of the seasonal rainfall pattern "suggests that the definition of an onset date may not be meaningful in all years, at least away from the coast."	Rainfall data from 11 stations across northern Queensland, Australia. Used a Patched Point Dataset, and described as Bureau of Meteorology data with the data gaps filled in synthetically; 1958-1998
(Davidson et al. 2007): Define as a sudden strengthening and deepening in the Lower-tropospheric westerly winds to a minimum threshold of 2.5 m/s and extend to at least 600 hPa. Easterlies in the upper troposphere must overlay westerlies. This structure must persist for at least 4 days.	Wind data from ERA-40 reanalysis datasets to analyse wind patterns over a monsoonal region (15°–5° S, 110°–140° E); 1978-1999
(Lo et al. 2007): Defined a wet season onset as the date after 1 September on which 50 mm is accumulated.	Northern Australia, Australian Water Availability Project (AWAP) gridded rainfall dataset; 1948-2004
(Smith et al. 2008): Defined a "rainy season" onset as the date between 1 September to 30 April when 15% of the end of season total is accumulated and the end date as the date when 85% of the end of season total is accumulated. In other words, "the two dates between which 70% of the seasonal rainfall is accumulated, independent of the actual total" (Smith et al., 2008).	Northern Australia , AWAP gridded rainfall dataset, 1951-2004
(Pope et al. 2009): Divided different synoptic weather regimes of the northern Australian wet season into distinct "weather regimes". Defined monsoon onset as the first day where the "deep west" regime is observed at Darwin and retreat as the last date on which the regime is observed for the season.	2300 UTC Darwin sounding, 1957-2005 (excl. 1992-93)
(Balston and English 2009): Using rainfall patterns in a plant growth model to find the "green break of the season" or the transition from the dry to wet season relevant for pasture growth; defined onset as 57mm over 21 days after 1 October.	Rainfall data from Ravenswood, Queensland and surrounding rainfall stations, 1890-1996

Author(s) / Onset definitions	**Description of data used (location/region, resolution, seasons)**
(Kajikawa et al. 2010): Created an Australian Monsoon Index (AUSMI), defined as area averaged 850 hPa zonal winds. Onset defined as "the first day after 1 November that satisfies three criteria: 1. on onset day and during the 5 days after onset the averaged AUSMI must be greater than 0 (meaning the westerly is steadily established); 2. in the subsequent four pentads, AUSMI must be positive in at least three pentads; 3. the accumulative four-pentad mean AUSMI >1m/s (meaning a persistent seasonal transition)." (Kajikawa et al., 2010)	5-15° S 110-130° E (NW Australia and surrounding tropics); OLR from NOAA-CIRES; precipitation data from GPCP and NCEP reanalysis; 1948-2006
(Zhang 2010): Defined as the date when two criteria are met: (1) normalised precipitable water index >0.65 for 3 continuous days. (2) An 850 hPa monsoon westerly is established: defined as the mean zonal wind of the 9 adjacent points around the location remaining westerly for 3 consecutive days.	A normalised precipitable water index based on data from ERA-40 reanalysis for Northern Australia (20–12.5°S and 120–135° E) and the 9 grid points around Darwin; 1958–2001
(Evans et al. 2014): Divide the weather patterns at Darwin into eight distinct "states". Onset defined as the first 24 hour period in "state 7" characterised as: deep westerly wind, cyclonic rotation, low surface pressure, high relative humidity, increase in clouds and rain.	ECMWF ERA Reanalysis; Darwin ARM (Atmospheric Radiation Measurement) site data; 1979-2012
(Marshall and Hendon 2015): Defined using two monsoon indices, which are treated separately. Active monsoon days are defined as when the rainfall index is greater than or equal to one daily standard deviation of the 1981-2010 mean. An active monsoon period is also defined when the wind index exceeds one standard deviation.	POAMA, Daily rainfall anomaly area averaged over the northern Australian landmass (all land points equatorward of 25°S). Wind data is the area-averaged u850 anomaly over the box region 110–125°E and 0–10°S; 1981-2010
(Berry and Reeder 2016): Does not define an "onset" but rather defines a monsoon burst. A monsoon burst is defined as when the area-averaged rain transitions from at least 0.5 standard deviations below the seasonal average to at least 0.5 standard deviations above the seasonal average in less than a 7-day period	AWAP; ERA-Interim for Northern Australia, 10–20° S, 120–150° E; 1979–2010

3. Analysis of onset definitions and dates

Of the 25 onset definitions found in this review, fifteen papers provided an onset date for each season studied (see Figure 3 and Table 3). Ten papers provided a summary of overall statistics from the seasons studied but did not provide onset dates for individual seasons (Nicholls et al. 1982; Tanaka 1994; Cook and Heerdegen 2001; Kim et al. 2006; Robertson et al. 2006; Lo et al. 2007; Pope et al. 2009; Drosdowsky and Wheeler 2014; Marshall and Hendon 2015; Berry and Reeder 2016).

3.1 Definition comparison

Monsoon/wet season onset definitions can be categorised and compared in several ways, here we will examine the criteria used, the location or region assessed, and usability.

The criteria used to define the monsoon onset can generally be grouped into four types. Those that are based on rainfall only (most authors specify that this is a wet season onset rather than a monsoon onset), those that are based on wind only, those that are based on a combination of wind and rainfall and those that are based on some other criteria (e.g. cloudiness or surface pressure).

Another way to categorise the onset definitions is by region considered. Of the 25 definitions listed in Table 1, 14 papers define the onset at individual point location, usually Darwin, Northern Territory, Australia, and eleven papers define the onset using the average of some criterion over a broad area. Table 2 shows these groups and which studies fall into which group. Tanaka (1994) and Zhang (2010) analysed the monsoon onset both for Darwin and for an area averaged monsoon region.

