DEVELOPING A BETTER UNDERSTANDING OF THE AUSTRALIAN MONSOON AND WET SEASON ONSET CLIMATOLOGY

A thesis submitted by

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ABSTRACT

By some estimates, about 40-60% of the world's population lives within a monsoonal climate. For all of these people, the timing of the monsoon onset is an annual event that is critical for sustainable agriculture, fire management, water management, travel and tourism, and so much more. A late monsoon onset can create serious issues in ways that are similar to drought conditions in higher latitudes but they may onset faster and last only a few weeks. The topic of this thesis focuses on the Australian monsoon, a singular monsoon region in a global weather pattern, which experiences high wet season rainfall variability, including in the timing of the precipitation, which can cause short-term, rapid-onset droughts. For example, by most definitions the Australia monsoon onset has a standard deviation of more than ±2 weeks and a range of onset dates of nearly two months from the earliest to the latest.

This research has the following two objectives:

1. Determine which monsoon onset definitions provide the most predictability at seasonal time scales, and which seasonal-scale climate drivers provide the strongest influence on onset timing.
2. Investigate the frequency of “false onsets”—when an onset criterion is met, but follow-up rainfall is not received—and if these lead to “flash drought” conditions over northern Australia.

These objectives were accomplished by, first performing a systematic literature review of Australian monsoon onset definitions. Second, recreating 11 dynamical monsoon onset datasets and extending them to the same time period to test their seasonal predictability through correlations with large-scale seasonal climate drivers. And, third, when considering a standard wet season rainfall onset criterion, the date after 1 September that 50 mm of precipitation is accumulated, quantify the frequency of occurrence of false onsets as a physical characteristic of the north

Australian climate, rapid soil moisture declines and drought development.

Results presented in this thesis from the first research objective demonstrate that while the wet season rainfall onset (first rainfall of the season, usually mesoscale features and not the global monsoon) is highly predictable on a seasonal time scale, the dynamical monsoon onset (i.e. the global-scale weather pattern) is not easily predictable at these timescales by traditional seasonal climate influences. Only a strong (<-1 standard deviation) La Niña pattern shows a statistically significant correlation with an early onset of the dynamical monsoon. A weak La Niña, ENSO-neutral, and a weak or strong El Niño pattern has only a weak or non-statistically significant correlation and should not be used to make monsoon onset predictions. A negative and neutral Indian Ocean Dipole (IOD) do not have a statistically significant correlation with onset dates, but a strong positive IOD correlates with a delayed monsoon onset and could be used in monsoon onset predictions.

The outcomes of the second objective show that false wet season onsets are relatively common across northern Australia; 30% to 50% of wet seasons experience a false onset. False onsets are more common during La Niña and negative IOD events. False onsets do not always coincide with a “flash drought” (investigated here as a rapid drop in soil moisture). These rapid drops in soil moisture are relatively common across northern Australia in the wet season, occurring on average at least once within about 25% of seasons. These rapid drops in soil moisture are common enough that they probably should not be a considered a drought (i.e. a climatological extreme).

The findings presented in this thesis significantly advance our knowledge of Australian monsoon temporal variability. This includes: A systematic and comprehensive assessment of the literature on Australian monsoon onset definitions and timing; An analysis of monsoon onset dates and the correlations of onset timing with climate drivers; A study of wet season onset variability, false onsets and flash drought.

The significance of this work extends well beyond the Australian monsoon. Similar analysis could be applied to other monsoon regions. It is also very likely that, given the variability of global monsoon patterns, other monsoon regions may experience seasons with false onsets. Investigation of the frequency of occurrence of false onsets would give residents of other monsoon regions an understanding of their climatological propensity toward drought.

CERTIFICATION OF THESIS

This Thesis is the work of Joel Lisonbee except where otherwise acknowledged, with the majority of the authorship of the papers presented as a Thesis by Publication undertaken by the Student. The work is original and has not previously been submitted for any other award, except where acknowledged.

Principle Supervisor: Dr. Christa Pudmenzky

Associate Supervisor: Professor Joachim Ribbe

Student and supervisors' signatures of endorsement are held at the University

STATEMENTS OF CONTRIBUTIONS

The peer review articles produced from this thesis were a joint contribution of the authors. The details of the scientific contribution of each author are provided below:

Research paper I: Lisonbee, J., Ribbe, J. and Wheeler, M. (2020) ‘Defining the north Australian monsoon onset: A systematic review’, Progress in Physical Geography: Earth and Environment. SAGE Publications Ltd, 44(3), pp. 398–418. doi: 10.1177/0309133319881107.

- The overall contribution of Joel Lisonbee was 70% to concept development, compiling datasets, performing the analysis and interpretation of the results, drafting and revising the final submission;
- Joachim Ribbe contributed to the concept development, writing, editing and providing important technical inputs by 20%;
- Matthew Wheeler contributed to the concept development, editing and providing important inputs into discussion of draft and final Manuscript 10%.

Research paper II: Lisonbee, J. and Ribbe, J. (2021) ‘Seasonal climate influences on the timing of the Australian monsoon onset’, *Weather and Climate Dynamics*, 2(2), pp. 489–506. doi: 10.5194/wcd-2-489-2021.

- The overall contribution of Joel Lisonbee was 80% to the concept development, compiling the datasets, performing the analysis, interpreting the results and writing the draft manuscript.
- Joachim Ribbe was involved in planning, supervising the research, structure of the manuscript, writing and revising sections of the manuscript by 20%.

Research Paper III: Lisonbee, J., Ribbe, J., Otkin, J., Pudmenzky, C. (2021). ‘Wet

Season Rainfall Onset and Flash Drought: The Case of the Northern Australian Wet Season', *International Journal of Climatology.* (**In Review)**.

- The overall contribution of Joel Lisonbee was 70% to the concept development, compiling the datasets, interpreting results and writing the draft manuscript.
- Joachim Ribbe was involved in the concept development, supervising the research, editing the draft manuscript, and revising sections of the manuscript by 20%.
- Jason Otkin was involved in interpreting the results, and writing the manuscript by 7%.
- Christa Pudmenzky aided in discussing the results and editing the manuscript by 3%.

Research Paper IV: Lisonbee, J., Woloszyn, M. and Skumanich, M. (2021) 'Making sense of flash drought: definitions, indicators, and where we go from here', *Journal of Applied and Service Climatology*, 2021(1), pp. 1–19. doi: 10.46275/joasc.2021.02.001.

- The overall contribution of Joel Lisonbee was 60% to the concept development, compiled the datasets, performed the analysis, interpreted the results and wrote the draft manuscript.
- Molly Woloszyn, 20%, and Marina Skumanich, 20%, each were involved in planning, structure of the manuscript, interpretation of the results, writing and revising sections of the manuscript.

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My first exposure to atmospheric sciences came from Dr. Kevin Perry at the University of Utah. As a teacher, advisor, mentor and friend, Dr. Perry saw potential in me that I didn’t see in myself. I am sincerely thankful for Dr. Kevin Perry.

While working for the Australian Bureau of Meteorology at the Darwin Regional Climate Centre, I was privileged to work with Todd Smith, Max Gonzalez and Dr. Hakeem Shaik, who were instrumental in solidifying much of what I was taught while at University. These years in Darwin made me realise that defining the monsoon, and its onset, is not always clear. This is when I started forming research questions about monsoon climatology. I would like to thank Todd, Max, Hakeem, Andrew Tupper and many other colleagues who I’ve learned from over the years.

I would like to thank my supervisors. Professor Joachim Ribbe has been a fantastic mentor. I could not have been luckier. He taught me how to do a systematic literature review, how to construct a logical and readable paper, and to consider the global research community and applications outside of Australia. Toward the end of this research project Dr. Christa Pudmenzky also joined as a supervisor. I am also grateful for her input and direction in this work.

Finally, I would like to thank some other friends, colleagues, co-authors and leaders who provided encouragement, advice, reviews and suggestions when needed. These are in no particular order: Matt Wheeler, Jason Otkin, Peter Stone, Perry Wiles, Roger Stone, Alister Hawksford, Luke Shelly, Gary Allan, Greg Browning, Simon Allen, Jeri Tanner, Elizabeth Ossowski, Veva Deheza, and Bryn Weaver.

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ABBREVIATIONS

4max	4-month maximum
4min	4-month minimum
AAO	Antarctic Oscillation
AO	Arctic Oscillation
ASLI	Amundsen Sea Low Index
ASO	August September October
CLIVAR	Climate and Ocean: Variability, Predictability and Change
CSIRO	Commonwealth Scientific and Industrial Research Organisation
Dec	December
DMI	Dipole Mode Index
dt	detrended
IIsst	Indonesian sea surface temperature index
IO	Indian Ocean Basin
IOD	Indian Ocean Dipole
IPCC	Intergovernmental Panel on Climate Change
ismidx	Indian Summer Monsoon Index
JAS	July August September
JJA	June July August
JJAS	June July August September
lat	latitude
lon	longitude
M_SAM	Marshall Southern Annular Mode
MJO	Madden-Julian Oscillation
NINO1.2	El Niño 1.2 sea surface temperature index
NINO3	El Niño 3 sea surface temperature index
NINO3.4	El Niño 3.4 sea surface temperature index
NINO4	El Niño 4 sea surface temperature index
Nov	November
Oct	October
OND	October November December
PDO	Pacific Decadal Oscillation
QBO	Quasi-Biennial Oscillation
RelCP	Relative Central Pressure
Sep	September
SOI	Southern Oscillation Index
SON	September October November
wnpmidx	Western North Pacific Monsoon Index
wymidx	Webster and Yang Monsoon Index

CHAPTER 1: INTRODUCTION

1.1 Introduction, Background and Motivation

When we examine the climate we usually consider climate change and climate variability. Climate change is “any systematic change in the long-term statistics of climate elements (such as temperature, pressure, or winds) sustained over several decades or longer” (American Meteorological Society 2012a). Climate variability describes “the temporal variations of the atmosphere–ocean system around a mean state” (American Meteorological Society 2012b) including the occurrence of extremes, etc. at all spatial and temporal scales beyond that of individual weather events (IPCC 2021a). This thesis will focus on the climate variability of the Australian monsoon, which is one of six global monsoon regions (Wang and Ding 2008; IPCC 2021b).

The word “monsoon” is thought to stem from the Arabic word *mausim* meaning “season”, and has often been used in reference to the seasonal wind reversal from southwest to northeast along the Arabian Sea (Webster 1981). The term has been extended to apply to seasonal wind reversals over other parts of the planet (Ramage 1971; Holland 1986; Li and Zeng 2002; Kajikawa et al. 2010). The seasonal reversal of winds is also, usually, tied to a marked increase in rainfall (Hendon and Liebmann 1990; Qian et al. 2002; Wang and Ding 2008; Jiang et al. 2016).

For the billions of people living within a monsoon climate, the monsoon is far more than a shift in the winds; the dry/wet seasonal alternations of the global monsoon pattern govern their lives, livelihoods, and culture. After enduring several months of little to no rainfall, the first sign of rain in the wet season can provide both hope and relief. The start of the wet season means that bushfires will stop burning and crops or pasture will begin to grow. The timing of the onset of the monsoon is of critical importance for agriculture, fire management, water management and transportation in monsoonal regions.

Regional monsoon patterns are evident in Southeast Asia and India, Africa, North America, Central America, South America and northern Australia (Webster et al. 1998; CLIVAR 2015; Qian et al. 2002; IPCC 2021b). Variability in the monsoon pattern is usually a manifestation of the latitudinal variability and season changes in the Inter-Tropical Convergence Zone (Wang et al. 2014; CLIVAR 2015; UCAR 2021). All of these monsoon patterns see variability in the timing of the onset, but, as will be shown in this thesis, the variability of the Australian monsoon is particularly large (Lisonbee and Ribbe 2021).

The northern Australian climate can be characterized as a monsoon climate 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, comprising the months of October to April, receives over 90% of the annual rainfall across tropical northern Australia (Nicholls et al. 1982; Pope et al. 2009), and experiences intermittent westerly winds (Troup 1961).

It is important to note that for this research the *wet season* and the *monsoon* are distinctly separate. Within the wet season (roughly October through April) the rainfall patterns usually fall into two categories: (1) isolated mesoscale thunderstorms, usually prevalent in the early wet season months, October, November and December (colloquially referred to as the ‘build up’) and (2) the north Australian monsoon, a global-scale weather pattern that brings persistent, heavy rainfall to a large area, which usually occurs in late December, January, February and early March (Pope et al. 2009, see Figure 1). In other words, the “wet season” refers to the time of year while “monsoon” refers to a specific weather pattern. As will be discussed hereafter, there are many ways to define the monsoon, but in general, the monsoon refers to the dynamic reversal of the prevailing winds and a marked increase in rainfall. A large percentage (about 70%) of wet season rainfall comes after the monsoon onset (Nicholls et al. 1982).

The timing of the monsoonal weather is an important part of agriculture, ecology and bushfire management across Australia's northern savannahs. It has become intrinsically linked with northern Australian culture (Green et al. 2009).

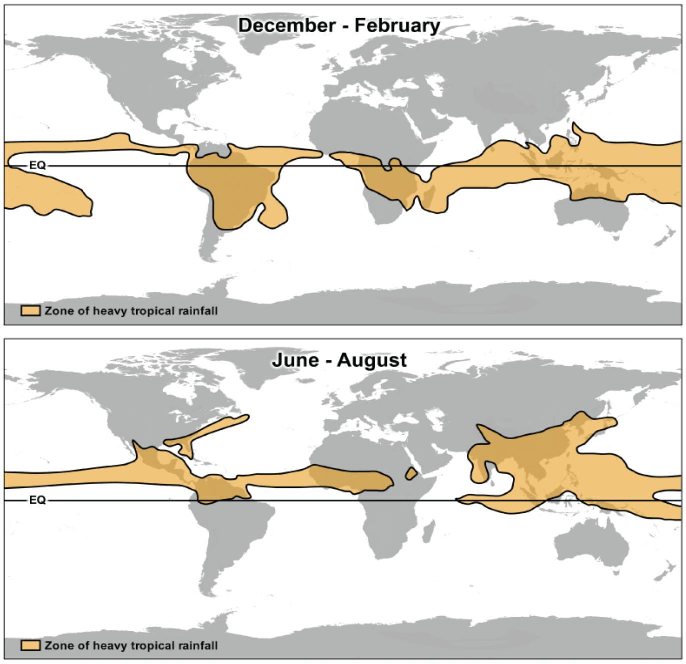

Figure 1 The locations of the heaviest tropical rainfall from December to February (top) and June to August (bottom). (Source: University Corporation for Atmospheric Research; https://scied.ucar.edu/learning-zone/storms/monsoons accessed 30 Sept 2021)

Within the monsoonal weather pattern there exists a great-deal of sub-seasonal variability. For northern Australia the week-to-week—and sometimes shorter—changes in the weather were first described by Troup (1961) as "bursts" or active periods and "breaks" or inactive periods within the monsoon season (Troup 1961; Wheeler and Hendon 2004; Wheeler and McBride 2012). The "monsoon onset" is naturally defined as the first burst, or active monsoon period of the 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, the exact criteria used to define the monsoon, and identify when a monsoon pattern is in place, are widely varied. Smith et al. (2008, p. 4299) note 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, p. 699) note, "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).

Because there is not a single accepted definition of the monsoon onset, seasonal prediction of the timing of the monsoon has also proven difficult. As will be shown hereafter, most monsoon definitions that consider rainfall as a component of the monsoon onset definition also show a strong correlation with El Niño–Southern Oscillation (ENSO). This may be problematic because the definitions tend to be falsely triggered by pre-monsoonal rainfall, i.e., they are more of a wet season onset indicator than a monsoon indicator. When the monsoon onset definition does not consider rainfall, the literature is conflicted about the significance of an ENSO connection, and point to other drivers, such as the Madden-Julian Oscillation (MJO), as the dominant driver of onset timing variability (Wheeler and Hendon 2004). Using the MJO as a predictor of the monsoon provides skilful forecasts at a multi-week timescale (Lim et al. 2018) rather than monthly or seasonal lead times. Fitzpatrick et al. (2015, p. 8673) wrote, "Given a seasonal forecasting model, it is possible to simultaneously have a good and a bad prediction of monsoon onset simply through selection of the onset definition and observational dataset used for comparison."

Indeed, as will be shown hereafter, there are times when the wet season begins and a wet season rainfall onset criterion is met, but the monsoon onset is delayed. To highlight the point made by Fitzpatrick et al. (2015), the onset definition chosen may provide a misleading (i.e. incorrect) impression of the seasonal variability experienced at a location. Not only does this make prediction difficult, but can create a difficult situation for farmers, fire managers and others across northern Australia. This can lead to a *flash drought*, or rapidly developed drought conditions that are sometimes short-lived, but may persist throughout the wet season, creating especially difficult conditions through the following dry season.

In summary, there remains significant uncertainty in regards to defining monsoon onset and identifying drivers of variability.

Therefore, the motivation of the research in this thesis is to improve our collective scientific understanding of the temporal variability in the Australian wet season and monsoon onsets, the underlying drivers of that variability on a seasonal timescale, and the impacts of that variability. This research would be of value to developing industry that can thrive in northern Australia's highly variable climate.

1.2 Aims and Objectives of the Research

The research presented in this thesis aims to provide further understanding of north Australia's climate and to determine if the onset timing of the north Australian wet season and the monsoonal weather pattern can be predicted on a seasonal timescale using seasonal-scale climate drivers. However, as was pointed out by Fitzpatrick et al. (2015), objectively deciding which onset criteria proved the most useful in dynamical models became problematic so it was decided to limit the scope of the present study to statistical correlations with known climate indices, as will be shown in Chapters 2, 3 and 4.

This research has the following two objectives:

1. Determine which monsoon onset definitions provide the most predictability at seasonal time scales and which seasonal-scale climate drivers provide the strongest influence on onset timing.
2. Investigate the frequency of "false onsets"—when an onset criterion is met, but follow-up rainfall is not received—the influence of seasonal climate

drivers on false onsets and if these lead to “flash drought” conditions over northern Australia.

This research focuses on the north Australian monsoon, which adds to similar research being done in the international scientific community on other monsoonal systems (for example, see http://www.clivar.org/clivar-panels/monsoons). The variability of monsoon onset is a challenge in other regions (Wang et al. 2004; Kim et al. 2006; Smith et al. 2008; Fitzpatrick et al. 2015; Noska and Misra 2016), and this research will contribute to that global conversation. Similar research should be done for other monsoon regions, especially for monsoonal regions that experience a slow build-up to the monsoon and where the wet season rainfall experiences a large temporal variability.

1.3 Overview and Outline of Thesis

The thesis is presented as a series of chapters in the form of research papers. Three have been published in peer-reviewed journals. A final paper is currently under review. The thesis is composed of four research papers that collectively address the two research objectives. Three research papers comprise the core of the thesis and are included as Chapters 2–4. A fourth research paper is included as Appendix A; it presents a second systematic literature review that, while it did not directly address either of the research objectives, it strongly underpinned and greatly informed the analysis included in Chapter 4. The research papers associated with each research objective are as follows:

Chapters 2 and 3 address research objective one. These include the following papers:

- Lisonbee, J., Ribbe, J. and Wheeler, M. (2020) ‘Defining the north Australian monsoon onset: A systematic review’, Progress in Physical Geography: Earth and Environment. SAGE Publications Ltd, 44(3), pp. 398–418. doi: 10.1177/0309133319881107.

- Lisonbee, J. and Ribbe, J. (2021) ‘Seasonal climate influences on the timing of the Australian monsoon onset’, *Weather and Climate Dynamics*, 2(2), pp. 489–506. doi: 10.5194/wcd-2-489-2021

Chapter 4 addresses research objective two:

- Lisonbee, J., Ribbe, J., Otkin, J., Pudmenzky, C. (2021). ‘Wet Season Rainfall Onset and Flash Drought: The Case of the Northern Australian Wet Season’, *International Journal of Climatology.* (**In Review)**.

Appendix A presents a second literature review that supports Lisonbee et al. (**In Review**), see Chapter 4:

- Lisonbee, J., Woloszyn, M. and Skumanich, M. (2021) ‘Making sense of flash drought: definitions, indicators, and where we go from here’, *Journal of Applied and Service Climatology*, 2021(1), pp. 1–19. doi: 10.46275/joasc.2021.02.001.