Table 2 also includes the mean onset date and retreat date for each paper (where one is provided). A simple comparison of the onset dates suggests that the different definitions pick different events to mark the start of the season but cluster around the same time of year. When considering the mean onset of the four definition types the means are similar. The average of the rainfall definitions is 9 December, the average of the wind definitions is 22 December, the average of the wind and rain definitions is 21 December and the average of the "other" definitions is 16 December. However, the similar means may be misleading considering the large variability within the rainfall and "other" categories. For example the rainfall onset near or around Darwin ranges from 25 October (Lo et al. 2007) to 1 January (Nicholls et al. 1982). The papers that provide a mean onset date using observations from Darwin Airport [excluding Lo et al. (2007) which used 1° gridded data] average to 19 December and are all fairly similar, ranging from the earliest mean of 13 December (Evans et al. 2012) to the latest mean of 1-5 January (Tanaka 1994). The definitions that consider the average over a large monsoonal region range from an average onset date of 21-26 November (Murakami and Matsumoto 1994) to 5 January ± 5 days (Kim et al. 2006) with an average of 18 December.

Some of the definitions that are based on area-averaged monsoon regions only partially intersect with the Australian continent and calculate the onset of the Australian monsoon based on weather changes to the north of the Continent. Figure 2 shows the geographical extent of the area-averaged monsoon criteria and

Table 2 includes a percentage that represents the proportion of the monsoon area that covers the Australian land mass. While these definitions provide useful insight to the progression of the global-scale monsoonal weather pattern, they also could potentially flag a monsoon onset while the north coast of Australia is still under an easterly wind pattern and has not received any monsoonal rainfall.

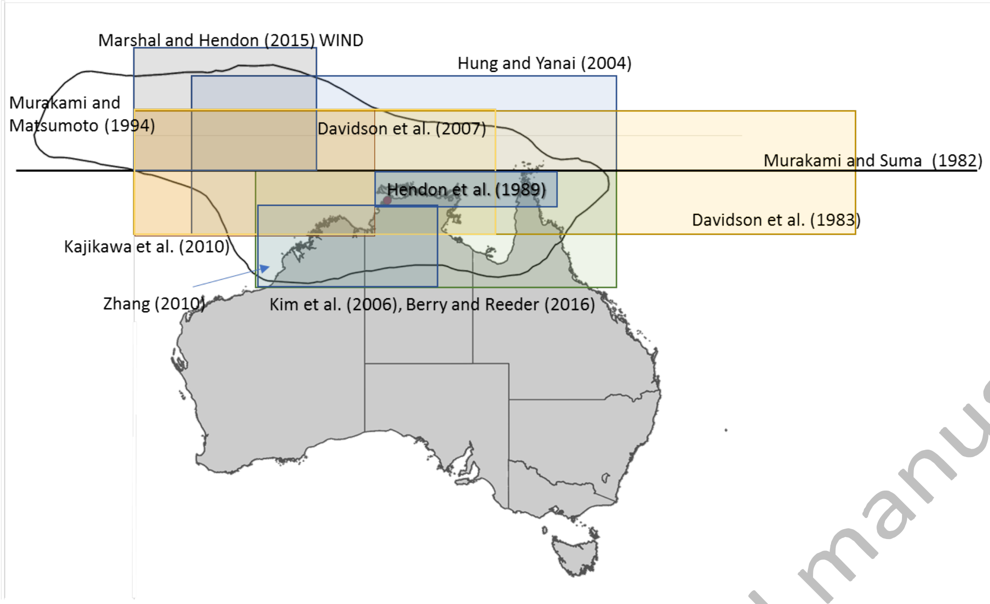

Figure 2 Australian monsoon regions from previously published literature.

The usefulness of a definition would depend on the application. Definitions based on wind and other criteria can contribute to the general understanding of monsoonal dynamics (Troup 1961; Davidson et al. 1983; Hendon and Liebmann 1990a; Drosdowsky 1996; Robertson et al. 2006; Pope et al. 2009; Evans et al. 2014). However, some of these have been criticised for missing the actual monsoon or producing false alarms. It includes Holland (1986) who defines the onset as the first passing of westerly winds at the 850 hPa level at Darwin. This definition has been criticised for being triggered by shallow wind changes and for data-smoothing over abrupt events (Drosdowsky 1996; Shaik and Cleland 2010).

Some authors have argued that the potential users of long range weather forecasts are primarily interested in rainfall rather than the dynamic features that produced that rainfall (Nicholls et al. 1982; Nicholls 1984; Cook and Heerdegen 2001; Balston and English 2009). Hence for agricultural applications, the rainfall-only or the wind-and-rain definitions would be more applicable.

Drosdowsky (1996) points to the merits of the deep-level mean wind definition due to its ability to be applied in an operational environment. The review by Shaik and Cleland (2010) supports the idea that the ability to monitor the progress of the Australian monsoon through the season is necessary for any operational applications. Of the 25 onset definitions reviewed here, 10 could be monitored operationally (daily) from easily accessible and frequently updated data (Troup 1961; Nicholls et al. 1982; Davidson et al. 1983; Nicholls 1984; Holland 1986; Hendon and Liebmann 1990a; Drosdowsky 1996; Robertson et al. 2006; Lo et al. 2007; Balston and English 2009). Of these, only six could also be used to track bursts and breaks throughout the season (Troup 1961; Davidson et al. 1983; Holland et al. 1986; Hendon and Liebmann 1990a; Drosdowsky 1996; Robertson et al. 2006).

Table 2 Australian onset definitions sorted by general criteria (columns) and by geographic extent (rows). The mean onset and retreat dates are given in square brackets. The rectangular monsoon regions also include the percentage area of the region that covers the Australian continent in curly brackets.

	Region	Rainfall only	Wind only	Wind and Rain	Other
Point locations	Darwin, NT, and surrounds	Nicholls et al. 1982 [1-Jan]	Holland 1986 [24 Dec] [7 Mar] Drosdowsky 1996 [28-Dec] [13-Mar]	Troup 1961 [18-Dec] Hendon and Liebmann 1990a [25-Dec]	Tanaka 1994 [1-5 Jan / 15 Dec] [17-26 Mar]* Pope et al. 2009 [19-Dec] [14-Mar] Zhang 2010 [25-Dec]** Evans et al. 2012 [13-Dec] [28-Mar]
Point locations	Point locations across northern Australia	Lo et al. 2007 [varied by location, 25-Oct at Darwin] Cook and Heerdegen 2001 [varied by location, 21-Nov at Darwin] [14-Mar at Darwin] Smith et al. 2008 [varied by location, 7-Dec at Darwin][12-Mar at Darwin]			
Point locations	Northern Queensland	Robertson et al. 2006 [nil] Balston and English 2009 [16-Dec]			
Large Scale Averages	Nrthrn. Aus.	Nicholls 1984 [21-Dec]			
Large Scale Averages	Latitude bands		Murakami and Sumi 1982 [nil] {0%}		
Large Scale Averages	monsoon regions	Kim et al. 2006 [5-Jan +/- 5 Days] [5 Mar +/- 5 days]{45.1%} Berry and Reeder 2016 [nil] {45.1%}	Hung and Yanai 2004 [25-Dec] {6.3%} Davidson et al. 2007 [2-Jan] {7.1%} Kajikawa et al. 2010 ["strong monsoon" = 1 Dec, "weak monsoon" = 22 Dec] [mid-March] {1.5%}	Marshall and Hendon 2015 [nil] {0%}	Davidson et al. 1983 [19-Dec] {4.8%} Hendon et al. 1989 [nil] {14.0%} Murakami and Matsumoto, 1994 [21-26 Nov] [26-31 Mar] {17.9%}

*Also included an analysis at various latitude bands. Onset date varied by latitude. At Darwin: cloud onset was 1-5 January; winds onset by 15 Dec.

**Also included an area averaged analysis for northwest Australia. The mean onset date for the northwest Australia region was not given.

3.2 Comparison of dates

Fifteen papers calculated the actual onset date of each season and included these dates either in the text, a table, or it could be estimated from a figure. Table 3 and Figure 3 show a comparison of onset dates from these definitions for the seasons when two or more onset dates are provided. Hence the table begins with 1948–49 season as this was the first season with two available dates (Balston and English 2009; Kajikawa et al. 2010) and ends with the 2005–06 season (Smith et al. 2008; Kajikawa et al. 2010; Evans et al. 2014). Figure 4 shows the Mean Absolute Deviation (MAD) of all of the onset definitions shown in Figure 3. Some years show a fairly good agreement, e.g. 1978–79, however, others do not, e.g. 1986–87.

Table 3 (with data shown in Figure 3) includes three columns where the onset dates were estimated from figures within papers by Holland (1986, their figure 5) Smith et al. (2008, their figure 4), and Kajikawa et al. (2010, their figure 7). Where the dates were estimated an uncertainty estimate is also given. Both Holland (1986) and Smith et al. (2008) included some onset dates with ± 0 days uncertainty estimate, these were instances where the onset date for that year was mentioned in the text of those papers. For example, Smith et al. (2008) discussed the onset date for the 1989-90 season and Holland (1986) specifically mentions the seasons with the earliest and latest onset dates. We attempted to re-create the Smith et al. (2008) onset dates using the same criteria as Smith et al. (2008). Where our recreation generally matched the estimation from the figure, we provided an uncertainty estimate of ± 1 day. Otherwise, we estimated the date from the figure and gave it a large uncertainty estimate. The Kajikawa et al. (2010) figure 7 included grid lines at weekly intervals which allowed for easier estimation of onset dates.

The range of onset dates varies by definition. The largest range is 75 days (earliest onset, 1 Nov 1975, latest onset 15 Jan 1952) from the Nicholls (1984) rainfall definition. The smallest range came from the Davidson et al. (1983) study with only 20 days difference between the earliest onset and the latest onset. Troup (1961) showed only 21 days difference from the earliest onset to the latest onset. It is important to note that both Troup (1961) and Davidson et al. (1983) considered relatively few years—four and six, respectively—and would likely be very different if a greater sample was considered. On average, when considering the range from all the monsoon onset definitions in this study, there are 56 days difference between the earliest onset date and the latest onset date.

The 1979-80 season was included by most (13) studies and, therefore, provides an interesting case study into how different onset definitions provide different onset dates within the same season. Of the 13 dates provided for that season, the earliest onset date was 20 December (Nicholls 1984) while the latest was 1 January reported by two papers (Kim et al. 2006; Balston and English 2009); all three used rainfall only to define the onset date. The Nichols (1984) definition provided an onset date for Darwin, Kim et al. (2006) calculated the mean over a rectangular monsoon region covering northern Australia and Balston and English (2009) calculated the onset data for Ravenswood, Qld. When considering the wind-only definitions, the five papers in this category have a similar, but slightly contracted range to the rainfall-only definitions; 24 December ± 1 day (Holland 1986) at the earliest and 30 December (Drosdowsky 1996) at the latest. The one paper that included a wind-and-rain combined definition showed a similar onset date of 29 December (Hendon and Liebmann 1990a). The three papers from the “other” category for this year (Davidson et al. 1983; Evans et al. 2014; Zhang 2010) included one paper which identified the onset on 28 December and two which used placed the onset on 30 December even though both methods define the monsoon onset very differently. In fact, seven definitions placed the onset date for the 1979-80 season on 28, 29 or 30 December (this is not counting the uncertainty estimate from Smith et al. 2008) even though they all define the onset in a different way. It is possible that the 1979-80 onset was an unusually well-defined event where different onset definitions cluster the onset date around a few days, whereas for other seasons the onset may not be as clear. The 1979-80 season provides a useful example of how the monsoon onset, as a discrete weather event, can be simple enough that multiple definitions can capture the same event with relative agreement.