These chapters build upon each other to achieve the aim of this thesis. Chapter 2 includes a thorough and systematic review of the literature, using the process described in Pickering and Byrne (2014). This literature review finds that monsoon/wet season onset definitions that are based on rainfall only, were shown to correlate well with ENSO while those that are based on wind only or those that are based on a combination of wind and rain did not agree on the level or correlation between monsoon onset and ENSO. The disparity among published research on the existence and strength of the influence of ENSO on monsoon onset timing needed further investigation. Thus, Chapter 3 considers the role of seasonal-scale climate drivers that influence the timing of the north Australian monsoon onset and considers the various defining criteria (Research Objective 1). Lisonbee et al. (2020) also note that the Indian Ocean Dipole (IOD) was missing from literature as most assessments on the timing of the onset were done before the discovery of the IOD (Saji et al. 1999; Verdon and Franks 2005; Taschetto et al. 2011). Chapter 4 investigates this period between the wet season onset and the monsoon onset.

Chapter 4 provides a thorough investigation of false wet season rainfall onsets across northern Australia and the frequency of occurrence of flash drought periods when the monsoon onset is delayed and the role ENSO plays in false onsets.

Chapter 5 demonstrates in more detail how all the papers included in this thesis build upon one another. It also offers further discussion on the conclusions made in Chapters 2-4.

As mentioned above, Appendix A includes a literature review of the use of the term “flash Drought”. In analysing the onset timing of the wet season rainfall and the dynamical monsoon it became apparent that there are seasons which might experience an early onset of the wet season rainfall and a delayed onset of the monsoon. Lisonbee et al. (**In Review**) investigates if these early wet season dry periods are a normal aspect of the north Australian climate, or if their occurrence was relatively rare (see Chapter 4). Lisonbee et al. (**In Review**) also investigates if these dry periods could be considered a drought and if the droughts develop quickly enough to be considered a flash drought. This flash drought literature review greatly informed the analysis included in Chapter 4 (Lisonbee et al. **In Review**).

CHAPTER 2: LITERATURE REVIEW ON AUSTRALIAN MONSOON VARIABILITY

Research Paper 1: Defining the north Australian monsoon onset: A systematic review

This chapter includes a thorough and systematic literature review of previous research on the Australian monsoon onset. The results highlight that there is no consensus on the variability or predictability of the monsoon onset for Australia. Lisonbee et al. (2020) show that 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. There appears to be no universally accepted method to define the Australian monsoon onset. This systematic review of the literature provides an analysis of the methods that have been proposed.

This shows that, from the first Australian monsoon onset definition (Troup 1961) to May 2018, when the review was conducted, there were 170 papers written about the onset of the north Australian monsoon, and of these papers 25 provided a unique definition of the monsoon and/or wet season onset. These definitions are compared and contrasted. Monsoon/wet season onset definitions can generally be categorised into four types: those that are based on rainfall only, 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. precipitable water or mean sea level pressure).

Each definition has pros and cons. For example, the rainfall-only definitions may be more useful for decision makers who have to manage livestock or bushfire through the dry season when it is common to go 130 days or more without any rainfall. Nicholls et al. (1982, p. 15) points out that "many users…are primarily interested in rainfall rather than any large-scale rearrangement of the troposphere". However, transportation/aviation and flood management may be interested in the dynamical monsoon, and the marked changes that come in the broad-scale rainfall patterns and the change in wind direction.

Lisonbee et al. (2020) show that different onset definitions are capturing different events altogether and pin the “onset” to different dates throughout the progression of the Australian wet season. Some monsoon onset definitions capture a “wet season rainfall onset” while others capture the dynamical overturning of the atmosphere (i.e. the monsoon) with sometimes 2–3 months difference between the two “onset” dates within the same season. Most papers, especially more recent publications, clarify the difference between the wet season and the monsoon, but earlier publications blurred this distinction.

The analysis by Lisonbee et al (2020) also highlights the temporal and seasonal variability of the Australian monsoon. Most monsoon definitions showed a standard deviation of around two weeks but a range of about two months from the earliest to the latest onset dates. Monsoon onset definitions that included a precipitation component also showed a correlation with the El Niño–Southern Oscillation (ENSO). However, previous analyses that did not include a precipitation component (i.e. wind, pressure, etc.) in the defining criteria did not agree on the strength or significance of the correlation, or did not mention ENSO in their analysis.

Lisonbee et al. (2020) further conclude that there is still a lack in real-time monitoring or prognostic capabilities of monsoon onset dates as well as limited operational applicability despite a plethora of definitions. Therefore, the review resented in Chapter 2 strongly supports the research shown in the subsequent chapters where different onset definitions were tested for their prognostic capabilities.

Article

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Defining the north Australian monsoon onset: A systematic review

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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 in 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 an 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 limited operational applicability despite a plethora of definitions.

Keywords
Monsoon, onset, wet season, climate variability, Australia, tropical circulation

I Introduction

The word 'monsoon' has often been applied to the seasonal wind reversal from southwest to northeast along the Arabian Sea (Ramage,

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

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 (Nicholls et al., 1982; Pope et al., 2009), 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 (Green et al., 2009; Nicholls et al., 1982), 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 Australia 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 (Troup, 1961; Wheeler and McBride, 2012). 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 seasonal monsoon begins 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) summarized 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 the 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.

This paper aims 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 Australian 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 organized in the following way. The results of our systematic literature search are provided in section II. This is followed by an analysis of the different definitions and comparisons of dates in section III. Section IV provides a brief overview of climate influences on onset timing, and conclusions are in section V. 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.

II Literature summary

Previously published reviews of the Australian monsoon have given special attention to the timing and intra-seasonal variability of the Australian monsoon (Shaik and Cleland, 2010; Suppiah, 1992; Wheeler and McBride, 2012). Suppiah (1992) provided a thorough review of 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.

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 1978–1979 wet

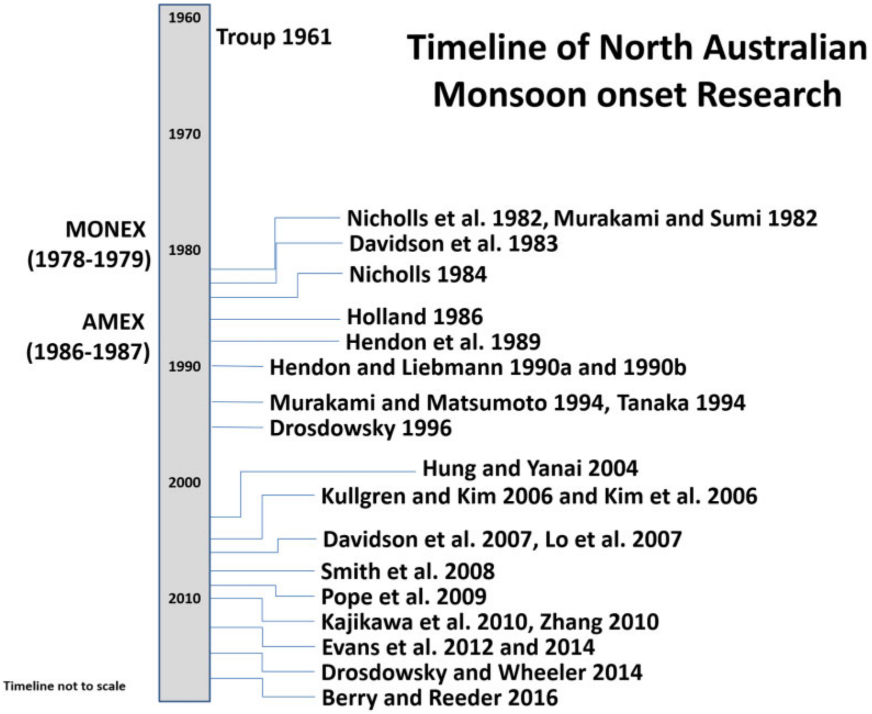

Figure 1. Timeline of Australian monsoon research. [MONEX (MONsoon EXperiment, sometimes called W-MONEX, the Winter MONsoon EXperiment) and AMEX (Australian Monsoon EXperiment) were two major field research experiments based in northern Australia (Holland 1986; Earth Observing Laboratory).]

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, 3000 ft (914.4 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
(Murakami and Sumi, 1982): Defined by using the mean 850 hPa zonal wind averaged along 10° S from 100° to 180° E; onset occurs at the first appearance of mean westerlies along this line.	Used WMONEX data; gridded tropospheric wind, pressure and temperature 100–180° E along 10° S; 1978–1979

(continued)

Table 1. (continued)

Author(s)/Onset definitions	Description of data used (location/region, resolution, seasons)
(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° S 110–170° 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; 1986–1987
(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° resolution gridded data of the geostationary satellite. Wind is the 5-day averaged 2.5° resolution ECMWF 850 hPa and 200 hPa wind; 1978–1992
(Murakami and Matsumoto, 1994): Defined the monsoon as when the Outgoing Longwave Radiation (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; 1975–1987
(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
(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	Station rainfall data for the Northern Territory, Australia

(continued)

Table 1. (continued)

Author(s)/Onset definitions	Description of data used (location/region, resolution, seasons)
that the probability of 10-day dry spells fell below 0.1'	
(Hung and Yanai, 2004): Onset is defined as the first day with average 850 hPa zonal wind exceeding 2 m/s over north Australia/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 (10–20° S), CMAP rainfall data, 1979–2002
(Robertson et al., 2006): Identified five 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, described as Bureau of Meteorology data with the data gaps filled in synthetically; 1958–1998
(Davidson et al., 2007): 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 analyze 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); 4299.	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	2300 UTC Darwin sounding, 1957–2005 (excl. 1992–1993)

(continued)

Table 1. (continued)

Author(s)/Onset definitions	Description of data used (location/region, resolution, seasons)
the last date on which the regime is observed for the season.	
(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 57 mm over 21 days after 1 October.	Rainfall data from Ravenswood, Queensland and surrounding rainfall stations, 1890–1996
(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); 1117.	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) normalized precipitable water index >0.65 for three continuous days. (2) An 850 hPa monsoon westerly is established: defined as the mean zonal wind of the nine adjacent points around the location remaining westerly for three consecutive days.	A normalized precipitable water index based on data from ERA-40 reanalysis for Northern Australia (20–12.5° S and 120–135° E) and the nine 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' characterized 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

season and results were documented by Murakami and Sumi (1982), Davidson et al. (1983), Davidson (1984), and Davidson et al. (1984).

Nicholls 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 1978–1979 wet season to describe not just the onset, but also the interannual 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-1990s, 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 2000s, 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.

III Analysis of onset definitions and dates

Of the 25 onset definitions found in this review, 15 papers provided an onset date for each season studied. Ten papers provided a summary of overall statistics from the seasons studied but did not provide onset dates for individual seasons (Berry and Reeder, 2016; Cook and Heerdegen, 2001; Drosdowsky and Wheeler, 2014; Kim et al., 2006; Lo et al., 2007; Marshall and Hendon, 2015; Nicholls et al., 1982; Pope et al., 2009; Robertson et al., 2006; Tanaka, 1994).

3.1 Definition comparison

Monsoon/wet season onset definitions can be categorized 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 categorize the onset definitions is by the region considered. Of the 25 definitions listed in Table 1, 14 papers define the onset at an individual point location, usually Darwin, Northern Territory, Australia, and 11 papers define the onset using the average of some criterion over a broad area. Two papers, Tanaka (1994) and Zhang (2010) analyzed the monsoon onset both for Darwin and for an area-averaged monsoon region. Table 2 shows these groups and which studies fall into which group.

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 landmass. 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.

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 (Davidson et al., 1983; Drosdowsky, 1996; Evans et al., 2014; Hendon and Liebmann, 1990a; Pope et al., 2009; Robertson et al., 2006; Troup, 1961). However, some of these have been criticized 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 criticized 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 (Balston and English, 2009; Cook and Heerdegen, 2001; Nicholls, 1984; Nicholls et al., 1982). 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 (Balston and English, 2009; Davidson et al., 1983; Drosdowsky, 1996; Hendon and Liebmann, 1990a; Holland, 1986; Lo et al., 2007; Nicholls, 1984; Nicholls et al., 1982; Robertson et al., 2006; Troup, 1961). Of these, only six could also be used to track bursts and breaks throughout the season (Davidson et al., 1983; Drosdowsky, 1996; Hendon and Liebmann, 1990a; Holland et al., 1986; Robertson et al., 2006; Troup, 1961).

3.2 Comparison of dates

Fifteen papers calculated the actual onset date of each season and included these dates either in the text or 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 the 1948–1949 season as this was the first season with two available dates (Balston and English, 2009; Kajikawa et al., 2010) and ends with the 2005–2006 season (Evans et al., 2014;

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][a] Pope et al., 2009 [19 Dec] [14 Mar] Zhang, 2010 [25 Dec][b] Evans et al., 2012 [13 Dec] [28 Mar]
	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]			
	Northern Queensland	Robertson et al., 2006 [nil] Balston and English, 2009 [16 Dec]			
Large Scale Averages	Nrthrn. Aus.	Nicholls, 1984 [21 Dec]			
	Latitude bands		Murakami and Sumi 1982 [nil] {0%}		
	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%}

[a] 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 December.

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

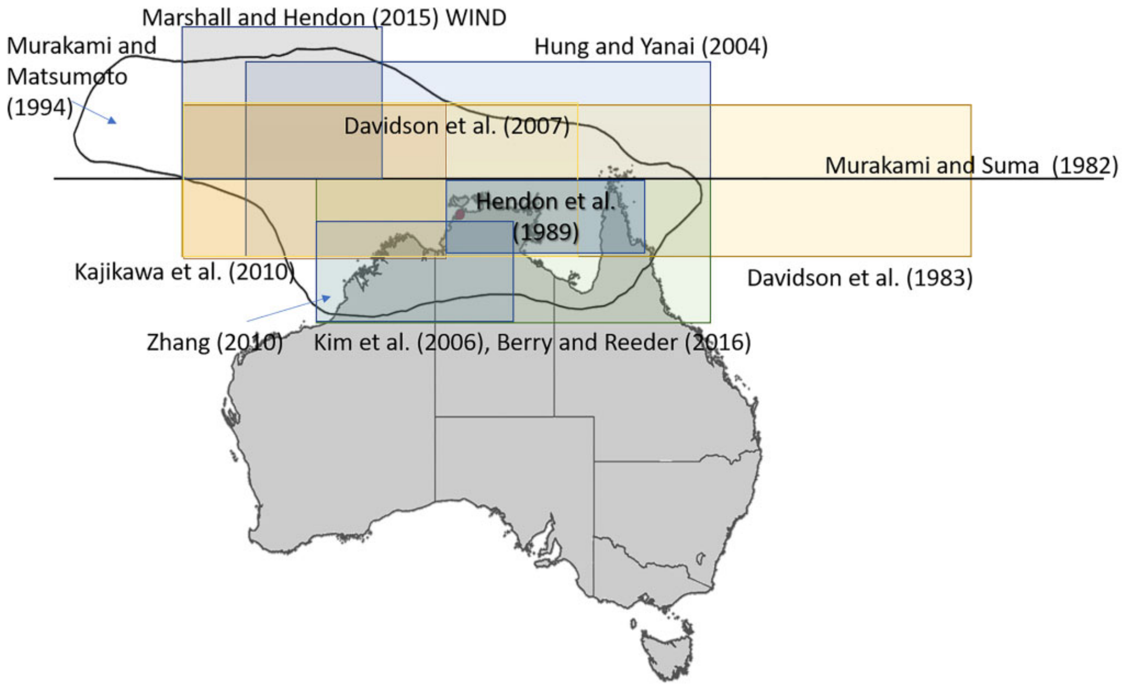

Figure 2. Australian monsoon regions from previously published literature.

Kajikawa et al., 2010; Smith et al., 2008). 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. 1978–1979, however, others do not, e.g. 1986–1987.

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 1989–1990 season and Holland (1986) specifically mentions the seasons with the earliest and latest onset dates. We attempted to recreate 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 approximately 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 November 1975, latest onset 15 January 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

Table 3. Onset dates, all papers.

	Rainfall only				Wind only					Wind and rain		Other		
Season start year	Nicholls (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 ± 10 days	15-Jan-52	13-Jan-52 ± 2 days				01-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	07-Dec-54		21-Nov-54 ± 10 days	25-Jan-55	02-Jan-55 ± 2 days				27-Dec-54 ± 2 days					
1955	09-Dec-55		02-Dec-55 ± 10 days	06-Dec-55	04-Jan-56 ± 3 days				09-Jan-56 ± 2 days	12-Jan-56				
1956	05-Dec-56		29-Nov-56 ± 1 day	02-Oct-56	04-Dec-56 ± 2 days				10-Dec-56 ± 2 days	11-Dec-56				
1957	26-Dec-57		15-Dec-57 ± 1 day	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	01-Jan-59	31-Dec-58			03-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			08-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	02-Jan-62 ± 0 days	06-Jan-62			04-Jan-62 ± 2 days		04-Jan-62			05-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			02-Jan-64 ± 1 days		01-Jan-64			03-Jan-64
1964	02-Dec-64		13-Nov-64 ± 1 day	24-Nov-64	03-Dec-64 ± 2 days	03-Dec-64			06-Jan-65 ± 2 days		03-Dec-64			30-Jan-65
1965	25-Dec-65		17-Dec-65 ± 1 day	07-Dec-65	07-Dec-65 ± 3 days	15-Jan-66			25-Dec-65 ± 2 days		03-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	07-Jan-68		02-Jan-68 ± 1 day	19-Dec-67	12-Jan-68 ± 3 days	14-Jan-68			03-Dec-67 ± 2 days		05-Jan-68			17-Jan-68
1968	09-Jan-69		05-Jan-69 ± 0 days	25-Feb-69	14-Jan-69 ± 3 days	07-Jan-69			18-Dec-68 ± 2 days		07-Jan-69			07-Jan-69
1969	08-Dec-69		25-Dec-69 ± 10 days	23-Dec-69	27-Jan-70 ± 0 days	22-Dec-69			05-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		02-Dec-70			05-Dec-70
1971	06-Dec-71		30-Nov-71 ± 8 days	21-Dec-71	07-Dec-71 ± 3 days	07-Dec-71			02-Dec-71 ± 2 days		06-Dec-71	10-Dec-71		08-Dec-71
1972	06-Jan-73		04-Dec-72 ± 1 day	16-Jan-73	22-Jan-73 ± 3 days	25-Jan-73			03-Jan-73 ± 2 days		23-Jan-73			06-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	05-Dec-74		04-Dec-74 ± 1 day	19-Nov-74	31-Dec-74 ± 1 day	25-Dec-74			20-Dec-74 ± 2 days		04-Jan-75			26-Dec-74
1975	01-Nov-75		22-Nov-75 ± 1 day	28-Oct-75	03-Dec-75 ± 2 days	06-Dec-75			30-Nov-75 ± 1 days		01-Dec-75			06-Dec-75
1976	10-Dec-76		14-Jan-77 ± 1 day	26-Oct-76	07-Jan-77 ± 3 days	12-Jan-77			03-Dec-76 ± 2 days		09-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	07-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	07-Jan-81 ± 3 days	06-Jan-81	04-Jan-81	06-Jan-81	03-Jan-81 ± 2 days		04-Jan-81		16-Dec-80	06-Jan-81
1981	02-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	01-Jan-83	31-Dec-82 ± 1 days		07-Jan-83		30-Dec-82	08-Dec-82

(continued)

Table 3. (continued)

	Rainfall only				Wind only					Wind and rain		Other		
Season start year	Nicholls (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 range	16 Dec 1 Nov–15 Jan	1 Jan 27 Nov–5 Feb	9 Dec ± 3 days 1 Nov–15 Feb	12 Dec 4 Oct–9 Mar	26 Dec ± 2 days 24 Nov–28 Jan	29 Dec 23 Nov–26 Jan	26 Dec 28 Nov–15 Jan	2 Jan 14 Dec–23 Jan	16 Dec ± 2 days 15 Nov–17 Jan	26 Dec 11 Dec–12 Jan	25 Dec 23 Nov–23 Jan	20 Dec 11–31 Dec	13 Dec 11 Nov–12 Jan	24 Dec 23 Nov–31 Jan
1983		04-Jan-84	26-Nov-83 ± 1 day	10-Jan-84		04-Dec-83	05-Jan-84	31-Dec-83	25-Nov-83 ± 2 days		05-Jan-84		28-Nov-83	26-Nov-83
1984		19-Dec-84	26-Nov-84 ± 4 days	23-Oct-84		16-Dec-84	08-Dec-84		07-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	01-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	09-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	06-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	06-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						03-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						08-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	