The 1964–65 season showed 78 days between the earliest and the latest onset date. Excluding Balston and English's (2009) rainfall onset date for eastern Queensland, this season showed the largest range of any year. Eight papers included an onset date for this season, the wind and rain definition from Hendon and Liebmann (1990b), three rainfall-only definitions (Nichols 1984; Smith et al. 2008; Balston and English 2009), three wind-only definition (Holland 1986; Drosdowsky 1996; Kajikawa et al. 2010), and the precipitable water index from Zhang (2010). Four of these onset dates place the season onset at Darwin on the 2nd or 3rd of December when tropical cyclone Flora moved over the Cobourg Peninsula and tracked less than 200 km to the east of Darwin (Hendon and Liebmann 1990b; Nichols 1984; Holland 1986; Drosdowsky 1996). Smith et al. (2008) provided a "rainy season" onset date at Darwin of 13 November (± 1 day). Balston and English (2009) give a wet season onset date on 24 November for Ravenswood, Qld. Kajikawa et al. (2010) and Zhang (2010) provide an onset date of 6 January (± 2 days) and 30 January, respectively, both calculate the onset as the average over a large monsoonal region.

Another interesting case is the 2001-02 season where there are 67 (± 2) days between the earliest onset date and the latest. Only four papers included an onset date for this season, two rainfall-only definitions (Kim et al. 2006; Smith et al. 2008), one wind-only definition (Kajikawa et al. 2010), and the “state 7” definition from Evans et al. (2014; briefly sumarised inTable 2). The Smith et al. (2008) “rainy season” onset date, the Kajikawa et al. (2010) 850 hPa monsoonal winds index date and the Evans et al. (2014) “state 7” date all roughly converge with the onset dates of 30 November(± 1 day), 29 November (±2 days) and 5 December 2001. Kim et al. (2006) defined the onset date as the occurrence of positive precipitation anomalies, i.e. when the local precipitation exceeds the austral summer mean value at that location. Using the Kim et al. (2006) definition, the monsoon onset occurred on 5 February that season; a difference of 62 days from the next latest onset date (5 December). One possible reason for the large discrepancy is that Kim et al., (2006) considered data from December through March of each season and would have missed a large rainfall event, in excess of 100 mm at many northern Australia location, in the week ending 30 November 2001.

The 1979-80, 1964–65 and 2001-02 seasons provide contrasting examples of the issue of defining the seasonal onset date. When considering all seasons where more than one onset definition is provided, the average range of dates within the season is 44 days. Years with early onset of rains do not always correspond with years with early onset of westerly winds. These suggest that, in most seasons, different onset definitions are capturing different events altogether.

Table 3 Onset dates from different published onset definitions. The dates shown in the table are only those included in each respective study. Murakami and Sumi (1982) was excluded because it considered only one season, 1978-79. Where indicated, dates were estimated from a graph and uncertainty estimates are given for these estimations, the other dates were included either in the text or from a table within the paper. The columns are grouped according to the same categories shown in Table 2 and then ordered chronologically within the groups by the date of the publication. Only those years with two or more onset dates are shown here to allow for comparison between onset definitions.

	Rainfall Only				Wind Only					Wind and Rain		Other		
Season start year	Nichols (1984)	Kim et al. (2006)	Smith et al. (2008) "rainy season" onset at Darwin, estimated from their Fig. 4	Balson and English (2009)	Holland (1986) as estimated from their Fig. 5	Drosdowsky (1996)	Hung and Yanai (2004)	Davidson et al. (2007)	Kajikawa et al. (2010) as estimated from their Fig. 7	Troupe (1961)	Hendon and Liebmann (1990b)	Davidson (1983)	Evans et al. (2014)	Zhang (2010)
mean	16-Dec	1-Jan	9-Dec ± 3 days	12-Dec	26-Dec ± 2 days	29-Dec	26-Dec	2-Jan	16-Dec ± 2 days	26-Dec	25-Dec	20-Dec	13-Dec	24-Dec
range	1 Nov–15 Jan	27 Nov–5 Feb	1 Nov–15 Feb	4 Oct–9 Mar	24 Nov–28 Jan	23 Nov–26 Jan	28 Nov–15 Jan	14 Dec–23 Jan	15 Nov–17 Jan	11 Dec–12 Jan	23 Nov–23 Jan	11–31 Dec	11 Nov–12 Jan	23 Nov–31 Jan
1948				04-Jan-49					24-Dec-48 ± 2 days					
1949				10-Jan-50					11-Dec-49 ± 2 days					
1950	23-Nov-50		17-Nov-50 ± 1 day	28-Nov-50					14-Nov-50 ± 2 days					
1951	15-Jan-52		28-Nov-51 ± 1 day	15-Jan-52	13-Jan-52 ± 2 days				1-Jan-52 ± 1 days					
1952	27-Dec-52		09-Dec-52 ± 1 day	28-Oct-52	28-Dec-52 ± 2 days				25-Dec-52 ± 2 days					
1953	24-Dec-53		15-Dec-53 ± 1 day	05-Jan-54	23-Dec-53 ± 1 day				16-Jan-54 ± 1 days					
1954	7-Dec-54		21-Nov-54 ± 1 day	25-Jan-55	2-Jan-55 ± 2 days				27-Dec-54 ± 2 days					
1955	9-Dec-55		02-Dec-55 ± 1 day	06-Dec-55	4-Jan-56 ± 3 days				9-Jan-56 ± 2 days	12-Jan-56				
1956	5-Dec-56		29-Nov-56 ± 1 day	02-Oct-56	4-Dec-56 ± 2 days				10-Dec-56 ± 2 days	11-Dec-56				
1957	26-Dec-57		15-Dec-57 ± 6 days	21-Jan-58	22-Dec-57 ± 1 day	28-Dec-57			18-Dec-57 ± 2 days	19-Dec-57	25-Dec-57			
1958	22-Dec-58		04-Dec-58 ± 1 day	23-Dec-58	28-Dec-58 ± 2 days	03-Jan-59			26-Dec-58 ± 2 days	1-Jan-59	31-Dec-58			3-Jan-59
1959	25-Dec-59		09-Dec-59 ± 10 days	08-Dec-59	18-Dec-59 ± 2 days	21-Dec-59			17-Dec-59 ± 1 days		17-Dec-59			8-Dec-59
1960	28-Dec-60		05-Dec-60 ± 1 day	22-Nov-60	21-Dec-60 ± 0 days	24-Dec-60			23-Dec-60 ± 2 days		22-Dec-60			24-Dec-60
1961	21-Dec-61		29-Nov-61 ± 1 day	14-Nov-61	2-Jan-62 ± 0 days	06-Jan-62			4-Jan-62 ± 2 days		4-Jan-62			5-Jan-62
1962	22-Dec-62		04-Dec-62 ± 1 day	13-Nov-62	22-Dec-62 ± 1 day	21-Jan-63			23-Dec-62 ± 2 days		25-Dec-62			28-Dec-62
1963	13-Jan-64		05-Dec-63 ± 1 day	07-Jan-64	13-Dec-63 ± 3 days	03-Jan-64			2-Jan-64 ± 1 days		1-Jan-64			3-Jan-64
1964	2-Dec-64		13-Nov-64 ± 1 day	24-Nov-64	3-Dec-64 ± 2 days	03-Dec-64			6-Jan-65 ± 2 days		3-Dec-64			30-Jan-65
1965	25-Dec-65		17-Dec-65 ± 4 days	07-Dec-65	7-Dec-65 ± 3 days	15-Jan-66			25-Dec-65 ± 2 days		3-Jan-66			14-Jan-66
1966	31-Dec-66		06-Dec-66 ± 1 day	07-Mar-67	13-Jan-67 ± 3 days	21-Jan-67			27-Dec-66 ± 2 days		17-Jan-67			21-Jan-67
1967	7-Jan-68		02-Jan-68 ± 1 day	19-Dec-67	12-Jan-68 ± 3 days	14-Jan-68			3-Dec-67 ± 2 days		5-Jan-68			17-Jan-68
1968	9-Jan-69		05-Jan-69 ± 0 days	25-Feb-69	14-Jan-69 ± 3 days	07-Jan-69			18-Dec-68 ± 2 days		7-Jan-69			7-Jan-69
1969	8-Dec-69		25-Dec-69 ± 10 days	23-Dec-69	27-Jan-70 ± 0 days	22-Dec-69			5-Dec-69 ± 2 days		20-Dec-69			20-Dec-69
1970	10-Dec-70		28-Nov-70 ± 10 days	10-Nov-70	23-Dec-70 ± 1 day	04-Dec-70			26-Nov-70 ± 2 days		2-Dec-70			5-Dec-70
1971	6-Dec-71		30-Nov-71 ± 8 days	21-Dec-71	7-Dec-71 ± 3 days	07-Dec-71			2-Dec-71 ± 2 days		6-Dec-71	10-Dec-71		8-Dec-71
1972	6-Jan-73		04-Dec-72 ± 1 day	16-Jan-73	22-Jan-73 ± 3 days	25-Jan-73			3-Jan-73 ± 2 days		23-Jan-73			6-Jan-73
1973	15-Nov-73		27-Dec-73 ± 3 days	06-Nov-73	14-Dec-73 ± 3 days	22-Nov-73			15-Nov-73 ± 1 days		13-Dec-73	18-Dec-73		22-Nov-73