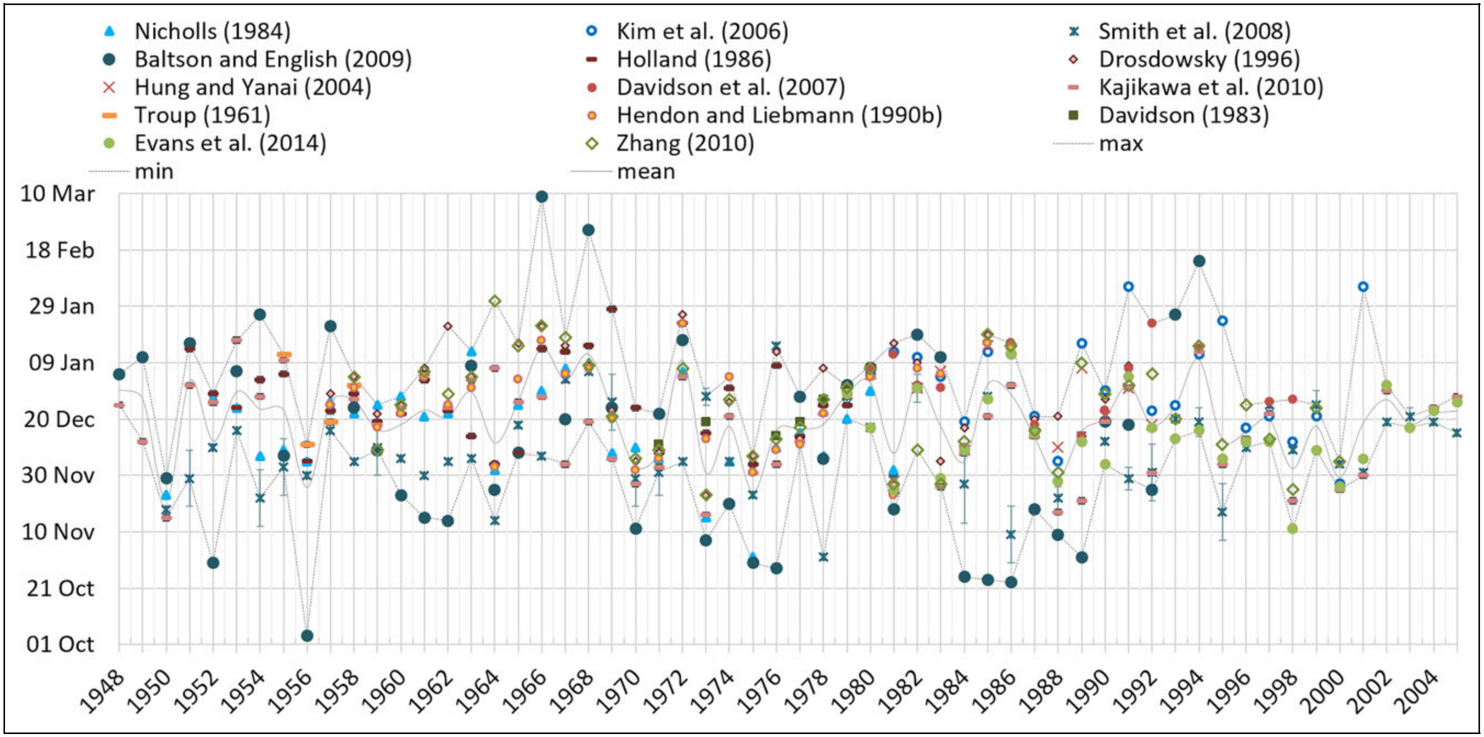

Figure 3. Onset dates provided in the literature, as shown in Table 3. Onset definitions are grouped by definitions type. Rainfall-only definitions are represented by blue markers, wind-only definitions are represented by red markers, definitions that combine wind and rain are represented by the yellow 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.

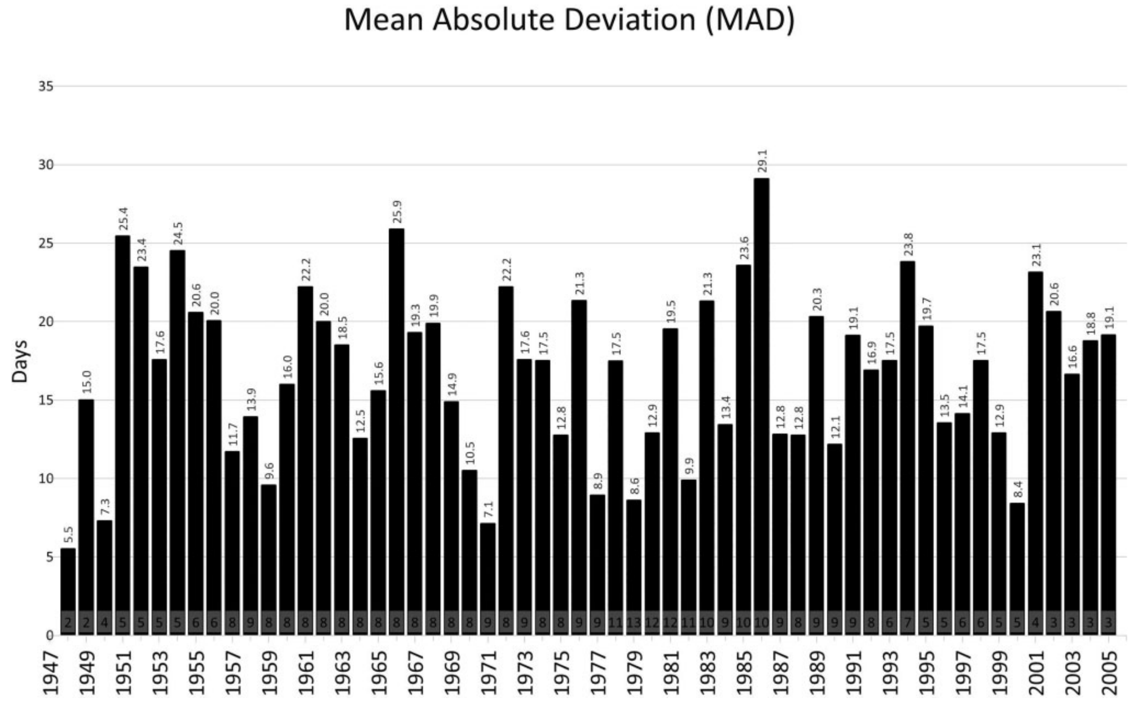

Figure 4. The Mean Absolute Deviation (MAD) for all years for the different onset dates as shown in Figure 3. The number above the bars is the calculated MAD and the numbers at the base of the bars show the number of onset dates provided for each year.

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 is a difference of 56 days between the earliest onset date and the latest onset date.

The 1979–1980 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 (Balston and English, 2009; Kim et al., 2006); 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 date for Ravenswood, Queensland. 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 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 1979–1980 season on 28, 29 or 30 December (this is not counting the uncertainty estimate from Smith et al., 2008) even though they all defined the onset differently. It is possible that the 1979–1980 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 1979–1980 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 1964–1965 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 (Balston and English, 2009; Nicholls, 1984; Smith et al., 2008), three wind-only definition (Drosdowsky, 1996; Holland, 1986; Kajikawa et al., 2010) and the precipitable water index from Zhang (2010). Four of these onset dates place the season onset at Darwin on 2 or 3 December when tropical cyclone Flora moved over the Cobourg Peninsula and tracked less than 200 km to the east of Darwin (Drosdowsky, 1996; Hendon and Liebmann, 1990b; Holland, 1986; Nicholls, 1984). 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, Queensland. 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 2001–2002 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 sumarized in Table 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 locations, in the week ending 30 November 2001.

The 1979–1980, 1964–1965 and 2001–2002 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.

IV 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 El Niño—

Southern Oscillation (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) were the first 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 sea level pressure 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 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 (Drosdowsky and Wheeler, 2014; Kim et al., 2006; Kullgren and Kim, 2006; Nicholls, 1984; Nicholls et al., 1982; Smith et al., 2008; Webster et al., 1998) 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 showed only a weak link between ENSO and monsoon onset, no link at all, or it did not get a mention (Drosdowsky, 1996; Holland, 1986; Kajikawa et al., 2010). Kajikawa et al. (2010) show a correlation coefficient between the September-through-November SOI and monsoon onset of −0.48. 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), who use 850 hPa winds averaged over a specified area of Northern Australia, cite El Niño as a possible reason for delayed onset in 1982–1983 and 1991–1992 but otherwise do not mention ENSO as a factor contributing to monsoon onset. Drosdowsky (1996), who defined the monsoon using deep-layer mean winds at Darwin, showed a correlation coefficient between onset date and the SOI of −0.56 for 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 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) is another major factor in monsoon onset date (Hendon and Liebmann, 1990a,b; Hendon et al., 1989; Joseph et al., 1991; Pope et al., 2009; Wheeler and Hendon, 2004; Wheeler and McBride, 2012). 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 (Pope et al., 2009; Wheeler and McBride, 2012).

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.

Wilks 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 sea surface temperature (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 Wilks 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 20 years old; do the correlations remain robust when more decades of data are considered? The authors intend to address these questions in future research.

V Conclusion

This paper has aimed 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 issue 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 (Evans et al., 2014; Hung and Yanai, 2004; Kajikawa et al., 2010; Kim et al., 2006; Murakami and Matsumoto, 1994; Tanaka, 1994; Xie and Arkin, 1997; Zhang, 2010).

Future research includes the recreation (as much as possible) of the different monsoon criteria for a consistent period to do a true side-by-side comparison of the strengths, weaknesses and utility of all the 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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CHAPTER 3: STANDARDISING MONSOON ONSET DATASETS AND TESTING THEIR SEASONAL PREDICTABILITY

Research Paper 2: Seasonal climate influences on the timing of the Australian monsoon onset

Even with the wealth of research available on the variability of the Australian monsoon season, shown by Lisonbee et al. (2020) in Chapter 2, the timing of the monsoon onset is one aspect of seasonal variability that still lacks skilful seasonal prediction. Due to the disparity among published research on the existence and strength of the influence of El Niño–Southern Oscillation (ENSO) on monsoon onset timing, Lisonbee et al. (2020) also proposed further investigation into the correlation of onset timing with large-scale, seasonal climate influences.

Lisonbee et al. (2020) showed the onset dates for 15 different onset definitions. These are from papers that included a list of onset dates by season within the publication. One aspect of the predictability of these different methods was tested by calculating the statistical correlation between the monsoon onset dates and seasonal climate influences. Previous research has investigated the impact of climate influences, such as ENSO, on monsoon variability, but most studies considered only the impact on rainfall and not the timing of the onset. The hypothesis posed by Lisonbee and Ribbe (2021), included in this Chapter, is that some onset definitions would correlate well with ENSO while others did not. Lisonbee and Ribbe (2021) aims to discover which onset definitions and which climate influences correlated with each other and, therefore, could be statistically paired for seasonal predication.

To test this, Lisonbee and Ribbe (2021) re-created 11 of the 15 previously published Australian monsoon onset datasets which included a dynamical component (i.e. not based on precipitation only). These datasets were then extended to cover the same period from the 1950/1951 through the 2020/2021 Australian wet seasons. The extended datasets were then tested for correlations with several standard climate indices to identify which climate indices could be used as predictors for monsoon onset timing. The complete correlations table is included as Appendix B.

The primary conclusions shown by Lisonbee and Ribbe (2021) are that many of the relationships between monsoon onset dates and ENSO that were previously published are not as strong when considering the extended datasets. Only a strong La Niña pattern usually has an impact on expediting the monsoon onset, while ENSO-neutral and El Niño patterns lack a similar relationship. The detrended Indian Ocean Dipole (IOD) data showed a weak relationship with monsoon onset dates, but when the trend in the IOD data is retained, the relationship with onset dates diminishes. Other patterns of climate variability showed little to no notable, statistically significant relationship with Australian monsoon onset dates.

Correlations provide an intuitive sense of the relevance of these drivers on the onset, but additional statistics could shed some more light on these relationships. The interpretations from correlation analysis can be ascertained through a regression analysis which could be applied in future research.

While the scope of the analysis presented in Lisonbee and Ribbe (2021) is limited to northern Australia, ENSO is a tropical climate process with global impacts. It is prudent to further re-examine its influences in other monsoon regions too, with the aim to evaluate and improve previously established prediction methodologies. The value of such research comes from the simple application of climate indices in strategic planning and the use of ENSO, IOD and other indices as a forecasting tool among operational seasonal forecasters.

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Seasonal climate influences on the timing of the Australian monsoon onset

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Abstract. The timing of the first monsoon burst of the season, or the monsoon onset, can be a critical piece of information for agriculture, fire management, water management, and emergency response in monsoon regions. Why do some monsoon seasons start earlier or later than others? Previous research has investigated the impact of climate influences such as the El Niño–Southern Oscillation (ENSO) on monsoon variability, but most studies have considered only the impact on rainfall and not the timing of the onset. While this question could be applied to any monsoon system, this research presented in this paper has focused on the Australian monsoon. Even with the wealth of research available on the variability of the Australian monsoon season, the timing of the monsoon onset is one aspect of seasonal variability that still lacks skilful seasonal prediction. To help us better understand the influence of large-scale climate drivers on monsoon onset timing, we recreated 11 previously published Australian monsoon onset datasets and extended these to all cover the same period from the 1950/1951 through the 2020/2021 Australian wet seasons. The extended datasets were then tested for correlations with several standard climate indices to identify which climate drivers could be used as predictors for monsoon onset timing. The results show that many of the relationships between monsoon onset dates and ENSO that were previously published are not as strong when considering the extended datasets. Only a strong La Niña pattern usually has an impact on monsoon onset timing, while ENSO-neutral and El Niño patterns lacked a similar relationship. Detrended Indian Ocean Dipole (IOD) data showed a weak relationship with monsoon onset dates, but when the trend in the IOD data is retained, the relationship with onset dates diminishes. Other patterns of climate variability showed little relationship with Australian monsoon onset dates. Since ENSO is a tropical climate process with global impacts, it is prudent to further re-examine its influences in other monsoon regions too, with the aim to evaluate and improve previously established prediction methodologies.

1 Introduction

The livelihood of about 50 % to 60 % of the world's population is impacted by the global monsoon system (e.g. Qiao et al., 2012; Wang and Ding, 2008; Yancheva et al., 2007). The monsoon is generally understood to be the seasonal change from dry to wet along with a reversal of the prevailing winds (Ramage, 1971). Monsoonal climates are characterised by dry winters followed by very wet summers when, by at least one definition, over 70 % of the annual rainfall accumulates (CLIVAR, 2015; Qian et al., 2002; Zhang and Wang, 2008). With all regional monsoon systems, the seasonal monsoon onset, or the first burst of monsoon rains of the season, is a much-anticipated event with documented temporal variability (Ali et al., 2020; Fitzpatrick et al., 2015; Lisonbee et al., 2020; Parija, 2018; Pradhan et al., 2017). This variability may be driven by larger-scale climate variability, such as the El Niño–Southern Oscillation (ENSO). Correlations between ENSO and the monsoon onset have been reported for the South Asian and East Asian monsoons (Wang et al., 2008b; Zhou and Chan, 2007), the Indian monsoon (Misra et al., 2018; Misra and Bhardwaj, 2019; Noska and Misra, 2016), the African and southern African monsoons (Semazzi et al., 2015), the South American monsoon (Grimm et al., 2015), the Mexican and southwest US monsoon (Gochis, 2015), and the Australian monsoon (Drosdowsky, 1996; Holland, 1986;

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Kajikawa et al., 2010; Lisonbee et al., 2020). However, for the Australian monsoon the literature does not completely agree on the degree of influence had by ENSO.

The Drosdowsky (1996) monsoon onset definition is often used as a standard for Australian monsoon onset research (e.g. Berry and Reeder, 2016; Davidson et al., 2007; Evans et al., 2014; Kajikawa et al., 2010; Kim et al., 2006; Pope et al., 2009; Wheeler and Hendon, 2004; Zhang and Wang, 2008) and its practical application in an operational environment in the Darwin Regional Forecast Centre (Shaik and Lisonbee, 2012). Drosdowsky (1996) defined the Australian monsoon as a burst of westerly winds as represented by a deep layer tropospheric mean, with easterly winds aloft as measured at Darwin, Northern Territory, Australia. Using data from the 35 years from 1957/1958 to 1991/1992, Drosdowsky (1996) calculated a $-56\,\%$ correlation with the September–November (SON) Southern Oscillation Index (SOI), a measure of the state of ENSO. During those years, there were eight El Niño and six La Niña events. Subsequently, there have been seven more El Niño events and seven more La Niña events until the 2020/2021 season (see Sect. 5.2). The original motivation for this research was to test if the correlations reported by Drosdowsky (1996) are still valid when including 28 more years of data (i.e. seasons 1992/1993–2020/2021) in the calculation with the overall goal to better understand and utilise the potential predictability of the climate system based on seasonal-scale climate variations. The subsequent research questions that arose are these. Firstly, can a similar correlation be seen from other ENSO or non-ENSO indices? Drosdowsky (1996) was published before the discovery of the Indian Ocean Dipole (IOD) by Saji et al. (1999) and other climate indices, such as central Pacific sea surface temperatures (SSTs), rose to prominence. What other seasonal-scale climate variations may be influencing the timing of the Australian monsoon onset? Secondly, this research question was extended to other Australian monsoon onset methodology. Others have defined the monsoon onset in ways that pin the “onset” to different events in the wet season (Lisonbee et al., 2020) and report varying relationships with ENSO. For example, Kajikawa et al. (2010) reported a correlation coefficient between the SON SOI and Australian monsoon onset of -0.48, while Holland (1986) showed no significant correlation between seasonal monsoon onset and the SOI prior to the summer monsoon season. Do these correlations remain robust when more decades of data are considered? How can the relationships between monsoon onset and climate influences from different onset criteria accurately be compared when each respective dataset covers different time periods? Therefore, the aim of this study is to further investigate how much seasonal-scale climate drivers influence the timing of the Australian monsoon onset based on various onset criteria over the same time period.

For this analysis we will focus on monsoon onset definitions that include a dynamical component, such as a wind reversal. Lisonbee et al. (2020) categorised Australian monsoon onset definitions by those that are based on a wind-criteria and those that are based on a rainfall-criteria. We consider “monsoon” definitions based solely on rainfall to indicate the onset date of the wet season rains and not the dynamical monsoon. While defining and predicting the beginning of the rainy season has useful applications (Balston and English, 2009; Cook and Heerdegen, 2001; Cowan et al., 2020; Drosdowsky and Wheeler, 2014; Lo et al., 2007; Nicholls, 1984; Nicholls et al., 1982; Smith et al., 2008), understanding and predicting the onset of the dynamical monsoon on a seasonal timescale aids our understanding of what drives variability in the monsoon weather pattern and is thus likely to improve monsoon onset forecasting skill when using statistical models. While this study focuses on the Australian monsoon, from a global perspective an understanding of the dynamical monsoon onset is important because tropical cyclones are more likely to form along the monsoon trough (Choi and Kim, 2020; Davidson et al., 1989; Mcbride, 1983; Wheeler and McBride, 2011); and monsoon bursts, whether they include a tropical cyclone or not, can have serious impacts on public health and safety (Martinez et al., 2020), transport and aviation (Pramono et al., 2020), flooding and ecological effects (Crook et al., 2020), and the local economy (Jain et al., 2015). The impacts of wet season rainfall may appear in the early wet season, but the likelihood increases under a persistent monsoon pattern. Nicholls et al. (1982) showed that $30\,\%$ of the wet season rainfall occurs before the monsoon onset. Pope et al. (2009) showed that pre-monsoonal rainfall is characterised by meso-scale thunderstorms, which may produce large rainfall totals locally on individual days, while monsoonal rainfall can produce large rainfall totals for multiple days and over a very broad area. It is known that early wet season (October–December, OND) rainfall correlates well with ENSO (McBride and Nicholls (1983), but even with the wealth of research available on the variability in the Australian monsoon season, the timing of the dynamical monsoon onset is one aspect of the monsoon that still lacks skilful seasonal prediction. The Madden–Julian Oscillation (MJO) provides predictability of the monsoon onset at multi-week timescales. If there was a connection between monsoon onset and climate drivers on a seasonal (multi-month) timescale, it could provide a valuable planning mechanism for agricultural producers and so many others in tropical Australia. This paper presents a statistical analysis of seasonal-scale (1–6 month) climate influences on the timing of the dynamical onset of the Australian monsoon for the period 1950/1951 to 2020/2021. With the acknowledgement that monsoon onset occurs on a sub-seasonal timescale, we are investigating this possibility because it has been proposed in previous research (Drosdowsky, 1996; Hendon et al., 1989; Kim et al., 2006; Kullgren and Kim, 2006; Nicholls, 1984; Smith et al., 2008; Webster et al., 1998), and we would like to test these possible connections.