1974	5-Dec-74		04-Dec-74 ± 1 day	19-Nov-74	31-Dec-74 ± 1 day	25-Dec-74			20-Dec-74 ± 2 days		4-Jan-75			26-Dec-74
1975	1-Nov-75		22-Nov-75 ± 10 days	28-Oct-75	3-Dec-75 ± 2 days	06-Dec-75			30-Nov-75 ± 1 days		1-Dec-75			6-Dec-75
1976	10-Dec-76		14-Jan-77 ± 1 day	26-Oct-76	7-Jan-77 ± 3 days	12-Jan-77			3-Dec-76 ± 2 days		9-Dec-76	13-Dec-76		12-Dec-76
1977	15-Dec-77		18-Dec-77 ± 1 day	27-Dec-77	13-Dec-77 ± 3 days	12-Dec-77			11-Dec-77 ± 2 days		11-Dec-77	18-Dec-77		16-Dec-77
1978	7-Dec-78		31-Oct-78 ± 1 day	05-Dec-78	24-Dec-78 ± 1 day	06-Jan-79		26-Dec-78	21-Dec-78 ± 2 days		22-Dec-78	26-Dec-78		26-Dec-78
1979	20-Dec-79	01-Jan-80	27-Dec-79 ± 1 day	01-Jan-80	24-Dec-79 ± 1 day	30-Dec-79	28-Dec-79	29-Dec-79	28-Dec-79 ± 2 days		29-Dec-79	30-Dec-79	28-Dec-79	30-Dec-79
1980	30-Dec-80	05-Jan-81	16-Dec-80 ± 1 day	06-Jan-81	7-Jan-81 ± 3 days	06-Jan-81	4-Jan-81	6-Jan-81	3-Jan-81 ± 2 days		4-Jan-81		16-Dec-80	6-Jan-81
1981	2-Dec-81	13-Jan-82	28-Nov-81 ± 1 day	17-Nov-81	23-Nov-81 ± 0 days	15-Jan-82	27-Nov-81	11-Jan-82	24-Nov-81 ± 1 days		23-Nov-81		24-Nov-81	26-Nov-81
1982		11-Jan-83	31-Dec-82 ± 5 days	18-Jan-83	31-Dec-82 ± 1 day	08-Jan-83	31-Dec-82	1-Jan-83	31-Dec-82 ± 1 days		7-Jan-83		30-Dec-82	8-Dec-82
1983		04-Jan-84	26-Nov-83 ± 1 day	10-Jan-84		04-Dec-83	5-Jan-84	31-Dec-83	25-Nov-83 ± 2 days		5-Jan-84		28-Nov-83	26-Nov-83
1984		19-Dec-84	26-Nov-84 ± 4 days	23-Oct-84		16-Dec-84	8-Dec-84		7-Dec-84 ± 2 days		10-Dec-84		08-Dec-84	11-Dec-84
1985		13-Jan-86	27-Dec-85 ± 1 day	22-Oct-85		18-Jan-86	14-Jan-86	15-Jan-86	20-Dec-85 ± 2 days		16-Jan-86		26-Dec-85	18-Jan-86
1986		12-Jan-87	08-Nov-86 ± 10 days	21-Oct-86		15-Jan-87	13-Jan-87	15-Jan-87	1-Jan-87 ± 1 days		14-Jan-87		11-Jan-87	14-Jan-87
1987		21-Dec-87	14-Dec-87 ± 1 day	17-Nov-87		19-Dec-87	14-Dec-87	17-Dec-87	13-Dec-87 ± 2 days				14-Dec-87	15-Dec-87
1988		05-Dec-88	21-Nov-88 ± 4 days	08-Nov-88		20-Dec-88	9-Dec-88		16-Nov-88 ± 1 days				27-Nov-88	30-Nov-88
1989		16-Jan-90	13-Dec-89 ± 0 days	31-Oct-89		13-Dec-89	6-Jan-90	13-Dec-89	20-Nov-89 ± 2 days				11-Dec-89	08-Jan-90
1990		31-Dec-90	11-Dec-90 ± 1 day	18-Dec-90		26-Dec-90	20-Dec-90	22-Dec-90	18-Dec-90 ± 2 days				03-Dec-90	28-Dec-90
1991		06-Feb-92	28-Nov-91 ± 4 days	17-Dec-91		07-Jan-92	31-Dec-91	6-Jan-92	30-Dec-91 ± 2 days				03-Jan-92	01-Jan-92
1992		23-Dec-92	30-Nov-92 ± 10 days	24-Nov-92			17-Dec-92	22-Jan-93	30-Nov-92 ± 1 days				16-Dec-92	04-Jan-93
1993		25-Dec-93	19-Dec-93 ± 1 day	25-Jan-94					12-Dec-93 ± 2 days				12-Dec-93	19-Dec-93
1994		12-Jan-95	18-Dec-94 ± 5 days	14-Feb-95				13-Jan-95	12-Jan-95 ± 2 days				15-Dec-94	14-Jan-95
1995		24-Jan-96	16-Nov-95 ± 10 days						3-Dec-95 ± 2 days				05-Dec-95	10-Dec-95
1996		17-Dec-96	09-Dec-96 ± 0 days						12-Dec-96 ± 2 days				11-Dec-96	24-Dec-96
1997		21-Dec-97	24-Dec-97 ± 1 day					25-Dec-97	21-Dec-97 ± 2 days				11-Dec-97	12-Dec-97
1998		12-Dec-98	08-Dec-98 ± 1 day					26-Dec-98	20-Nov-98 ± 2 days				10-Nov-98	24-Nov-98
1999		21-Dec-99	24-Dec-99 ± 5 days						8-Dec-99 ± 1 days				08-Dec-99	23-Dec-99
2000		27-Nov-00	03-Dec-00 ± 1 day						24-Nov-00 ± 1 days				25-Nov-00	04-Dec-00
2001		05-Feb-02	30-Nov-01 ± 1 day						29-Nov-01 ± 2 days				05-Dec-01	
2002			18-Dec-02 ± 1 day						29-Dec-02 ± 2 days				01-Jan-03	
2003			20-Dec-03 ± 3 days						16-Dec-03 ± 1 days				16-Dec-03	
2004			18-Dec-04 ± 1 day						23-Dec-04 ± 2 days				22-Dec-04	
2005			14-Dec-05 ± 1 day						27-Dec-05 ± 2 days				25-Dec-05	