To do this we, firstly, isolated monsoon onset definitions that (1) focus on northern Australia, (2) required some dynamical component (e.g. reversal of lower tropospheric winds) to determine when the monsoon was active over the region, and (3) included a list of onset dates within the respective publications (see Lisonbee et al., 2020). Secondly, we recreated the annual monsoon onset dates using the methods described in each of these papers. Thirdly, we extended these monsoon onset datasets to cover the same time period (1950/1951 through 2020/2021). Finally, with a standard dataset for each monsoon onset definition, we computed statistical correlations with known seasonal-scale climate drivers to investigate if the timing of the Australian monsoon onset can be reliably predicted on a seasonal timescale (including testing the correlations reported in Drosdowsky, 1996) and also which climate drivers and which monsoon onset definitions provide the best predictability.

The climate indices considered in this study include six ENSO indices, three Indian Ocean SST indices including the Dipole Mode Index (DMI) as a measure of the IOD (Saji et al., 1999; Taschetto et al., 2011; Verdon and Franks, 2005), three polar annular mode indices (Dai and Tan, 2017; Marshall and National Center for Atmospheric Research Staff (Eds.), 2018; Mo, 2000; Thompson and Wallace, 1998), the stratospheric Quasi-Biennial Oscillation (QBO), the North Atlantic Oscillation (Barnston and Livezey, 1987), the three components of the Amundsen Sea index (Raphael et al., 2016), and three Northern Hemisphere monsoon indices (Wang et al., 2001; Wang and Fan, 1999; Webster and Yang, 1992). The physical connection between the Indian monsoon and the Australian monsoon has been investigated previously (Chang and Li, 2000; Kim and Kim, 2016; Li et al., 2001; Meehl, 1994; Meehl and Arblaster, 2002; Pillai and Mohankumar, 2007; Stuecker et al., 2015; Suppiah, 1992; Wang et al., 2003, 2008a; Wu and Chan, 2005; Yu et al., 2003), but these studies considered seasonal rainfall and not the timing of the Australian monsoon onset; hence we have chosen to include these in our analysis. The Madden–Julian Oscillation (MJO) was not included in this study for two reasons. First, the link between the MJO and the onset of the Australian monsoon has been heavily investigated in the literature (most notably by Wheeler and Hendon, 2004 but also by Hendon and Liebmann, 1990a, b; Hendon et al., 1989; Joseph et al., 1991; Pope et al., 2009; Wheeler and McBride, 2012). Secondly, the MJO provides skilful predictability on a timescale of weeks (Lim et al., 2018), while the analysis presented in this paper focuses on the predictive correlations at the seasonal timescale.

2 Data

The data used in this research came from various sources, including the European Centre for Medium-Range Weather Forecasts (ECMWF), the National Centre for Atmospheric Research (NCAR), and the Australian Bureau of Meteorology. As much as possible, the reproduced monsoon onset dates used the same data used in each respective publication. When those data are no longer available, substitutions were made. The original data used and the data used in the recreation are listed in Sect. 2.1. The climate indices used, including their source data, are listed in Sect. 2.2.

2.1 Onset data

In this study, it is important to compare all previously published monsoon onset detection methods to the same temporal period to ensure all cover the same "events" of climate variability (i.e. the same ENSO, IOD, etc. patterns). Table 1 includes the reference of each of the onset criteria reproduced, the description of the meteorological data from the original source, and the data used to reproduce that methodology.

Darwin sounding data were used for several monsoon onset recreations (Drosdowsky, 1996; Holland, 1986; Troup, 1961). Sounding data were obtained from the Australian Bureau of Meteorology directly (available upon request from http://www.bom.gov.au/climate/data-services/, last access: 4 June 2021). One of the limitations of this study is the use of pre-1957 sounding data at Darwin. It should be noted that prior to 1957/58 the sounding timings, methods, and reported heights were non-standard and sometimes irregular (Ramella Pralungo et al., 2014). The inclusion of these data means that onset dates that were calculated using sounding data pre-1957 should be used and interpreted with caution.

2.2 Climate data

The data sources for seasonal climate indices that were used to check for correlations in this study are listed in Table 2.

3 Method

The method to test the correlations of monsoon onset criteria with seasonal climate influences took four steps:

- The first step was to isolate Australian monsoon onset definitions that fit the scope and desired outcomes of this project. We required some dynamical component (e.g. reversal of lower tropospheric winds) to determine when the monsoon was active over the region. A final limit in the scope of this work was to recreate only those works that included a list of onset dates within the respective publications so that we could test if we were recreating the onset dates correctly (see Lisonbee et al., 2020).
- The second step was to recreate the onset dates by following the methodology described in each paper. Only those works that could be sufficiently reproduced were tested for correlations with climate indices.

Table 1. Data used to calculate Australian monsoon onset dates. The web links listed in the table were valid as of the date this work was submitted.

Reference	Original data used in reference	Data used in recreation
Troup (1961)	Rainfall from six locations near Darwin and Darwin sounding data	Rainfall data from the SILO dataset https://www.longpaddock.qld.gov.au/silo/point-data/ (last access: 4 June 2021) Darwin sounding data
Murakami and Sumi (1982)	A custom-made dataset prepared of twice-daily, 2.5° resolution westerly wind data at 850 hPa (see Sumi and Murakami, 1981)	NCEP/NCAR 40-year reanalysis data (Kalnay et al., 1996) http://www.cdc.noaa.gov/ (last access: 4 June 2021)
Holland (1986)	Daily averaged Darwin Airport sounding	Daily averaged Darwin Airport sounding
Drosdowsky (1996)	Darwin Airport sounding	Darwin Airport sounding
Hung and Yanai (2004)	Wind data from 15 year (1979–1993) ECMWF reanalysis (ERA-15) project data (Gibson et al., 1999) Outgoing long-wave radiation (OLR) data source was not described	Wind data from ECMWF ERA5 reanalysis https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5 (last access: 4 June 2021) (Copernicus Climate Change Service C3S, 2017) (last access: 4 June 2021) OLR data were obtained from https://www.ncei.noaa.gov/ (last access: 4 June 2021) (Hai-Tien and NOAA CDR Program, 2011) https://www.ncdc.noaa.gov/cdr/atmospheric/outgoing-longwave-radiation-daily (last access: 4 June 2021)
Davidson et al. (2007)	NCEP/NCAR 40-year reanalysis data (Kalnay et al., 1996) http://www.cdc.noaa.gov/ (last access: 4 June 2021)	NCEP/NCAR 40-year reanalysis data (Kalnay et al., 1996) http://www.cdc.noaa.gov/ (last access: 4 June 2021)
Kajikawa et al. (2010)	NCEP/NCAR 40-year reanalysis data (Kalnay et al., 1996) http://www.cdc.noaa.gov/ (last access: 4 June 2021)	NCEP/NCAR 40-year reanalysis data (Kalnay et al., 1996) http://www.cdc.noaa.gov/ (last access: 4 June 2021)

- The third step was to extend each of the selected monsoon onset datasets to cover the same time period. The extended datasets cover the period from the 1950/1951 Australian wet season to the 2020/2021 season. This period is limited based on data availability in that, in this study, the ECMWF ERA-5 reanalysis used for the Hung and Yanai (2004) recreation begins in 1950 and, thus, presented the limit in dataset reproductions. This allowed comparisons of monsoon onset datasets that cover the same "events" of climate variability (i.e. the same ENSO, IOD, etc. patterns). For example, Kajikawa et al. (2010) show a correlation coefficient between the September–November (SOI) and monsoon onset of −0.48, calculated using the years 1948–2005 and including 10 La Niña events (SON SOI > 0.8), while Drosdowsky (1996) showed a correlation coefficient between onset date and the SON SOI of −0.56 for 1957 through 1992 which included only six La Niña events (SON SOI > 0.8). In the full period from 1950 to 2020, there were 11 positive IOD events (SON DMI > 0.4) and 16 negative IOD events (SON DMI < -0.4), and 16 positive and 21 negative ENSO events (this count using the SON NINO3.4 SST anomalies > 0.7 °C and < -0.7 °C, respectively).
- The final step was to test the correlations of the monsoon onset dates with the climate indices. Each monsoon onset definition (Table 1) was paired with each of the climate indices (Table 2). Each pair was tested for normalcy. When both pairs fit a Gaussian distribution, then the Pearson coefficient (ρ) and corresponding two-tailed significance test value (p) were calculated. When either of the two pairs did not fit a Gaussian distribution, then the Kendall's coefficient (τ) and corresponding p value were calculated. (As a matter of convention) we have considered $p<0.05$ to represent statistical significance. When the correlations were larger than ±0.3, we considered the monsoon onset to be somewhat influenced by the climate driver, and when the correlation coefficients were larger than ±0.6, we considered the monsoon onset to be largely influenced by the climate driver and sufficient to be used as a predictive tool.

Table 2. Data sources for major climate drivers used in this study. The web links listed in the table were valid as of the date this work was submitted.

	Index	Data source web address as of January 2021
ENSO	NINO 3 NINO 3.4 NINO 4	ERSST5 data from https://www.cpc.ncep.noaa.gov/data/indices/ (last access: 4 June 2021)
	El Niño Modoki index	http://www.jamstec.go.jp/frsgc/research/d1/iod/modoki_home.html.en (last access: 1 September 2020)
	Monthly Southern Oscillation Index (SOI)	http://www.bom.gov.au/climate/current/soi2.shtml (last access: 4 June 2021) (Troup, 1965)
Indian Ocean (SSTs)	Indian Ocean Dipole (IOD) Dipole Mode Index (DMI)	https://psl.noaa.gov/gcos_wgsp/Timeseries/DMI/ (last access: 4 June 2021) (Saji et al., 1999)
	Indian Ocean basin-wide SST index	ERSST.v5 data averaged from 25° N to 25° S, 30 to 120° E. (adapted from Taschetto et al., 2011)
	Indonesian index sea surface temperature (II SST)	ERSST.v5 (Verdon and Franks, 2005)
Northern Hemisphere monsoons	Indian Monsoon Index (IMI)	http://apdrc.soest.hawaii.edu/projects/monsoon/seasonal-monidx.html (last access: 4 June 2021) (Wang et al., 2001; Wang and Fan, 1999)
	Webster and Yang Monsoon Index (WYM)	http://apdrc.soest.hawaii.edu/projects/monsoon/seasonal-monidx.html (last access: 4 June 2021) (Webster and Yang, 1992)
	Western North Pacific Monsoon index (WNPMI)	http://apdrc.soest.hawaii.edu/projects/monsoon/seasonal-monidx.html (last access: 4 June 2021) (Wang et al., 2001; Wang and Fan, 1999)
Polar annular modes	Arctic Oscillation (AO)	https://www.ncdc.noaa.gov/teleconnections/ao/ (last access: 4 June 2021) (Dai and Tan, 2017; Thompson and Wallace, 1998)
	Antarctic Oscillation (AAO)	https://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/aao/aao.shtml (last access: 4 June 2021) (Mo, 2000)
	Marshall station-based Southern Annular Mode index (SAM)	https://climatedataguide.ucar.edu/climate-data/marshall-southern-annular-mode-sam-index-station-based (Marshall and National Center for Atmospheric Research Staff (Eds.), 2018)
Quasi-Biennial Oscillation (QBO)		Standardised westerly 50 hPa winds https://www.cpc.ncep.noaa.gov/data/indices/ (last access: 4 June 2021)
North Atlantic Oscillation (NAO)		https://www.ncdc.noaa.gov/teleconnections/nao/ (last access: 4 June 2021) (Barnston and Livezey, 1987)
Amundsen Sea Low index (ASLI)	Latitude variations	https://climatedataguide.ucar.edu/climate-data/amundsen-sea-low-indices (last access: 4 June 2021) (Raphael et al., 2016)
	Longitude variations	
	Relative central pressure	

3.1 Troup (1961) onset definition

Troup (1961) described the Australian monsoon onset using both wind and rainfall. For a rainfall onset, Troup (1961) analysed rainfall data at six locations near Darwin for the wet seasons from 1955/1956 to 1958/1959. For each season in the study period, Troup defined the onset to have occurred when four out of the six stations experienced their first rainfall event simultaneously after 1 November and the area-averaged rainfall over N days exceeded $0.75(N+1)$ in. (19 mm/d). Using upper-air data from Darwin airport, Troup isolated the westerly wind component at "3000 feet" (915 m) and identified spells of moderate west winds. A westerly wind spell of N days occurred when the cumulative westerly component exceeds $10(N+1)$ kn and ended when this component was less than 5 kn for 2 consecutive days. When extending the dataset, we considered the rainfall onset and wind onset separately, but we also noted the first day when both the wind and the rainfall criteria were met at the same time (similar to Hendon and Liebmann, 1990b).

3.2 Murakami and Sumi (1982) onset definition

Murakami and Sumi (1982) used the enhanced observation data networks of the Global Weather Experiment and of its component experiment, the Winter Monsoon Experiment (WMONEX), to analyse the Australian monsoon. They defined monsoon onset using the mean 850 hPa westerly wind averaged along 10° S from 100 to 180° E; onset occurred at the first appearance of mean westerlies along this line. Murakami and Sumi (1982) provided the onset date for only one monsoon season, 1978/1979. Following the Murakami and Sumi (1982) methodology, we were able to reproduce the 1978/1979 onset and extend the onset dataset using the NCEP/NCAR 40 year reanalysis data (Kalnay et al., 1996).

3.3 Holland (1986) onset definition

Holland (1986) defined monsoon onset as the first westerly winds at the 850 hPa level at Darwin Airport. Holland (1986) analysed seasons 1952/1953–1982/1983, and took a special focus in the 1978/1979 wet season as the year of the WMONEX study. Holland averaged the daily 850 hPa level winds to remove diurnal variations and produce a daily time series. He then smoothed out other minor variations in the data using a cubic spline method to the yearly time sequence of the daily mean winds. He was then able to analyse the onset and retreat and the burst and break periods within any season. Drosdowsky (1996) attempted to recreate the onset dates from Holland (1986) but was unable to recreate the results. To explain the differing results, Drosdowsky (1996) pointed to, and criticised, the use of a smoothed time series at a single pressure level. Drosdowsky (1996) points out examples when the smoothed single-level winds miss the actual onset events because either the winds at 850 hPa are not representative of the lower mid-tropospheric westerly wind or the low-pass filtering over the data blurs an abrupt change in the deep-layer winds over several days. Hendon and Liebmann (1990a) built upon the wind definition of Holland (1986), but they replaced the cubic spline with a 1-2-3-2-1 running mean to smooth out synoptic fluctuations.

3.4 Hendon and Liebmann (1990a) onset definition

Hendon and Liebmann published two papers on the NAM in 1990. The first (Hendon and Liebmann, 1990a) was specifically regarding the Australian monsoon onset, while the second (Hendon and Liebmann, 1990b) examined the mechanisms for the variability within the season. In these papers, Hendon and Liebmann define the onset using both wind and rainfall. The wind data are taken from the Darwin Airport upper-air record, and the rainfall is taken as the daily area averaged rainfall for stations north of 15° S in Australia. The seasons from 1957/1958 through 1986/1987 were considered. Onset was determined by the first detection of "wet westerlies" at 850 hPa – meaning area averaged rainfall of at least 7.5 mm/d coincident with the wind criteria adopted from Holland (1986) but filtered with a 1-2-3-2-1 running mean as opposed to the cubic spline filter that Holland used.

Drosdowsky (1996) attempted to recreate the Hendon and Liebmann (1990a) results without much success. He points to the lack of clarity in their description of their techniques and datasets. Drosdowsky (1996) is also very critical of the use of a filter to smooth the daily wind data, pointing to examples when the wind reversal was quite abrupt but the smoothed data produce a gradual reversal over several days.

Hendon and Liebmann (1990a) are vague on their description of the data used. For the 850 hPa westerly wind the use of the upper-air record at Darwin is "as per Holland (1986)". In attempting to recreate these results we used all available sounding data each day to produce daily averages of the 850 hPa level winds (as per the reproduction of Holland, 1986). We then smoothed the daily data with a 1-2-3-2-1 weighted running mean. Drosdowsky suspects that Hendon and Liebmann may have also removed the annual cycle from their daily wind dataset, although this was not mentioned in the Hendon and Liebmann (1990a) methodology (Drosdowsky, 1996). We did not attempt to remove an annual cycle.

The rainfall data used in Hendon and Liebmann (1990a) are described as "the daily record of area averaged rainfall for stations north of 15° S in Australia". They provide a list of rainfall stations used in their Table 1, but in that table Darwin Airport is the only location listed that is north of 15° S in Australia. In attempting to reproduce the Hendon and Liebmann (1990a) onset dates we used both the daily rainfall record at Darwin Airport and the gridded rainfall data for all points in Australia north of 15° S. These data were obtained from the SILO dataset (https://www.longpaddock.qld.gov.au/silo/gridded-data/, last access: 4 June 2021).

3.5 Drosdowsky (1996) onset definition

The Drosdowsky (1996) deep layer mean westerly wind definition defines the monsoon onset at Darwin using Darwin sounding data. Drosdowsky (1996) developed definitions of active and break cycles and the onset and retreat of the monsoon. Using the 23:00 UTC upper-air data from Darwin Airport, the monsoon was defined as deep low-level westerly flow overlain by strong upper-level easterlies. The mass-weighted deep layer mean winds in the lower troposphere is calculated using Eq. (1), and the mass-weighted deep layer mean winds in the upper troposphere is calculated using Eq. (2):

$$\begin{aligned}\mathrm{DLM}_{\mathrm{lower}} = {} & 0.1U_{\mathrm{sfc}} + 0.15U_{900\,\mathrm{hPa}} + 0.12U_{850\,\mathrm{hPa}} \\ & + 0.15U_{780\,\mathrm{hPa}} + 0.13U_{700\,\mathrm{hPa}} + 0.1U_{650\,\mathrm{hPa}} \\ & + 0.15U_{600\,\mathrm{hPa}} + 0.1U_{500\,\mathrm{hPa}}, \qquad (1)\end{aligned}$$

$$\mathrm{DLM}_{\mathrm{upper}} = 0.25U_{200\,\mathrm{hPa}} + 0.5U_{150\,\mathrm{hPa}} + 0.25U_{100\,\mathrm{hPa}}, \qquad (2)$$

where U is the westerly wind component and the subscripts indicate the pressure level of that wind measurement. Monsoon onset was considered when the average $\mathrm{DLM}_{\mathrm{lower}}$ over N days exceeded $2.5(N+1)/\mathrm{N}$ (in units of m/s) and $\mathrm{DLM}_{\mathrm{upper}}$ is easterly ($U<0$). These lower level westerly winds had to be in place for at least 2 consecutive days to be considered an active monsoon period, and the minimum break period between bursts is 3 d such that westerly wind bursts separated by only 1 or 2 d were concatenated. The monsoon onset was defined as the first day of the first active monsoon period within the season.

Drosdowsky (1996) found that some subjective assessment of onset dates cannot be avoided, but the onset dates from the 5 years from 1987/1988 to 1991/1992 were determined completely objectively. The years when a subjective analysis was needed, the choices made by Drosdowsky (1996) seemed logical and were also used in the recreation. In most years when objective analysis was applied the onset criteria were met for $\mathrm{DLM}_{\mathrm{lower}}$, but the upper level easterlies had not been established. For some other years missing data made objective analysis impossible – one obvious example was the monsoon onset on 25 December 1974 for which there are missing data from 25 to 30 December due to the passage of tropical Cyclone Tracey. The treatment of missing data is described in Drosdowsky (1996). For the extended dataset (1992/1993–2019/2020) subjective analysis was applied to the 1998/1999 and 2004/2005 seasons.

3.6 Hung and Yanai (2004) onset definition

Hung and Yanai (2004) defined the onset of the Australian monsoon using the reanalyses from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-15, outgoing long-wave radiation (OLR), and precipitation data for 1979–1993. Onset is defined as the first day with average 850 hPa westerly wind exceeding 2 m/s over a north Australian–Arafura sea domain (2–15° S, 115–150° E) when the westerly wind is sustained for longer than 10 d and the OLR is lower than 210 W/m^2 for “at least several days” during the 10 d period. Using this definition, the mean onset date from the 14 years studied is 25 December with a standard deviation of 2 weeks.

In reproducing the Hung and Hung and Yanai (2004) onset dates the ERA-15 data were no longer available. ERA-5 and ERA-interim reanalysis data were used as a substitution, both producing the same results; ERA-5 data are shown here. The recreated onset dataset matched the original dates to within 1 d in all but two cases (see Fig. 1) which will be discussed in the results section.

3.7 Davidson et al. (2007) onset definition

Davidson et al. (2007) defined the NAM onset using wind-only criteria in a fashion similar to Drosdowsky (1996) but for a general monsoon region as opposed to the point observations at Darwin Airport that were used in Drosdowsky (1996). Davidson et al. (2007) began with a comparison between both the NCEP and ERA-40 datasets. The close agreement in the westerly wind and mean sea level pressure (MSLP) indicated consistency in the datasets for these standard variables. They concluded that either of the reanalyses are suitable for their purposes since the temporal changes are consistent within each dataset, and they used the NCEP dataset in their analysis of monsoon onset dates. Davidson et al. (2007) defined the monsoon onset as a sudden strengthening and deepening in tropical westerly winds, which are overlain with upper-tropospheric easterlies over a monsoonal region (15°–5° S, 110°–140° E). The lower-tropospheric westerly winds had to meet a minimum threshold of 2.5 m/s and extend to at least 600 hPa. Easterlies in the upper troposphere must overlay the westerlies. This structure must persist for at least 4 d. The authors did not specify which pressure levels they considered to be “the lower troposphere” or which levels they considered to be “the upper troposphere”. In both the reproduced and extended datasets, we used 1000–500 hPa to represent the lower troposphere and levels 250–150 to represent the upper troposphere. For all other aspects of this reproduction we were able to follow the methodology described in Davidson et al. (2007).

3.8 Kajikawa et al. (2010) onset definition

Kajikawa et al. (2010) derived an Australian monsoon index (AUSMI) to examine intra-seasonal variability, including the onset. This index is defined using 850 hPa westerly wind averaged over the area 5–15° S, 110–130° E using daily NCEP reanalysis data in which positive values indicate a westerly wind.

Kajikawa et al. (2010) patterned their onset criteria after the Wang et al. (2004) monsoon onset definition for the South China Sea monsoon onset. The Australian monsoon onset is defined as the first day after 1 November that satisfies the following three criteria: (1) on the onset day and during the 5 d after the onset day the averaged AUSMI must be positive; (2) the pentad mean AUSMI is positive in at least three of the subsequent four pentads; and (3) the accumulative four-pentad mean AUSMI > 1 m/s (Kajikawa et al., 2010).

3.9 Zhang (2010) onset definition

Zhang (2010) defined the Australian monsoon onset using a normalised precipitable water index similar to Zeng and Lu (2004), who created a global monsoon index based on a

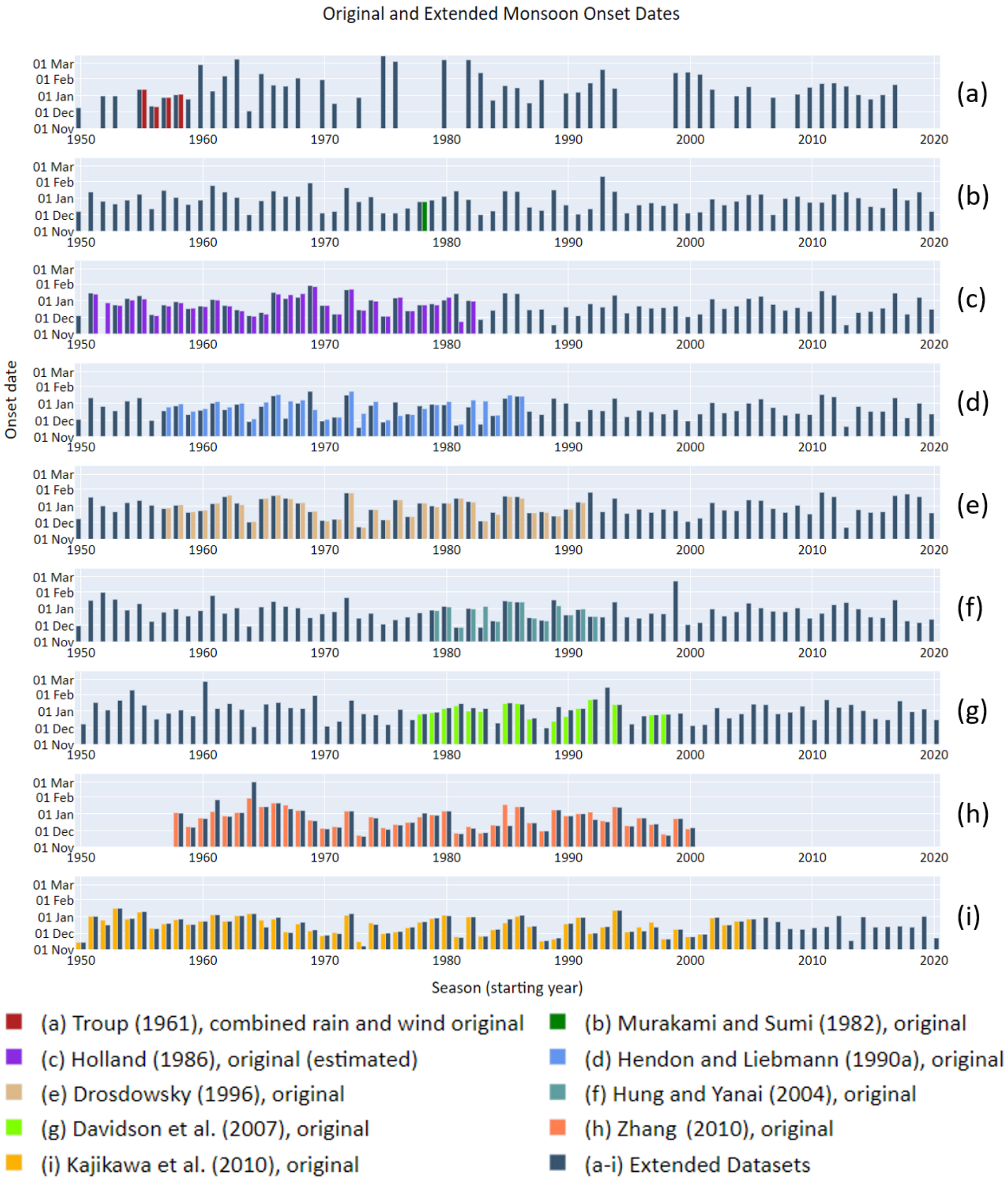


Figure 1. Recreated and extended monsoon onset dates using the methods described in each respective paper.

normalised precipitable water index. Zhang (2010) used this same index to define onset and retreat dates for northern Australia and Darwin. The normalised precipitable water (PW) index is defined as

$$\mathrm{PW}_n = \frac{(\mathrm{PW} - \mathrm{PW}_{\mathrm{min}})}{(\mathrm{PW}_{\mathrm{max}} - \mathrm{PW}_{\mathrm{min}})}, \qquad (3)$$

where $\mathrm{PW}_{\mathrm{max}}$ and $\mathrm{PW}_{\mathrm{min}}$ are the 44 year mean of daily PW maximum and minimum in each of the 44 years during the period of 1958–2001 and at each grid point. Once PW_n was calculated for each day and each grid point, they then define monsoon onset/retreat as follows: first, they assess if the PW_n exceeds 0.65 for 3 continuous days for at least seven of the nine points around a location; then they assess whether 850 hPa monsoon westerly is established, with averaged westerly wind of the nine points around the location remaining westerly for the same 3 d.

Zhang (2010) used daily and monthly ERA-40 reanalysis data for the period of 1958–2001. To test the ability to recreate the Zhang (2010) methodology we used the daily westerly wind component and total column water data from ERA-40. The primary limitation to using ERA-40 data is that they only cover the years 1958 to 2002. To extend the dataset we would need to use a different reanalysis dataset such as

ERA-interim or ERA-5. As will be shown below, we could not satisfactorily recreate the Zhang (2010) methodology for ERA-40, and, therefore, we did not repeat the process with a longer dataset.

4 Results

In the following subsections are the results of each stage of this analysis. First is a report on the accuracy of the recreated monsoon onset datasets in Sect. 4.1, followed by a detailed analysis of correlations with climate indices with the Drosdowsky (1996) extended dataset in Sect. 4.2, and then a summary of the same analysis for the other eight extended monsoon onset datasets in Sect. 4.3.

4.1 Monsoon onset reproductions

To answer the research question posed in the Introduction, we created monsoon onset data that covered a standard time period such that correlations of the individual onset methodologies overlapped with the same climate indices. Out results in reproducing the onset methods described in Section 3 are described here in chronological order of the respective publication date and are also shown in Fig. 1a–k. Recreated data are shown in comparison to the original data. Also shown are the onset data using each definition for the extended period.

Troup (1961) considered the rainfall onset and the wind onset to be two separate events that occasionally overlapped. When extending the dataset, we also considered the rainfall onset and wind onset separately, but we also noted the first day when both the wind and the rainfall criteria were met at the same time (similar to Hendon and Liebmann, 1990b). This method successfully reproduced the onset from the 4 years studied by Troup (1961; Fig. 1a), but we found that, when extending the dataset to the present, there were a few years when both criteria were not met at the same time at any point within the season. This also provided for a few very late onset dates (e.g. February and March). While Troupe (1961) included the dates for all monsoon "bursts" – a term Troup (1961) used to describe an active monsoon period – within each season, here we are considering only the dates of the first burst each season as the "onset". The extended dataset captured the onset for each year precisely; however, it did not capture the exact dates of each burst as described by Troup (1961), although the dates were off by only a day or two. We suspect Troup (1961) used some subjective analysis in determining these dates. The extended Troup (1961) dataset showed mean onset dates of 31 December using the rainfall criteria, 29 December using the wind criteria, and 20 January using both criteria combined, each with a standard deviation of 25 d.

Murakami and Sumi (1982) provided the onset date for only one monsoon season, 1978/1979 (Fig. 1b). Following the Murakami and Sumi (1982) methodology, we were able to reproduce the 1978/1979 onset and extend the onset dataset using the NCEP/NCAR 40 year reanalysis data (Kalnay et al., 1996). The reconstructed dataset shows a mean onset date of 26 December with a standard deviation of 16 d.

The Holland (1986) onset dates and associated uncertainty estimates were taken from Table 3 in Lisonbee et al. (2020). We could not recreate the Holland (1986) onset dates using a cubic spline smoothing method, experiencing similar problems as Drosdowsky (1996). Through some experimentation we were able to recreate most of the Holland (1986) dates to within the uncertainty estimates using 19 iterations of a 1-2-3-2-1 filter similar to Hendon and Liebmann (1990a). We recreated 22 onset dates (79 %) to within the uncertainty estimates, 5 onset dates (18 %) that are less than 1 week outside the uncertainty estimates, and 1 onset date that was more than 1 week outside the uncertainty estimate (Fig. 1c). Holland (1986) showed the average onset date for the 30 years from 1952/1953 to 1982/1983 was 24 December, with the earliest onset date of 23 November and the latest date of 27 January. When considering the full extended dataset, the mean onset date is 22 December with a standard deviation of 16 d. We could not recreate the earliest onset date from the original dataset, but later in the reconstructed dataset the earliest onset date is 15 November.

For the Hendon and Liebmann (1990a) onset dates, only 4 of the 30 seasons (13 %) were successfully reproduced, 17 seasons (47 %) were within 7 d, and 9 seasons (30 %) were more than 7 d away from the original Hendon and Liebmann (1990a) dates (Fig. 1d). Similar to the Drosdowsky (1996) attempt to reproduce the Hendon and Liebmann (1990a) onset dates, we found that there were aspects of their methodology and data used that were unclear. It is possible that Hendon and Liebmann (1990a) did not use daily averaged 850 hPa winds; perhaps they used only the 12:00 or 23:00 UTC soundings. Drosdowsky (1996) suggests Hendon and Liebmann (1990a) may have removed the mean seasonal wind cycle from their wind data without mentioning this in their methodology. It is also possible that the averaged gridded daily rainfall data we are using do not match the areal averaged station data for stations north of 15° S in Australia. Overall, we did not consider this a successful reproduction, and the extended Hendon and Liebmann (1990a) dataset was not included in correlations calculations.

Our recreation and extension of the Drosdowsky (1996) onset dates is shown in Fig. 1e. Our analysis reproduced the precise onset dates for 13 of 35 years (37 %), was different by 1 d for 17 of the 35 years (48 %), and was different by more than 1 d but less than 5 d for 5 of the 35 years (14 %). Drosdowsky (1996) included some subjective analysis in determining the onset data, but the 5 years from the 1987/1988 season to the 1991/1992 season were found completely by objective analysis, and we were also able to reproduce the dates precisely for three seasons and with a 1 d difference for the 1988/1989 and 1991/1992 seasons. Dros-

Table 3. Correlation coefficients of seasonal ENSO indices with Drosdowsky (1996) monsoon onset dates. Only statistically significant ($p<0.05$) values are shown.

Correlations with Drosdowsky (1996)					
	Index				
Season	NINO3	NINO3.4 (detrended)	NINO4 (detrended)	SOI	Modoki index
JJA	$\rho = 0.25$	$\rho = 0.32$ (0.33)	$\rho = 0.32$	$\rho = -0.25$	
JAS	$\tau = 0.17$	$\rho = 0.29$ (0.30)	$\rho = 0.34$ (0.38)	$\rho = -0.29$	$\tau = 0.20$
ASO	$\tau = 0.16$	$\rho = 0.29$ (0.30)	$\rho = 0.35$	$\rho = -0.33$	$\tau = 0.27$
SON	$\tau = 0.17$	$\rho = 0.31$ (0.31)	$\rho = 0.37$ (0.23)	$\rho = -0.40$	$\tau = 0.31$

dowsky (1996) showed the average onset date for the 35 years from 1957/1958 to 1991/1992 was “28–29 December”. When considering the full extended dataset, the mean onset date is 29 December with a standard deviation of 16 d.

The recreated Hung and Yanai (2004) onset dataset matched the original dates to within 1 d in all but two cases (Fig. 1f). The 1983/1984 and 1989/1990 seasons present a very large discrepancy which is probably due to using the ERA-5 data rather than the ERA-15 data. In the 1983/1984 season both the ERA-interim and the ERA5 data show a 12 d run of days with westerly wind greater than 2 m/s with 5 d of OLR below 220 w/m^2. If only 2 d within this spell did not meet the 2 m/s threshold in the ERA-15 data, then the next monsoonal burst, which occurred on 5 January 1984, would have been counted as the onset date, as was shown in Hung and Yanai (2004). In the 1989/1990 season the westerly winds reached the 2 m/s threshold on 6 January (the onset date for that season from Hung and Yanai, 2004) but dropped below 2 m/s on the 7th and then above it again on the 8th through the 14th, making only a 7 d run, and then above the threshold again from the 14th through the 31st. On the days below the threshold, the winds are still westerly and are close to 2 m/s. It is quite possible that the ERA-15 data maintained a strong enough burst to show a 10+ day run beginning on the 6th.

The extended Hung and Yanai (2004) dataset, with the outliers retained, shows a mean onset date of 27 December with a standard deviation of 20 d.

Davidson et al. (2007) report the mean onset date is 2 January. The reproduced dataset captured the precise onset dates as the original dataset in only 4 of the 15 seasons analysed by Davidson et al. (2007); it was off by only 1 d for 6 of the 15 seasons, off by more than 1 d but less than 7 d for 3 of the 15 seasons, and different by more than 1 week for two seasons (1989/1990 and 1990/1991; see Fig. 1g). The extended dataset shows a mean monsoon onset of 2 January with a standard deviation of 17 d.

Zhang (2010) original onset dates and the recreated onset dates are compared in Fig. 1h. Of the 43 years considered by Zhang (2010), we were able to successfully recreate the precise onset date for only 15 (35 %) of the years and within 3 d for 36 seasons (84 %). Of the remaining six seasons, the recreation differed from the original dates by 1 to almost 6 weeks, with the largest difference of −39 d in the 1985/1986 season. Because of the large differences in these seasons, we do not consider this to be a successful reproduction. It is not clear what caused the differences, although we found the analysis to be very sensitive to the period selected for the climatological mean PW$_{\text{max}}$ and PW$_{\text{min}}$ (i.e. whether the PW$_{\text{max}}$ and PW$_{\text{min}}$ were calculated over the full wet season or just the monsoon months). Due to these large discrepancies for more than 10 % of the recreated dataset and the limitations with the ERA-40 reanalysis data (mentioned in Sect. 3.9), we chose not to calculate an extended dataset (see Fig. 1h), and Zhang (2010) data are not included in the correlations calculations (Sect. 4.3).

For the Kajikawa et al. (2010) reproduction, we were able to successfully recreate the daily AUSMI values but found some discrepancies when applying the onset criteria. By adjusting the threshold of the third criterion listed in Sect. 3.8 we were able to find a closer match for most years. Of the 58 years included in the original study, we were able to reproduce 52 seasons (90 %) to within 3 d of the original dates including 20 onset dates matching the Kajikawa et al. (2010) dates precisely (see Fig. 1i). Two of the onset dates were different by more than 3 d but less than 1 week, and four had more than 7 d but less than 2 weeks difference between the original and reproduced onset dates. Kajikawa et al. (2010) noted a mean onset date of 15 December with a standard deviation of 16 d. The recreated dataset shows the same statistics for the same years, but when using the extended dataset, the standard deviation is 15 d.

4.2 Comparison with climate indices

Here we show the full analysis of statistics for the Drosdowsky (1996) onset methodology. We will then report the results of applying the same methodology to the other monsoon onset datasets.

Drosdowsky (1996) reported a correlation coefficient between onset date and the September–November (SON) SOI of $\rho = -0.56$ for the period of 1957 through 1992. However, when this dataset is extended to 2021, the correlation drops to $\rho = -0.40$ ($p<0.05$), and when analysing only the extended data (i.e. 1992 to 2021), the correlation is even lower ($\rho = -0.23$). Using an arbitrary threshold of a seasonal SON SOI value of $+/-7$ to define the ENSO state (i.e. values $>+7$ indicate a La Niña state and values <-7 indicate an El Niño state), we can see that in the original dataset there were eight El Niño years and six La Niña years. In the latter part of the dataset there were seven more El Niño years and seven more La Niña years with some strong La Niña events (SOI > 10, or 1 standard deviation of MSLP anomalies) that are not present in the earlier part of the record.

When considering sea surface temperatures rather than the SOI, the correlations are equally small. The correlation coefficient between the monsoon onset dates and ENSO indices are in Table 3. The onset dates showed the highest correlation with the SON NINO4 index ($\rho = 0.37$); however, that correlation weakens when the background warning trend is removed from the SST index. Both the NINO3.4 and the ENSO Modoki index showed correlation coefficients of 0.31. When filtering out neutral years (NINO3.4 anomaly > -0.7 and <0.7), the correlation coefficient increases to $\rho = 0.40$, and when filtering out all neutral and weak events (NINO3.4 index within 1 SD), the correlation coefficient increases to $\rho = 0.43$ ($p = 0.06$).

The delay in onset during strong El Niño years is small compared to the expedition of onset dates during strong La Niña years, $+2$ and -14 d, respectively (see Fig. 2c). Figure 2a shows the Drosdowsky (1996) onset dates for each season from 1950/1951 to 2020/2021 with each season shaded by weak/strong and $+/-$ ENSO state based on the NINO3.4 index. In Fig. 2b the data have been sorted by onset date, and in Fig. 2c the data have been grouped by ENSO state. The same analyses for the SOI, NINO3, NINO4, and ENSO Modoki (not shown) show similar patterns as the NINO3.4 analysis shown in Fig. 2. Our results show that only a strong La Niña has a meaningful impact on Australian monsoon onset timing at Darwin using the Drosdowsky (1996) onset method. The monsoon onset was earlier than the average for 12 out of 15 strong La Niña years, compared to 7 of 12 weak La Niña years, 10 out of 23 ENSO-neutral years, 5 out of 13 weak El Niño years, and 3 out of 8 strong El Niño years. Note that the three strong La Niña years that saw a later than average onset date all occurred before 1957 (see Fig. 2a), which, as stated in Sect. 2.1, should be interpreted with caution.

Using the 70 years in this study as a basic statistical model, there is a 60 % probability that onset will be delayed given an El Niño with SON NINO3.4 anomaly > 0.98 °C (1 standard deviation) and an 81 % probability that onset will be early given a La Niña with SON NINO3.4 anomaly < -0.98 °C, compared with a 48 % probability when using all data.

The correlations with non-ENSO climate drivers listed in Table 2 showed mixed results. Most of the correlations did not show statistical significance. Only the IOD, the Western North Pacific Monsoon Index (WNPMI) index, and the Indonesian Index SST (II SST; Verdon and Franks, 2005) showed statistical significance, yet the correlations were relatively low.