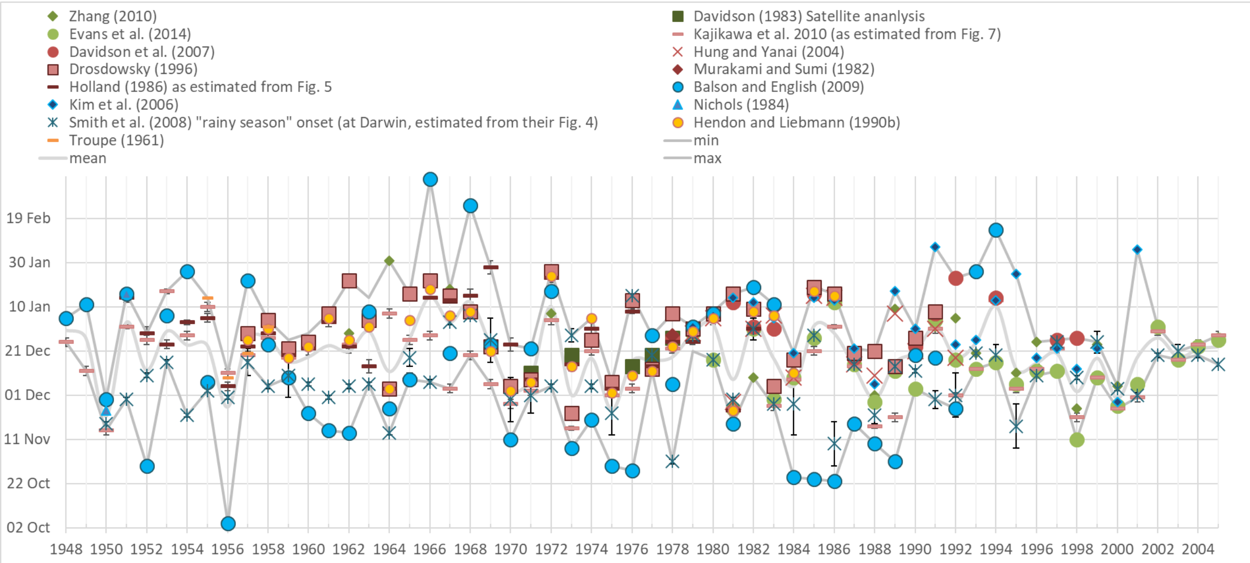

Figure 3 Onset dates provided in the literature as shown in table 3. Onset definitions are grouped by definitions type. Rainfall only definitions are represented by blue markers, wind only definitions are represented by red markers, definitions that combine wind and rain are represented by the yellow markers and the definitions that use other parameters to define onset are represented by green markers. The top and bottom lines show the definitions that give the latest and earliest onset date for each season. The centre grey line shows the average of all onset dates provided for that season within the literature regardless of the definition type. The year labelled on the x-axis represents the year that begins the season (e.g. 1948 is the 1948–1949 wet season). Only seasons where at least two dates were given are shown.

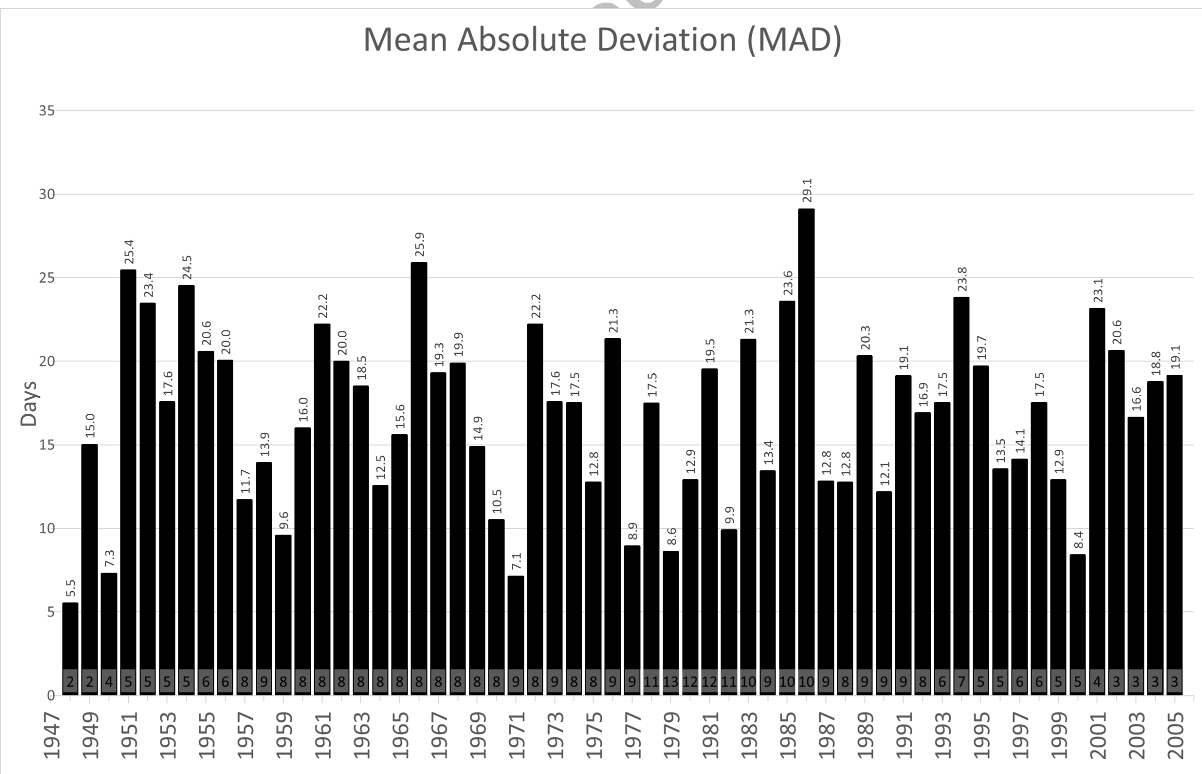

Figure 4 The Mean Absolute Deviation (MAD) for all years for the different onset dates as shown in Figure 3. The number above the bars is the calculated MAD and the numbers at the base of the bars show the number of onset dates provided for each year.

4. ENSO and other climate influences on onset timing

A review of the literature showed several major climate drivers that influence monsoon strength, which was usually measured by total seasonal rainfall. These drivers included ENSO, the Indian Ocean Dipole, the Tropical Biennial Oscillation, and the Southern Annular Mode/Antarctic Oscillation. In this review we focused on the climate influences on onset timing.

Nicholls et al. (1982) was the first study to suggest a link between the onset of the wet season at Darwin and the Southern Oscillation Index (SOI; Troup 1965), although instead of using the full SOI they focussed on just the seasonal pressure patterns at Darwin where there was a “significant correlation” between the winter seasonal mean MSLP and the timing of the first rainfall.

This idea was explored in great detail by McBride and Nicholls (1983) who showed that rainfall during the peak of the monsoon season (December–February) was only weakly related to the SOI especially as compared to the 'build-up' months of September–November. It was further noted that September–November is the season with the strongest relationship between the SOI and rainfall for all of Australia and not just the tropics; while December–February showed the weakest relationship for all of Australia.