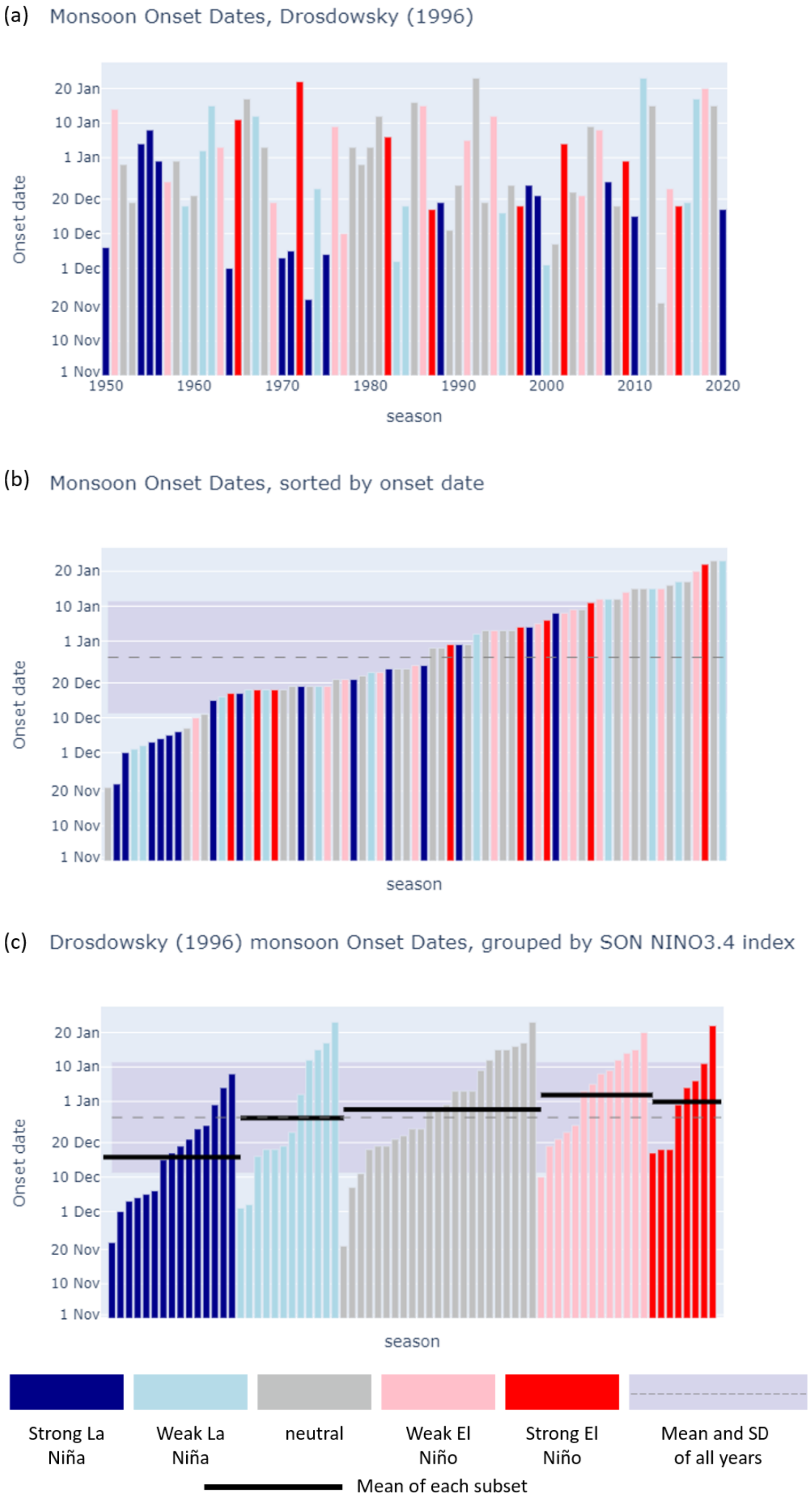
The detrended IOD showed positive correlations of over 30 % for the month of September ($\rho = 0.37$) and for the season of August–October (ASO; $\rho = 0.34$). When the trends were retained, the correlations were similar. A positive IOD has a stronger tendency toward delaying the monsoon onset than a negative IOD has in expediting the onset. Of the 70 years considered, 83 % of the monsoon onsets during a positive IOD were delayed, while only 58 % of the onset dates during a negative IOD were early. There were 2 years when the monsoon onset occurred in November (1973, 2013), and these were both neutral IOD years, suggesting the IOD was not a factor in the early onset. Nearly half of the onset dates occurred in December, although the IOD pattern has usually diminished by the time the monsoon has begun; there is no statistically significant link between the December IOD index and December onset dates.

The June–September WNPMI showed a correlation coefficient with monsoon onset timing of $\rho = 0.37$ ($p<0.05$). The II SST showed a small negative correlation with Drosdowsky (1996) onset dates. The mean SST for June–August had a correlation of $\rho = -0.24$ ($p<0.05$) which gradually increased to $\rho = -0.26$ ($p<0.05$) in the SON season. The present study found that the correlation between the June–September Indian Monsoon Index and the Drosdowsky (1996) monsoon onset dates was low and lacked statistical significance.

4.3 Correlation analysis

Following the same process as was followed to test the correlations with the Drosdowsky (1996) onset dates, here we show the results of the correlations with the other extended datasets.

For Troup (1961), the timing of neither the wind nor the rainfall onset criteria showed a significant correlation with any ENSO, IOD, or SST indicators. The extended dataset showed statistically significant, albeit small, correlations with high latitude variability, specifically the Amundsen Sea Low Index and a delayed correlation with the Antarctic Os-


(a) Monsoon Onset Dates, Drosdowsky (1996)

(b) Monsoon Onset Dates, sorted by onset date

(c) Drosdowsky (1996) monsoon Onset Dates, grouped by SON NINO3.4 index

Figure 2. Analysis of Drosdowsky (1996) onset dates with NINO3.4 SST anomalies. Colours are as follows: *dark blue* = SST < -0.99 °C; *light blue* = -0.99 °C $\leq$ SST < -0.5 °C; *grey* = -5 °C $\leq$ SST $\leq +0.5$ °C; *pink* = $+0.5$ °C $<$ SST $\leq +0.99$ °C; and *red* = SST $> +0.99$ °C. **(a)** Monsoon onset dates for each season, coloured by NINO3.4 SST anomalies. **(b)** Monsoon onset dates sorted by onset date and coloured by NINO3.4 SST anomalies. **(c)** Monsoon onset dates grouped by ENSO state and coloured by NINO3.4 SST anomalies.

cillation. The Troup (1961) rainfall onset correlated with the AAO for the seasons August–September ($\rho = 0.33$) and September–November ($\rho = 0.31$), as well as the October–December mean relative central pressure variation of the Amundsen Sea Low Index ($\rho = -0.37$). The Troup (1961) wind onset correlated with the longitude variation of the Amundsen Sea Low Index for the seasonal mean of June–August ($\rho = -0.40$), July–September (JAS; $\rho = -0.30$), and August–October ($\rho = -0.41$) and the latitude variation of the Amundsen Sea Low Index for the seasonal mean of September–November ($\rho = 0.37$) and October–December ($\rho = 0.45$). The physical mechanism causing this relationship should be the topic of future research but may be related to teleconnections with mid-latitude variability (see, for example, Berry and Reeder, 2016). The combined Troup (1961) wind and rainfall criteria did not show a statistically significant relationship with any climate indices.

Murakami and Sumi (1982) showed a statistically significant correlation with the detrended NINO4 index for the season July–September ($\rho = 0.32$). However, when the trend is retained, the relationship weakens such that only the September–November season shows a relationship with a correlation greater than 30 % ($\rho = 0.33$). Murakami and Sumi (1982) also showed a statistically significant correlation with the ENSO Modoki index and the NINO3 and NINO3.4 SST indices, but in all cases the correlation coefficient is less than ±30 %. When considering strong ENSO events, in which the seasonal index exceeds ±1 standard deviation, the correlations with the Murakami and Sumi (1982) onset dates increased. For the detrended SON NINO3.4 index the correlation coefficient increased from $\rho = 0.23$ to $\rho = 0.40$. Of the 70 years considered, 70 % of the monsoon onsets during a strong El Niño were delayed, while 90 % of the onset dates during a strong La Niña were early. We also considered the correlations with non-ENSO climate drivers listed in Table 2. Most of the correlations did not show statistical significance. Only the detrended IOD indices showed statistical significance, but the correlations were small, i.e. within ±30 %. When retaining the trend in the IOD pattern, the correlation coefficients were lower in every case, suggesting that what little correlation exists between the Murakami and Sumi (1982) monsoon onset dates and the IOD is diminishing over time. When the IOD is not present or the DMI is neutral, it is not a factor in driving monsoon onset timing, the correlation (τ) is near 7 % and onset dates range from 1 December to 10 February. However, when considering only the events when the detrended SON IOD is not neutral (seasonal average DMI is <-0.4 or $>+0.4$), the correlation coefficient with onset dates increases to $\tau = 0.43$ with $p<0.05$. This relationship is stronger for positive IOD events than for negative. For 9 of 10 events when the SON mean DMI was greater than $+0.4$, the onset was delayed. Only 1997 showed a positive IOD event with an early onset, and this onset date came only 4 d before the long-term average. Of the eight negative IOD events, six showed an early onset. This pattern breaks down when the trend is retained, for which the probability of a delayed onset for neutral, negative, and positive events are 49 %, 58 %, and 75 %, respectively. Thus, we conclude that when using Murakami and Sumi (1982) onset criteria, a positive IOD is likely to delay the monsoon onset, while neutral and negative IODs have little to no impact on onset timing.

Table 4. Correlation coefficients of seasonal climate indices with Kajikawa et al. (2010) monsoon onset dates. Only $|\rho|>0.3$ and $p<0.05$ are shown.

Correlations (ρ) with Kajikawa et al. (2010)					
	Index				
Season	NINO3.4 (detrended)	NINO4 (detrended)	SOI	II SST	Detrended IOD
JJA	0.36 (0.41)	0.34 (0.47)	−0.37	−0.35	
JAS	0.34 (0.39)	0.33	−0.41	−0.38	0.30
ASO	0.34 (0.38)	0.34	−0.42	−0.43	0.37
SON	0.36 (0.40)	0.36	-0.48	-0.43	

Holland (1986) reported “no significant correlation” between SOI values prior to onset and monsoon onset timing. The extended dataset also shows a lack of significant correlation with the SOI, any other ENSO index, the IOD, or any index used in this study. Due to the lack of statistical significance and the low correlation coefficients, we conclude that the Holland (1986) method of monitoring the onset of the Australian monsoon has low predictability on a seasonal timescale.

The recreated Hung and Yanai (2004) extended dataset showed a statically significant correlation with the ENSO Modoki indices, the WNPMI, and the seasonal IOD indices, but all the correlations were small, i.e. within ±30 %. The Hung and Yanai (2004) monsoon onset dates showed the highest correlation with the detrended monthly September IOD index with $\rho = 0.30$ ($p<0.05$)

The extended Davidson et al. (2007) onset dates show only a very weak correlation with ENSO indices. Of all the correlations with $p<0.05$, only three showed any correlation $> \pm 30$ %, and they are the detrended seasonal JAS NINO4 ($\rho = 0.34$), detrended seasonal June–August (JJA) NINO3.4 ($\rho = 0.31$), and the JAS seasonal average Amundsen Sea Low relative central pressure index, showing a correlation of $\rho = 0.35$.

The extended Kajikawa et al. (2010) monsoon onset dataset showed the strongest link with seasonal-scale climate indices of all the monsoon onset datasets examined here. These correlations are listed in Table 4 – correlation coefficients of seasonal climate indices with Kajikawa et al. (2010) monsoon onset dates. Only $|\rho|>0.3$ and $p<0.05$

Table 5. Correlation coefficients of September–October–November ENSO indices with monsoon onset dates from each onset dataset. Bolded values indicate statistically significant correlations ($p<0.05$).

	NINO1.2	NINO3	NINO3.4	NINO4	ENSO Modoki	SOI	IOD
Troup (1961) RAIN	$\tau = 0.05$	$\tau = 0.09$	$\rho = 0.14$	$\rho = 0.12$	$\tau = 0.13$	$\rho = -0.21$	$\rho = 0.15$
Troup (1961) WIND	$\tau = 0.12$	$\tau = 0.13$	$\rho = 0.16$	$\rho = 0.09$	$\tau = -0.06$	$\rho = -0.19$	$\rho = 0.16$
Troup (1961)	$\tau = 0.04$	$\tau = 0.03$	$\rho = 0.07$	$\rho = 0.03$	$\tau = 0.00$	$\rho = -0.08$	$\rho = 0.09$
Nichols (1984)	$\tau = \mathbf{0.35}$	$\tau = \mathbf{0.39}$	$\rho = \mathbf{0.58}$	$\rho = \mathbf{0.63}$	$\tau = \mathbf{0.45}$	$\rho = \mathbf{-0.61}$	$\rho = \mathbf{0.33}$
Smith et al. (2008)	$\tau = \mathbf{0.17}$	$\tau = \mathbf{0.22}$	$\rho = \mathbf{0.27}$	$\rho = \mathbf{0.25}$	$\tau = 0.16$	$\rho = -0.21$	$\rho = \mathbf{0.25}$
Holland (1986)	$\tau = 0.06$	$\tau = 0.07$	$\rho = 0.16$	$\rho = \mathbf{0.20}$	$\tau = 0.14$	$\rho = -0.20$	$\rho = 0.20$
Murakami and Sumi (1982)	$\tau = 0.13$	$\tau = \mathbf{0.18}$	$\rho = \mathbf{0.27}$	$\rho = \mathbf{0.33}$	$\tau = \mathbf{0.23}$	$\rho = \mathbf{-0.30}$	$\rho = \mathbf{0.26}$
Drosdowsky (1996)	$\tau = 0.12$	$\tau = \mathbf{0.17}$	$\rho = \mathbf{0.31}$	$\rho = \mathbf{0.37}$	$\tau = \mathbf{0.31}$	$\rho = \mathbf{-0.40}$	$\rho = \mathbf{0.32}$
Hung and Yanai (2004)	$\tau = 0.06$	$\tau = 0.11$	$\rho = 0.14$	$\rho = \mathbf{0.17}$	$\tau = \mathbf{0.26}$	$\rho = -0.22$	$\rho = 0.21$
Davidson et al. (2007)	$\tau = \mathbf{0.17}$	$\tau = \mathbf{0.18}$	$\rho = 0.23$	$\rho = \mathbf{0.29}$	$\tau = \mathbf{0.26}$	$\rho = \mathbf{-0.34}$	$\rho = 0.14$
Kajikawa et al. 2010	$\tau = 0.16$	$\tau = \mathbf{0.21}$	$\rho = \mathbf{0.36}$	$\rho = \mathbf{0.36}$	$\tau = \mathbf{0.26}$	$\rho = \mathbf{-0.48}$	$\rho = \mathbf{0.27}$

are shown. Kajikawa et al. (2010) reported correlation coefficients of −0.48 for onset dates and the SOI during November and December. Our recreated onset dates correlate with the SOI for November with $\rho = -0.50$ and for December with $\rho = -0.48$. When the datasets are extended to the 2020 season, the correlation coefficients become $\rho = -0.49$ and $\rho = -0.44$ for November and December, respectively, and $\rho = -0.48$ for the seasonal SON mean SOI.

5 Discussion and conclusions

Drosdowsky (1996) calculated a correlation of $\rho = -0.56$ with September–November (SON) mean SOI. We found the same correlation when considering the same time period (1957–1992), but the correlation lowered to $\rho = -0.40$ when the dataset is extended from 1950 to 2021. We suppose two possible explanations for this change: (1) the initial sample size was too small to correctly capture the full range of climate variability (and may still be) and/or (2) background trends in climate patterns are changing the link between the onset and the SOI in the months before the onset.

To roughly test these explanations, we split the data into two periods of 36 years each. A bootstrapping technique was applied to both periods, and changes in the data between the two periods were analysed. The mean onset date and SD changed by less than a day between each period. The SOI differs by only 0.4 between the two periods, and it is concluded that these changes are small compared to the changes seen in the correlation between the two datasets.

We then tested the correlation with the extended Drosdowsky (1996) onset dates and other ENSO indices. Correlation coefficients with NINO3, NINO4, NINO3.4, and ENSO Modoki indices all showed statistical significance, but the correlation values were all low with the highest correlation being the SON NINO4 index with $\rho = 0.37$. When using the statistical correlation as an indicator of possible predictability (i.e. >60 % correlation), we found that none of the ENSO indices showed a strong link with Australian monsoon onset timing at Darwin using the Drosdowsky (1996) onset method. When not considering the statistical correlation but simply analysing onset dates by ENSO state, we found that only a strong La Niña had a meaningful impact on monsoon onset timing (Fig. 2), suggesting a non-linearity in the relationship between ENSO and monsoon onset (see Sect. 4.2 for details).

We also considered the correlations with non-ENSO climate indices in seasons before the monsoon onset. Climate influences from the previous season that do not correlate well with the timing of the Drosdowsky (1996) onset dates include the stratospheric QBO, polar annular modes, the Indian monsoon in the previous season, the Amundsen Sea low, and Indian Ocean SST. The monthly September and October IOD, and the seasonal average ASO and SON IOD, measured by the Dipole Mode Index (DMI), showed a weak (30 %–40 %) correlation. The IOD pattern usually dissipates before the monsoon onset in late December or early January (Saji et al., 1999), as does the correlation with the DMI and onset dates in the OND season and the individual months, November and December. When isolating IOD states and then comparing with onset dates, it appears that a positive IOD tends to delay onsets more than negative IOD expedites onset, suggesting a non-linear relationship.

When considering other onset definitions of the dynamical monsoon onset, neither the Troup (1961) combined wind and rain index, Holland (1986), nor Hung and Yanai (2004) extended onset dates showed a statistically significant correlation larger than ±30 % with ENSO variability, Indian Ocean SST or any other climate indices considered in this study. Overall, these monsoon onset methods lacked a relationship with large-scale climate patterns. The Holland (1986) Australian monsoon onset definition was especially problematic when also considering the difficulty in recreating the methodology. The correlation coefficients for each monsoon onset definition and September–November ENSO and IOD indices are shown in Table 5.

The extended Kajikawa et al. (2010) dataset showed correlations with ENSO indices that were similar to the extended Drosdowsky (1996) dataset when all the data were considered, but when considering only strong ENSO events, the Drosdowsky (1996) data showed a stronger relationship with the seasonal NINO3.4 indices, while the Kajikawa et al. (2010) correlations showed little change. Overall, both the Drosdowsky (1996) and Kajikawa et al. (2010) methods provided insight into the monsoon dynamics and some level of predictability with seasonal-scale climate patterns.

The extended Murakami and Sumi (1982) onset dataset showed statistically significant but low (<30 %) correlations with the IOD and ENSO indices. These correlations changed when removing neutral ENSO and IOD events from the analysis; specifically, a positive SON mean DMI is often associated with a delayed monsoon onset, while neutral and negative SON mean DMIs have no relationship with onset timing. This onset criterion was relatively easy to calculate and use and could be included with the Drosdowsky (1996) and Kajikawa et al. (2010) methodologies as one that provides some prognostic capabilities.

The relationships between the SOI and monsoon onset dates that were reported in Drosdowsky (1996) weaken when the dataset is extended to include the monsoon seasons from 1950/1951 through 2020/2021. When considering other ENSO indices, only a strong La Niña (e.g. SON NINO3.4 index > 0.98 °C) has an impact on monsoon onset timing, in which 8 of 10 strong La Niña events were associated with an expedited monsoon onset. The extended Murakami and Sumi (1982) onset dataset and the extended Kajikawa et al. (2010) dataset showed similar relationships, although the correlations with Murakami and Sumi (1982) showed smaller correlations, and the Kajikawa et al. (2010) dataset did not show differences between strong and neutral ENSO events.

When considering the influence of other climate patterns on the monsoon onset dates, the seasonal and monthly detrended DMI showed similar correlations as the ENSO indices with the Drosdowsky (1996), Murakami and Sumi (1982), and Kajikawa et al. (2010) onset methodologies. However, these were small to moderate correlations ($< \pm$ 40 %) which diminish as the IOD pattern breaks down (usually in December). Also, when the trend in the IOD data is retained, the relationship with onset dates diminishes in most (but not all) cases.

To conclude, the relationship between ENSO and Australian monsoonal variability has been heavily studied, with most studies pointing to a positive correlation. However, we have shown that the timing of the dynamical monsoon onset is one aspect of variability that does not show a strong link with ENSO or other seasonal-scale indices. We have also shown that the relationship with some of these indices is non-linear, with a strong La Niña showing a stronger influence than a strong El Niño, and a strong positive IOD in the season leading up to onset tends to have a stronger influence than a negative onset. We have also shown that the already weak relationships between onset timing and the IOD and ENSO are weakening over time, but we have not assessed if this weakening is due to simply more data capturing a larger breadth of the climate variability or if the background warming trend in sea surface temperatures is changing the physical relationship between the climate pattern and the monsoon. Other global monsoon patterns, such as the Indian and the Southeast Asian monsoons, show a similar link with ENSO; could similar analysis of onset timing further our understanding of these monsoon patterns? Future research should look at the linkages to other monsoon patterns and the teleconnections and other physical relationships linking these climate drivers with onset dates. Another question for future research is, while statistical relationships are weak, could dynamical models predict the onset of the monsoon on seasonal timescales?

Data availability. All data analysed in this research are available via the URLs provided in Tables 1 and 2.

Author contributions. JL designed the study, carried out the analysis underpinning the paper, and wrote the draft manuscript. JR advised JL throughout this work and contributed to the interpretation of the results and to the writing of the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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CHAPTER 4: MAKING A CONNECTION BETWEEN ONSET TIMING AND DROUGHT

Research paper 3: Wet Season Rainfall Onset and Flash Drought: The Case of the Northern Australian Wet Season

Lisonbee et al. (2020), included as Chapter 2, demonstrated that different onset definitions pin the onset to different events in the wet season. There are clear and measurable differences between the wet season rainfall onset, or the first rainfall of the season, and the onset of the dynamical monsoon, or the global-scale weather pattern marked by a reversal of the winds and an increase in precipitation. While Lisonbee et al. (2020) showed that the wet season rainfall onset (definitions based on precipitation only) correlate well with ENSO, Lisonbee and Ribbe (2021), included as Chapter 3, demonstrated that the dynamical onset can experience high variability that is not strongly tied to seasonal climate indices.

In this chapter, Lisonbee et al. (**In Review**) investigates more about the temporal variability of the wet season and monsoon onset. Are there seasons when the wet season onset occurs early but the monsoon onset occurs late? If so, how often does the north Australian climate system experience a “false onset”, when an onset criterion is met, but follow-up rainfall is not received, and how often do false onsets create a “flash drought” condition?

Lisonbee et al. (**In Review**) establish the concept of a “false onset”, which occurs when a wet season rainfall onset criterion, such as an accumulated rainfall threshold or a vegetative “green date”, is met but follow-up rainfall is not received before the monsoon arrives much later. Lisonbee et al. (**In Review**) calculate the frequency of occurrence of these false onsets for all years, positive and negative

ENSO years and positive and negative IOD years.

To make a connection between seasonal rainfall timing variability and potential impacts to agriculture, and other practices in northern Australia, Lisonbee et al. (**In Review**) also shows that periods of false onsets can sometimes, but not always, have characteristics similar to a flash drought (Lisonbee et al. 2021; Appendix A), when the soil moisture is rapidly depleted. Lisonbee et al. (**In Review**) show that flash drought, defined as rapid drops in soil moisture percentile, is a relatively common occurrence and only occasionally corresponds to false onset. In fact, Lisonbee et al. (**In Review**) find that rapid drops in soil moisture occur so frequently during the northern Australian wet season that they probably should not be considered a drought, but should be acknowledged as a regular feature of this climate. The frequency of occurrence of these rapid drops in soil moisture leading to a flash drought across northern Australia averages to 25% of wet seasons, or about one every four years. In a few locations these flash droughts can occur as frequently as 60% of the seasons, or more than every other year.

The primary conclusion from Lisonbee et al. (**In Review**) is that the space between the wet season onset as defined by Lo et al. (2007; see Chapter 2) and the monsoon onset [based on Drosdowsky (1996) for Darwin and the average onset date for the rest of the region (see Chapter 2)] can be highly prone to false wet season rainfall onsets. False wet season onsets occur about once every two to three years across northern Australia. Lisonbee et al. (**In Review**) further conclude that La Niña and negative IOD—climate patterns that are usually associated with the non-monsoonal, early wet season rainfall onset and above average early wet season rainfall—are also associated with seasons with a false onset. This proves that, for wet season rainfall, earlier is not always better when there are long breaks between rainfall events. Lisonbee et al. (**In Review**) also found that wet seasons that experience a false rainfall onset only occasionally coincide with a rapid depletion of soil moisture and may not always have negative impacts on agriculture.

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Wet Season Rainfall Onset and Flash Drought: The Case of the Northern Australian Wet Season

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Key words: Monsoon onset, rainfall, El Niño-Southern Oscillation, Madden-Julian Oscillation, Indian Ocean Dipole

Abstract

In this paper, we report on the frequency of false onsets of wet season rainfall in the case of the Northern Australian wet season and investigate the role of large-scale tropical climate processes such as the El Nino-Southern Oscillation, Indian Ocean Dipole and Madden-Julian Oscillation. A false onset occurs when a wet season rainfall onset criterion is met, but follow-up rainfall is not received for weeks or months later. Our analysis of wet season rainfall data from 1950 through 2020 shows a false onset occurs, on average, between 20–30% of wet seasons across all of northern Australia. This increases at a regional and local level such as at Darwin, the Northern Territory, and parts of Queensland's north coast to over 50%. Seasonal climate influences, such as a La Niña pattern and a negative Indian Ocean Dipole that typically expedite the wet season rainfall onset, also increase the likelihood of a false onset over northern Australia. Our analysis also finds that periods of false onsets can sometimes, but not always, coincide with periods of rapid soil moisture depletion. The false rainfall onsets that develop into flash drought can be potentially disruptive and costly and are of potential significance for agriculture and fire management in Northern Australia, and in other monsoonal climates that also typically experience a slow build-up to the seasonal monsoon. In conclusion, effective rainfall indicates that many seasons experience "false onsets" with dry conditions after early rainfall. We propose that false onsets are a physical characteristic of the climate of northern Australia which occurs with relatively high frequency. In addition, these false onsets may sometimes co-occur with a flash drought.

1. Introduction

An estimated 50% to 60% of the world's population is impacted by the global monsoon system (Rajan et al. 2005; Yancheva et al. 2007; Wang and Ding 2008; Qiao et al. 2012). Variability in timing of the monsoonal rains has a significant impact on agriculture and economies across monsoonal climates (Fitzpatrick et al. 2015; Pradhan et al. 2017; MacLeod 2018; Parija 2018; Bliefernicht et al. 2019; Ali et al. 2020; Lisonbee et al. 2020; Pirret et al. 2020). In many respects, delayed onsets, low seasonal precipitation totals, or prolonged breaks in monsoon precipitation can be considered a drought. Drought in tropical climates have similar impacts on agriculture and water availability as traditional droughts at higher latitudes (Duncan et al. 2013; Zhang et al. 2020). Monsoonal climates experience high temperatures, direct solar radiation, periods of high evaporation rates along with high rainfall variability, thus drought characteristics in tropical climates may include a rapid onset and/or a short duration (Zhang et al. 2019b; Yang et al. 2020). Short-duration tropical droughts may be similar to the *"verânicos"* of Brazil (Borges et al. 2018). The rapid onset of droughts in the tropics may also be similar to a "flash drought" (Otkin et al. 2018b).

The aim of this study is to better understand some of the nuances of the northern Australian climate especially in regard to the wet season rainfall and monsoon onset. Northern Australia experiences a monsoonal climate (Zhang 2010) with variability in the timing of the dry-to-wet season transition, and high variability in the timing of the monsoon onset (Lisonbee et al. 2020) and bursts and breaks in precipitation throughout the monsoon season (Drosdowsky 1996). Lo et al. (2007) showed that the timing of the Australian wet season rainfall onset has high variability with a standard deviation that ranges from 10 days at the shortest over Australia's Top End Region (the region of the Northern Territory north of about 15° S) to over 30 days near the Tropic of Capricorn. Lisonbee et al. (2020) showed that, by several definitions, in Australia the onset of the dynamical monsoon (e.g. the global-scale weather pattern, as opposed to the seasonal increase in precipitation) has a standard deviation of about two weeks and a range of almost two months from the earliest to the latest onset dates. This means that there could be times when the wet season rainfall begins early but the monsoon may be delayed (Lisonbee et al. 2020). Hence, we propose the following research questions: Are there times when the northern Australian wet season rainfall experiences a "false onset", i.e. the wet season begins but low rainfall or high evaporative demand dries the soils and creates a type of drought condition before the monsoon begins? Or, are there times when prolonged breaks in the monsoon create flash drought conditions? The focus of this research is to investigate periods of false onset in the Australian wet season, the frequency at which they occur, if their occurrence coincides with a flash drought, and if the frequency of occurrence is impacted by large-scale climate influences such as the El Niño–Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD; Saji et al. 1999) and the Madden-Julian Oscillation (MJO; Madden and Julian 1971, 1972). To do so, we use precipitation and evaporation data at 6 locations across northern Australia and gridded rainfall and evaporation datasets to calculate how often a false onset to wet season rainfall occurs across northern Australia. We also use a gridded root-zone soil moisture dataset to investigate when these false onsets also coincide with a flash drought, as defined by a rapid reduction in soil moisture.

In the following, we review the key literature that characterises northern Australia's wet season in Section 2.1 and flash droughts in Section 2.2. In Section 3, we describe the data and methodology used in our study, and Section 4 presents our results. Findings and implications for managing agriculture and other activities are discussed in Section 5 concluding with some key recommendations.

2. Background

2.1. Wet Season Rainfall Onset

In this paper, we draw a clear distinction between the Australian monsoon, the Australian wet season and the wet season rainfall onset. The monsoon is the global-scale weather pattern marked by a seasonal reversal of trade winds and an increase in precipitation (Ramage 1971; Webster 1981). The northern Australian wet season is defined as the months of October to April , and receives over 90% of the annual rainfall across tropical northern Australia (See Figure 1; Nicholls et al. 1982; Pope et al. 2009). Within the wet season, the seasonal rainfall usually begins slowly as isolated mesoscale thunderstorms. These increase in frequency and coverage as the season progresses until the onset of Australian monsoon, characterised by widespread and heavy rainfall. The monsoon usually begins in late December or early January (Keenan and Carbone 1992; Drosdowsky 1996; Pope et al. 2009; Lisonbee et al. 2020) with a mean onset date in the last week of December (Lisonbee et al. 2020). Although a large percentage (about 70%) of wet season rainfall comes from the monsoon (Nicholls et al. 1982) many potential users of long-range weather forecasts and historical weather information are primarily interested in the timing of the first rainfall of the season rather than the large-scale rearrangement of the troposphere. Thus, the research community has also defined a wet season rainfall onset (Nicholls et al. 1982; Nicholls 1984; Cook and Heerdegen 2001; Kullgren and Kim 2006; Robertson et al. 2006; Lo et al. 2007; Balston and English 2009; Drosdowsky and Wheeler 2014; Berry and Reeder 2016). After enduring four to six months with no rainfall, the first wet season rainfall is critical to replenish water supplies, reduce the fire risk and instigate grass growth in pasture (McCown 1981; McKeon et al. 1990; Cook and Heerdegen 2001; Lo et al. 2007).

The northern Australian wet season rainfall onset has been defined in several ways (Lisonbee et al. 2020). McCown (1981) used rainfall and a water balance model to define the commencement of a “green season”. Nicholls et al. (1982) defined the wet season onset using varying accumulated rainfall thresholds. Nicholls (1984) defined wet season onset at a station in northern Australia when 15% of the mean annual rainfall was accumulated after 1 September, the onset dates at 10 locations were then averaged to derive a northern Australia wet season onset. Cook and Heerdegen (2001) defined the “rainy season” as the period when the probability of 10-day dry spells was less than 50%. Kim et al. (2006) calculated the seasonal (December-March) precipitation mean in mm/day; when the pentad rainfall anomaly first became positive relative to the seasonal mean at that location then the onset has occurred. Lo et al. (2007) defined a wet season onset as the date after 1 September when seasonal accumulated rainfall total exceeds 50 mm. Considering rainfall between 1 September to 30 April, Smith et al. (2008) define the onset of a "rainy season" as the date 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. Balston and English (2009) use 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, for Ravenswood, Queensland (Qld), and surrounding rainfall stations; they defined the green date as 57mm over 21 days after 1 October. Berry and Reeder (2016) define the wet season rainfall onset 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 (they call this a "monsoon burst"). Berry and Reeder (2016) also made mention of “false onsets” when the early season rainfall pattern is “short-lived”.

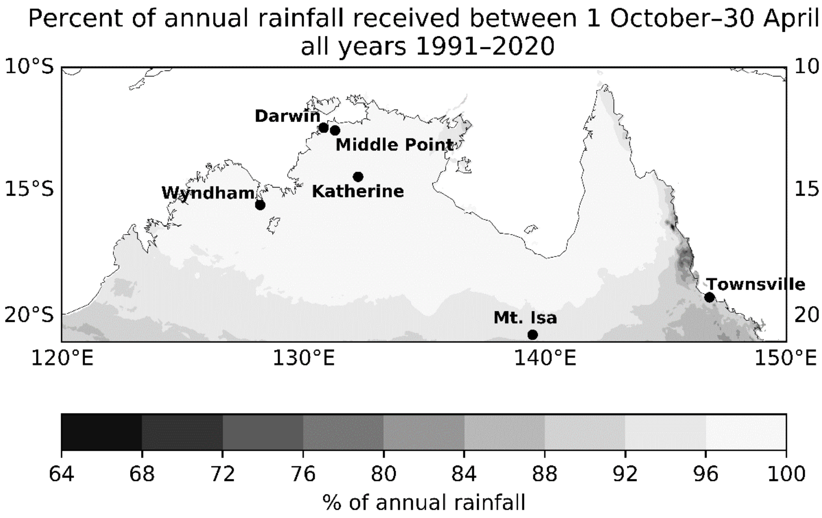


Figure 1 Locations used in this study and percentage of annual precipitation that falls within the wet season (October–April).

The start of the wet season rainfall correlates well with ENSO indices (Troup 1965; McBride and Nicholls 1983; Lo et al. 2007; Drosdowsky and Wheeler 2014), but the onset of the dynamical monsoon does not correlate as well with ENSO with only a strong La Niña pattern correlating with an early onset (Lisonbee and Ribbe 2021). The IOD has been shown to have a meaningful influence on rainfall totals in the early wet season (Risbey et al. 2009; Taschetto et al. 2011). A search of the literature for the influence of the IOD on the timing of the wet season rainfall onset did not yield any results, but the IOD has been shown to have only a small impact on the onset of the dynamical monsoon where a positive IOD correlates with a delayed monsoon onset at Darwin while a negative IOD did not show a statistically significant correlation (Lisonbee and Ribbe 2021).

The MJO influences both rainfall rates and totals and the monsoon onset over northern Australia. Earlier research focused on the dynamical monsoon and a link was found between the active phases of the MJO over Australia and monsoon onset (Mcbride 1983; Holland 1986; Hendon and Liebmann 1990; Drosdowsky 1996; Hung and Yanai 2004; Wheeler and Hendon 2004; Pope et al. 2009; Jackson et al. 2018).

The present work, however, is focused on the wet season onset. Wheeler et al. (2009) and Risbey et al. (2009) focused on the impact of the MJO on rainfall rates across northern Australia and in various seasons. Wheeler et al. (2009) showed that September–November precipitation is slightly enhanced when the Realtime Multivariate MJO index (RMM; Wheeler and Hendon 2004) is in phase 6-7 (or over Australian longitudes) but suppressed in phases 1-2, which may have implications on false onsets to the Australian wet season. When considering the wet season as a whole, Giangrande et al. (2014) showed that precipitation at Darwin during active MJO phases is twice that during suppressed phases. Berry and Reeder (2016) showed that, when averaged over northern Australia, sharp increases in rainfall rates are weakly modulated by the MJO where these rainfall bursts are more likely, but not exclusive to, when the MJO is active and in the vicinity of the Australian continent, consistent with previous studies. Ghelani et al. (2017) showed that the MJO increased rainfall in RMM phases 5 and 6 and decreased it in phases 2 and 3 and that this signal is enhanced during El Niño as compared to La Niña. Moron et al. (2019) found that early wet season weather patterns are not influenced by the MJO, but early bursts of the monsoon (occasionally in November and December) can be enhanced when the MJO is in RMM phases 6-8. Murphy et al. (2016) showed regional variations in the effect of the MJO across northern Australia and also showed that November rainfall is the most variable of any month and that the MJO has a nominal impact on rainfall in November, a stronger impact in December and a strong impact on Monsoonal precipitation in January and February. Narsey et al. (2017) showed that the influence of the MJO on early wet season moisture bursts is secondary to the influence of a southerly moisture flux that is associated with higher latitude synoptic patterns.

2.2. Flash Drought

A "flash drought" is usually considered to be "an unusually rapid onset drought event characterized by a multiweek period of accelerated intensification that culminates in impacts to one or more sectors (agricultural, hydrological, etc.)" (American Meteorological Society 2019; Otkin et al. 2018b). The application of the term *flash drought* has usually been applied to higher-latitude drought events (Lisonbee et al. 2021 and references therein), such as the major drought in the central United States in 2012 (Otkin et al. 2016), the Murray Darling Basin, Australia, in 2017/2018 (Nguyen et al. 2019), southern Africa in 2015/2016 (Yuan et al. 2018), the Yellow River Basin, China, in 1991 (Liu et al. 2020), Jiangxi Province, China, in 2003 (Zhang et al. 2017) to name just a few. While at least one study examining flash drought intentionally defined the phenomena in a way that did not apply the term to monsoon onset (Mo and Lettenmaier 2016), more recent research has investigated the frequency of flash droughts during the wet seasons of tropical locations around the world:

- Mahto and Mishra (2020) analysed the occurrence of flash drought during the Indian monsoon season;
- Zhang et al. (2020) examined the link between drought and monsoon variability over southern China;
- Stojanovic et al. (2020) examined flash droughts in Vietnam;
- Christian et al. (2019), while not the focus of their paper, suggest that a delayed monsoon onset may contribute to the development of flash drought in the southwest United States.

Only three previous studies have investigated flash droughts in Australia. Nguyen et al. (2019) used a standardised evaporative stress index (ESI) that depicts anomalies in the ratio of the actual to potential evapotranspiration (ET) to identify flash drought in Australia's northern Murray Darling Basin in 2017/2018. Nguyen et al. (2021) used the ESI to examine large-scale climate drivers' influence on rapid intensification of drought conditions over eastern Australia in 2019. Finally, Parker et al. (2021) tested several methods to identify flash drought in Australia and compared these to a standardised soil moisture index (Ford and Labosier 2017) to show that flash drought occurs relatively frequently in Australia and that northern Australia is among the more flash drought prone regions of the continent.

3. Data and Method

False onsets to the wet season rainfall were identified using a combination of rainfall and evaporation data and periods of flash drought were identified using root-zone (0-1 m) soil moisture data. These data were used to calculate the frequency of occurrence of false onsets and flash drought at a subset of locations across northern Australia using gridded precipitation, evaporation and soil moisture data. The frequency of occurrence was calculated for all wet seasons and for seasons when ENSO and IOD patterns were non-neutral. We also examined the phase of the MJO for seasons that experienced a flash drought.

3.1. Data

Rainfall and evaporation data, both gridded and at point locations, were obtained from the Scientific Information for Land Owners (SILO) database of Australian climate data. SILO data products provide Australia-wide coverage with interpolated infills for missing data from 1889 to the present (Jeffrey et al. 2001; State of Queensland Government 2021). SILO is hosted by the Science and Technology Division of the Queensland Government's Department of Environment and Science. The rainfall and pan evaporation point data available from SILO originated from the Australian Bureau of Meteorology but with missing rainfall data infilled using a spatial interpolation method and evaporation data is derived where observations are not available (Jeffrey *et al.*, 2001; Beesley, Frost and Zajaczkowski, 2009 see also SILO documentation at https://longpaddock.qld.gov.au/silo/, last accessed 30 June 2021).

In this analysis, a La Niña event is defined as any year when the December to February mean NINO3.4 sea surface temperature anomaly is less than or equal to -0.8 °C, and El Niño is when the same index is greater than or equal to +0.8 °C. NINO3.4 values are from the Bureau of Meteorology (www.bom.gov.au/climate/enso, last accessed 18 June 2021). Based on these criteria, 14 El Niño events and 17 La Niña events occurred between 1950 and 2021. The seasons used in this study are listed in Table 1.