It followed that monsoon onset definitions that were based on rainfall only (Nicholls 1984; Kullgren and Kim 2006; Drosdowsky and Wheeler 2014; Smith et al. 2008; Kim et al. 2006; Webster et al. 1998; Nicholls et al. 1982) all showed a strong connection between the SOI or other ENSO indicators and the onset of the wet season. Studies that did not include rainfall in their definition of the monsoon onset either showed only a weak link between ENSO and monsoon onset, no link at all, or it did not get a mention (Holland 1986; Drosdowsky 1996; Kajikawa et al. 2010). Drosdowsky (1996) and Kajikawa et al. (2010) show correlation coefficients between the September through November SOI and monsoon onset of -0.56 and -0.48, respectively. Holland’s (1986) wind-only definition, requiring westerly winds at the 850 hPa level from the Darwin sounding, showed some connection with ENSO parameters; however, no significant correlation was found between seasonal onset and the SOI in the year leading up to the summer monsoon season; in particular, the length of the season is quite poorly related to the SOI (Holland 1986). Hung and Yanai (2004), which use 850 hPa winds averaged over a specified area of Northern Australia, cites El Niño as a possible reason for delayed onset in 1982–83 and 1991–92, but otherwise do not mention ENSO as a factor contributing to monsoon onset. Drosdowsky (1996), which defined the monsoon using deep layer mean winds at Darwin, showed a correlation coefficient between onset date and the SOI of -0.56 for the period of 1957 through 1992.

Hendon et al. (1989) focussed on the monsoon onset of the 1986-1987 wet season from the AMEX study. 1986-1987 was an El Niño year and the monsoon onset was delayed by more than one standard deviation, occurring on 14 January 1967 (using the 850 hPa wind onset definition from Holland 1986). Hendon et al. (1989) were able to focus on the physical mechanisms that that were influencing the monsoon onset. They point to the broad scale subsidence over the Maritime Continent region as a cause for convective inhibition during the expected monsoon onset.

The Madden-Julian Oscillation (MJO) has been shown to be another major factor in monsoon onset date (Joseph et al. 1991; Hendon and Liebmann 1990a,b; Wheeler and McBride 2012; Wheeler and Hendon 2004; Pope et al. 2009; Hendon et al. 1989). It has been shown that when the MJO signal is strong, 85% of the monsoon onset dates occur while the MJO is in phases 4–7 and only 15% of the onset dates occur in the other phases (Wheeler and McBride 2012; Pope et al. 2009).

Joseph et al., (1991) used the Hendon and Liebmann, (1990a) onset definition to show a correlation (-0.56) between Australian monsoon onset dates and the strength of the Indian summer monsoon. They found that years of below (above) normal Indian summer monsoon rainfall were followed by delayed (early) Australian monsoon onset.

Rogers and Beringer (2017) use the Smith et al. (2008) definition of rainy season onset and the Kajikawa et al. (2010) Australian monsoon index (AUSMI) to investigate which climate indices have the strongest influence on northern Australian rainfall. They show that strongest correlated indices with annual rainfall in the tropics are an Indonesian SST index, a Tasman Sea SST index, and the ENSO modoki index. The physical mechanisms linking these indices and north Australian rainfall were not explained in Rogers and Beringer (2017) and should be a topic of further research.

A question that remains when considering the climate influences on Australian monsoon onset timing is: does the correlation shown in these papers remain as strong when applied to other monsoon onset definitions? Some of these studies are over twenty years old, do the correlations remain robust when more decades of data are considered? The authors intend to address these questions in future research.

5. Conclusion

The aim of this paper has been to assess the different methods used to define the Australian monsoon and wet season onset. We have identified 25 unique ways to define the Australian monsoon, and its onset, from the scientific literature. The quantity of different onset definitions for the Australian monsoon highlights a known difficulty in this area of research. While the broad definition of the monsoon is generally accepted, the exact criteria used to define the monsoon, and identify when a monsoon pattern is in place, are widely varied (Kim et al. 2006; Smith et al. 2008; Wang et al. 2004). Different methods pin the “onset” to different events throughout the progression of the north Australian wet season—some capture a “wet season onset” while others capture the dynamical overturning of the atmosphere, i.e. “the monsoon”.

Many studies have introduced monsoon indices (e.g., Kajikawa et al. 2010; Li and Zeng 2002) which have provided greater insight to monsoon patterns, however, each index has some marked limitations in spatial and/or temporal scope. For example, the Drosdowsky (1996) criterion produces accurate diagnostics for monsoon patterns at one particular location, Darwin, rather than the broader tropics region and cannot be applied to other point locations (This issues was addressed by Davidson et al., 2007). Drosdowsky (1996) has the added benefit of being able to be applied in near-real time and can be used operationally by weather forecasters, while other indices (e.g. Kim et al. 2006; Nicholls 1984) can be applied only to seasonal or interannual monsoonal variability and cannot give insight to current, real-time or short-term weather patterns. Some other weaknesses of current indices and criteria are that many lack real-time monitoring or prognostic capabilities, or are based on data that is difficult to obtain or are not updated in real-time and therefore cannot be used operationally (Tanaka 1994; Murakami and Matsumoto 1994; Xie and Arkin 1997; Hung and Yanai 2004; Kim et al. 2006; Kajikawa et al. 2010; Zhang 2010; Evans et al. 2014).

Future research includes the re-creation (as much as possible) of the different monsoon criteria for a consistent time period to do a true side-by-side comparison of the strengths, weaknesses and utility of all the different monsoon indices mentioned above. There needs to be further examination into the physical mechanisms that influence monsoon onset timing on a seasonal timescale (i.e. why are some seasons late and other seasons early?) and intra-seasonal variability in the hopes that a consistent mechanism can be found that could provide some insight into seasonal predictions. This study focused on the Australian monsoon, the authors acknowledge that a more detailed analysis would be valuable for other global monsoon systems adding to this work as well as that by Wang et al. (2004) for the South China Sea monsoon, Fitzpatrick et al. (2015) for the African monsoon, and by Noska and Misra (2016) for the Indian summer monsoon.

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