IOD data using the Dipole Mode Index (Saji et al. 1999; Verdon and Franks 2005; Taschetto et al. 2011) is from the National Oceanic and Atmospheric Administration's Physical Science Laboratory (https://psl.noaa.gov/gcos_wgsp/Timeseries/DMI/ last accessed 18 June 2021; Saji and Yamagata 2003). Dipole Mode Index thresholds used herein are ±0.4 °C based on the September–November mean. From 1950 to 2021 there were 11 positive IOD events and 16 negative IOD events based on this criterion. The seasons used in this study are listed in Table 1.

MJO analysis was done using RMM phase and amplitude data from the Australian Bureau of Meteorology (http://www.bom.gov.au/climate/mjo/ accessed 17 January 2022). RMM data is available from June 1974.

Table 1 Years when the ENSO and IOD criteria were met. Where ENSO data are a three-month average of December through February of the next year, e.g. 1957 is the average NINO3.4 index for December 1957 through February 1958.

El Niño years	1957, 1963, 1965, 1968, 1972, 1982, 1986, 1987, 1991, 1994, 1997, 2002, 2009, 2015
La Niña years	1950, 1955, 1970, 1973, 1975, 1984, 1988, 1995, 1998, 1999, 2005, 2007, 2008, 2010, 2011, 2017, 2020
Positive IOD years	1961, 1963, 1972, 1982, 1994, 1997, 2006, 2011, 2015, 2018, 2019
Negative IOD years	1954, 1955, 1956, 1958, 1959, 1960, 1964, 1968, 1974, 1975, 1980, 1981, 1984, 1992, 1996, 1998

3.1.1. Station Data

The locations for station data are shown in Figure 1, which also shows the percentage of annual precipitation that falls within the wet season (October–April). While data is available from 1889, the current analysis uses data beginning from the first year of record at each location, primarily due to concerns with data sparsity across northern Australia in the early part of the record. Darwin, Northern Territory (NT), rainfall and evaporation data uses station number 14015, which has a consistent record beginning in 1941. Rainfall for the Katherine, NT, region came from Katherine Council station, station number 14902. The first full year of rainfall measurements in Katherine were taken in 1885. There are some gaps in the Katherine rainfall record in the decades of the 1980’s, 1990’s and 2000’s, but the interpolated dataset fills in the gaps with nearby stations. Middle Point, NT, data is from Middle Point Rangers Station number 014090. Data at Middle Point Rangers Station began in 1959, with some gaps in the latter part of the record and modelled evaporation data. Mt. Isa, Queensland (Qld), rainfall and evaporation data is from station number 029127, the records are from 1966 to present. Data for northern Western Australia (WA) came from the town of Wyndham, WA, with station number 01013 where rainfall records began in 1968. Townsville, Qld, data came from Townsville Aero, station number 032040 where records began in 1941.

3.1.2. Gridded data

The gridded precipitation and synthetic pan evaporation datasets from the 1950/1951 through 2020/2021 wet seasons were obtained through the SILO data portal. This data originated from the Australian Bureau of Meteorology’s Australian Water Availability Project (AWAP; Jones et al. 2009).

The data used in this analysis have a spatial resolution of 0.05° (or about 5km) and a daily temporal resolution. There are caveats and limitations associated with any evaporation dataset; the gridded analysis used synthetic pan evaporation to approximate evaporative demand without making assumptions about vegetation type/height and with known limitations in the instrument record (Zajaczkowski and Jeffrey 2020).

Soil moisture data is from the Australian Water Resources Assessment Landscape model (AWRA-L). AWRA-L is a daily, 0.05° grid-based, distributed water balance model (Frost et al. 2018). Daily gridded soil moisture percentile data is available from 2000-2021. In this study, root-zone soil moisture data was used, which is an integration of soil moisture from 0-1 m depth.

3.2. Method

The wet season rainfall onset date is defined as the date when 50 mm of rainfall is accumulated after 1 September as described by Lo et al. (2007) and further explored by Drosdowsky and Wheeler (2014) and Cowan et al. (2020). Lo et al. (2007) used this definition noting its simplicity and usefulness for northern Australian agriculture and showed that onset timing can be predicted using a statistical relationship with ENSO indices. Drosdowsky and Wheeler (2014) and Cowan et al. (2020) showed that there is skill in predicting this onset threshold using dynamical models at seasonal time scales. In order to capture both the accumulation and loss of water on the landscape, this study presents an adaptation of the 50 mm rainfall onset criteria by using the effective rainfall (precipitation minus evaporation) instead of the actual rainfall. A check of rainfall onset dates at Darwin Airport, for example, shows that in 20% of wet seasons the 50mm threshold is accumulated within a single day and the accumulated total rainfall and accumulated effective rainfall are the same.

To identify false onsets, the total daily pan evaporation was subtracted from the total rainfall for that day to get an effective rainfall total. The daily effective rainfall was added to the previous day's total to find the accumulated effective rainfall amount. A false onset occurs when the accumulated effective rainfall reaches 50 mm at least once after 1 September and then returns to 0 mm at least once before the end of December of the same year (the average monsoon onset date at Darwin, NT).

An example of one wet season that experienced a false onset is shown in Figure 2. This example is from Darwin Airport for the 2018-2019 wet season. The accumulated rainfall reached the 50 mm threshold on 26 October 2018 (shown by the purple line in Figure 2), the accumulated effective rainfall reached 50 mm on 15 November 2018 (shown by the blue line in Figure 2) but the accumulated effective rainfall returned to 0 mm by 5 December 2018. Thus, the 2018-2019 wet season was counted as a season with a false onset. The overall frequency of occurrence *(FOC)* of a false onset across the tropical north is calculated by:

$$FOC = \frac{n}{N} \times 100$$

n is the number of seasons where a false wet season onset occurred and *N* is the total number of seasons considered. This method was applied to six locations across northern Australia. The method was also applied to gridded precipitation and evaporation data to calculate the frequency of occurrence of false wet season rainfall onsets across northern Australia.

The frequency of occurrence was also calculated using the rainfall and evaporation grids for only the wet seasons from 1950-2021 when ENSO and the IOD were non-neutral based on the threshold definition given in Section 3.1. The influence of the MJO was analysed by looking at the progression of MJO phases for seasons that experienced a false onset.

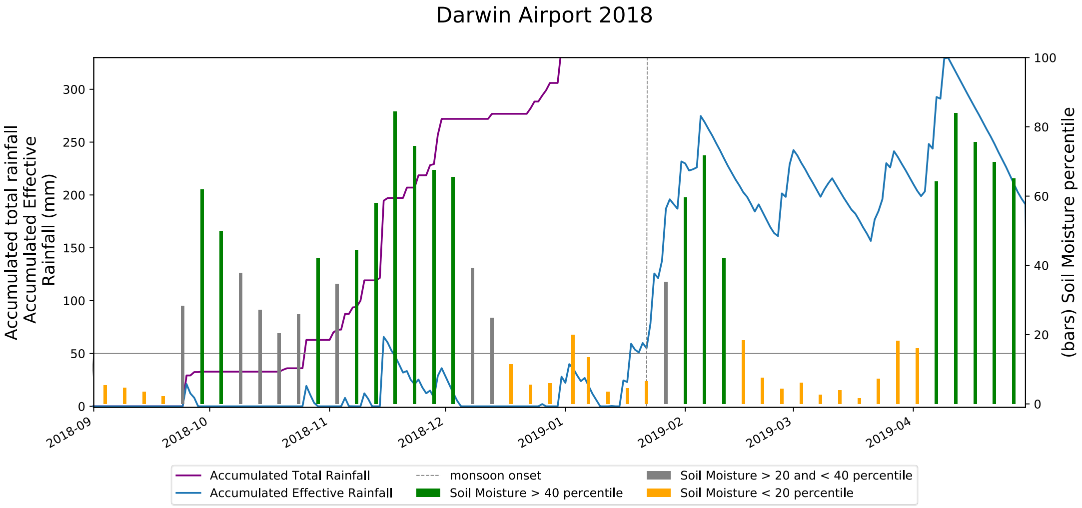


Figure 2 Accumulated effective rainfall (mm, blue), accumulated total rainfall (mm) for the same season (purple) and root-zone soil moisture (bars) at Darwin Airport for the 2018 wet season. Soil moisture bars are coloured by value with soil moisture above the 40th percentile in green and below the 20th percentile in orange. The 50 mm wet season onset threshold is marked by the horizontal grey line and the monsoon onset is marked by the vertical dotted grey line.

Flash drought was analysed following an adaptation of the methodology first introduced by Ford and Labosier (2017). The same approach has been used to investigate flash droughts in Australia (Parker et al. 2021) and India (Mahto and Mishra 2020). A soil moisture flash drought is defined as when the pentad-average root-zone (0–1 m) soil moisture percentile declines from at or above the 40th percentile to at or below the 20th percentile in four pentads (20 days) or less. Following Mahto and Mishra (2020), we further defined that a flash drought must have a minimum duration of four pentads, and we define the termination of a flash drought to occur when soil moisture rises to the 25th percentile. We did not apply a maximum duration criterion for a flash drought. Some flash droughts were short and lasted only for the four pentads needed to meet the minimum requirement for a flash drought while some droughts experienced a rapid onset near the end of the wet season and the drought continued throughout the dry season.

4. Results

4.1. Analysis at Point Locations: Darwin, Katherine, Middle Point, Wyndham, Mt. Isa and Townsville

Figure 2 shows an example of a false wet season onset and was briefly mentioned in the Methods Section (3.2) above. This example is from Darwin Airport for the 2018/2019 wet season; an especially dry season when the total monthly rainfall for December was only 67.2 mm, a quarter of the long-term monthly mean, and the January 2019 rainfall total was 362 mm, nearly 70 mm below the long-term average. The accumulated 50 mm wet season onset threshold (Lo et al., 2007; purple line in Figure 2) was met on 26 October. When considering the accumulated effective rainfall, the onset threshold was met on 15 November 2018 when Darwin Airport received 73.2 mm of rainfall (blue line in Figure 2). Even with some small rainfall totals in the following days, the accumulated effective rainfall had returned to 0 mm by 5 December. During this time the soil moisture declined from above the 60th percentile on December 1st to below the 20th percentile by December 15th and remained below the 20th percentile for 8 pentads, when the monsoon began (as defined by Drosdowsky 1996; the vertical dashed line in Figure 2) on 23 January 2019. This dry period qualified as both a false onset and a flash drought embedded within the wet season. The 2018/2019 wet season saw a second period in February and March that also met the flash drought criteria based on soil moisture percentile alone, but due to this being a very wet time of year, the soils were 58% of saturation for February and 33% of saturation for March (not shown) and may highlight a limitation to using soil moisture as the defining feature of flash drought in monsoonal locations.

Calculating the frequency of occurrence for all years from 1941 (when records began at Darwin Airport) to 2020, a false onset to the wet season occurred at Darwin Airport in 52% of wet seasons, or about once every other year. Middle Point Rangers, Katherine and Wyndham and Townsville experienced a false onset in 36%, 34%, 33% and 30% of wet seasons, respectively, or about once every third year. Mt. Isa experienced a false onset to the wet season in 21% of wet seasons, or about once every five years, on average.

4.2. Spatial analysis of wet season false onsets

To analyse the spatial distribution of the frequency of a false onset to the northern Australia wet season rainfall we analysed gridded data for every wet season from 1950 to 2020. For each wet season day, the effective rainfall was calculated at each grid point and added to the effective rainfall of the previous day. If the accumulated effective rainfall reached the 50 mm wet season onset threshold after 1 September and then reduced to at or below 0 mm before 31 December of that year then that grid point was counted as a false onset to the wet season for that year.

This analysis shows two regions in northern Australia where over 50% of the years experienced a false onset to the wet season rainfall (Figure 3). These are along the east coast of northern Qld, stretching from roughly Townsville, Qld, in the south to Cairns, Qld, in the north, and the grid cells over Darwin, Northern Territory. It's worth noting that coastal Queensland experiences a different climate from the rest of northern Australia. The Queensland coast has been described as the "wet tropics" (CSIRO and Bureau of Meteorology 2015) where the rainfall is strongly influenced by the orographic effects of moist easterlies meeting the Great Dividing Range. As such, the region does not experience a distinct dry season in the same way that the rest of northern Australia does, but can still experience long periods without meaningful rainfall, as shown in this analysis.

Darwin Airport is located near the coast and experiences local coastal effects in the seasonal rainfall patterns. While the frequency of occurrence of false onsets exceeds 50% near Darwin, the frequency drops quickly to 30-40% just inland from Darwin, including at Middle Point (~50 km from Darwin Airport) and Katherine (~280 km). For most of the western Top End region, the frequency of false onsets is 20-30%. The frequency of occurrence for all years from 1950-2020 for all of northern Australia is shown in Figure 3.

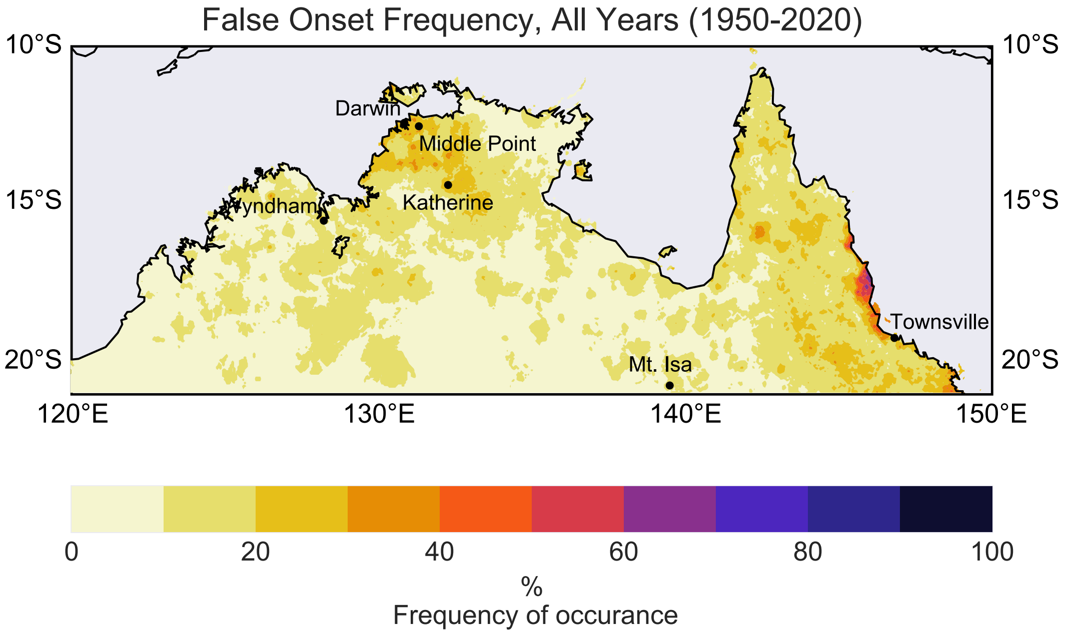


Figure 3 False onset frequency for all years from 1950 to 2020.

4.3. The influence of seasonal climate patterns

Our analysis shows that false onsets are closely tied to seasons with below average rainfall (not shown). Across Cape York, the Top End of the Northern Territory, and the northern Kimberley region of Western Australia all seasons that experienced a false onset from the years 1950–2020 occurred in a year with below average October–December total precipitation (based on the 1991–2020 average). When considering the opposite concurrence, between 5% and 35% of seasons when the October–December total rainfall was below average also experienced a false onset.

False wet season onsets are more prevalent during La Niña when compared to both El Niño (Figure 4) and all years (Figure 3) from 1950-2020. The prevalence of early wet season onsets in La Niña years and delayed onsets in El Niño years (Lo et al. 2007) may explain this pattern. Lisonbee and Ribbe 2021 showed that only strong La Niña patterns expedited the monsoon while weak La Niña, neutral and El Niño patterns did not have a statistically significant impact on the monsoon onset. The present analysis did not differentiate between weak and strong ENSO events. Therefore, one possible explanation for the increased occurrence of false onsets during La Niña events is that the time between the wet season onset and the monsoon onset in La Niña years would be longer than that of neutral or El Niño years, giving more time for a false onset to occur. A similar but opposite argument could be applied to El Niño years.

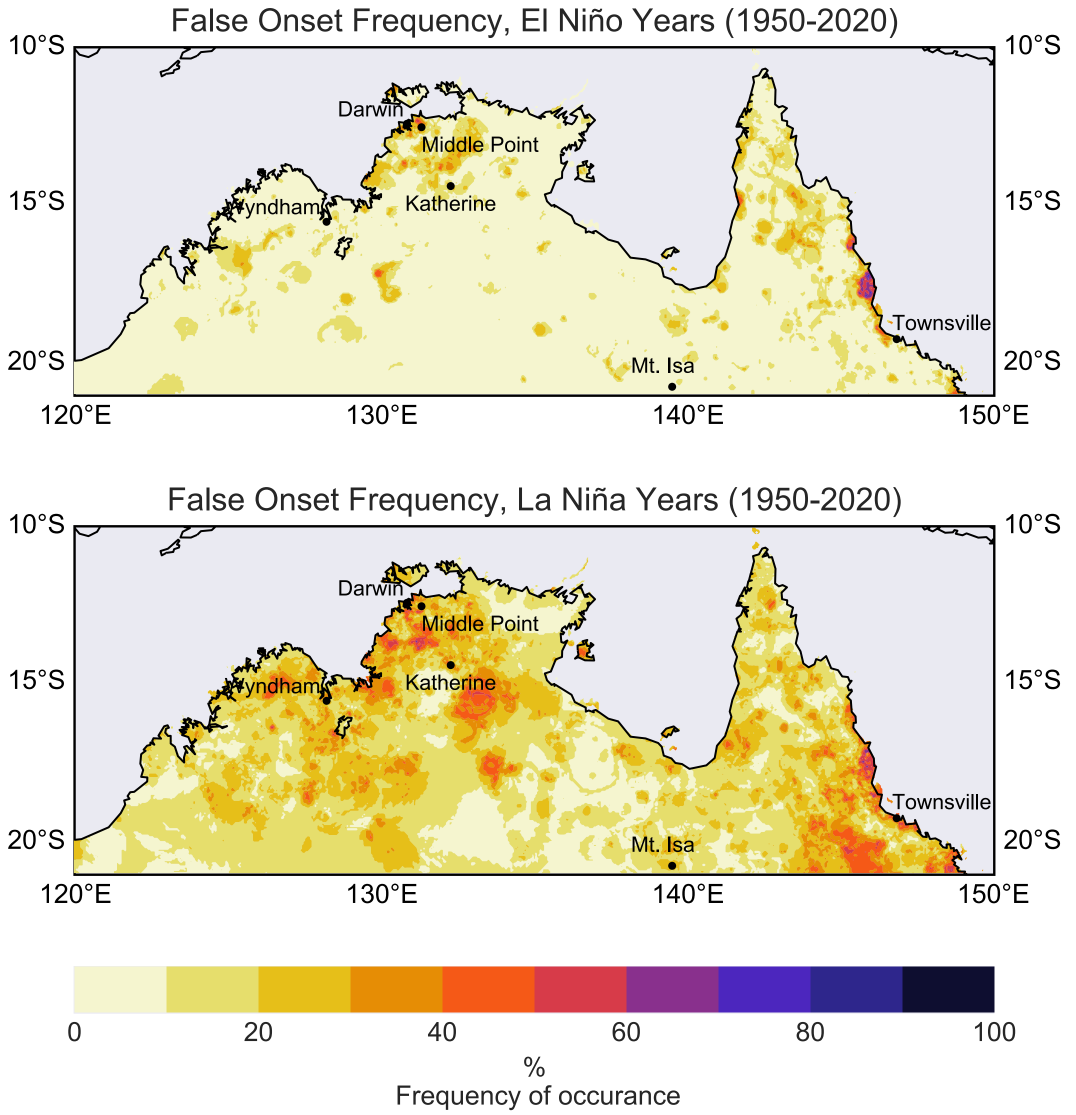


Figure 4 False onset frequency for all El Niño years (top) and all La Niña years (bottom) from 1950-2020.

Figure 5 shows the frequency of false wet season onsets during positive and negative IOD years over northern Australia. During a positive IOD event the north western Northern Territory sees an increase in frequency when compared to all years (see Figure 3) while most of the rest of northern Australia sees a decrease in the frequency of false onsets. In contrast, most of northern Australia generally sees a slight increase in the frequency during negative IOD years as compared to all years from 1950-2020.

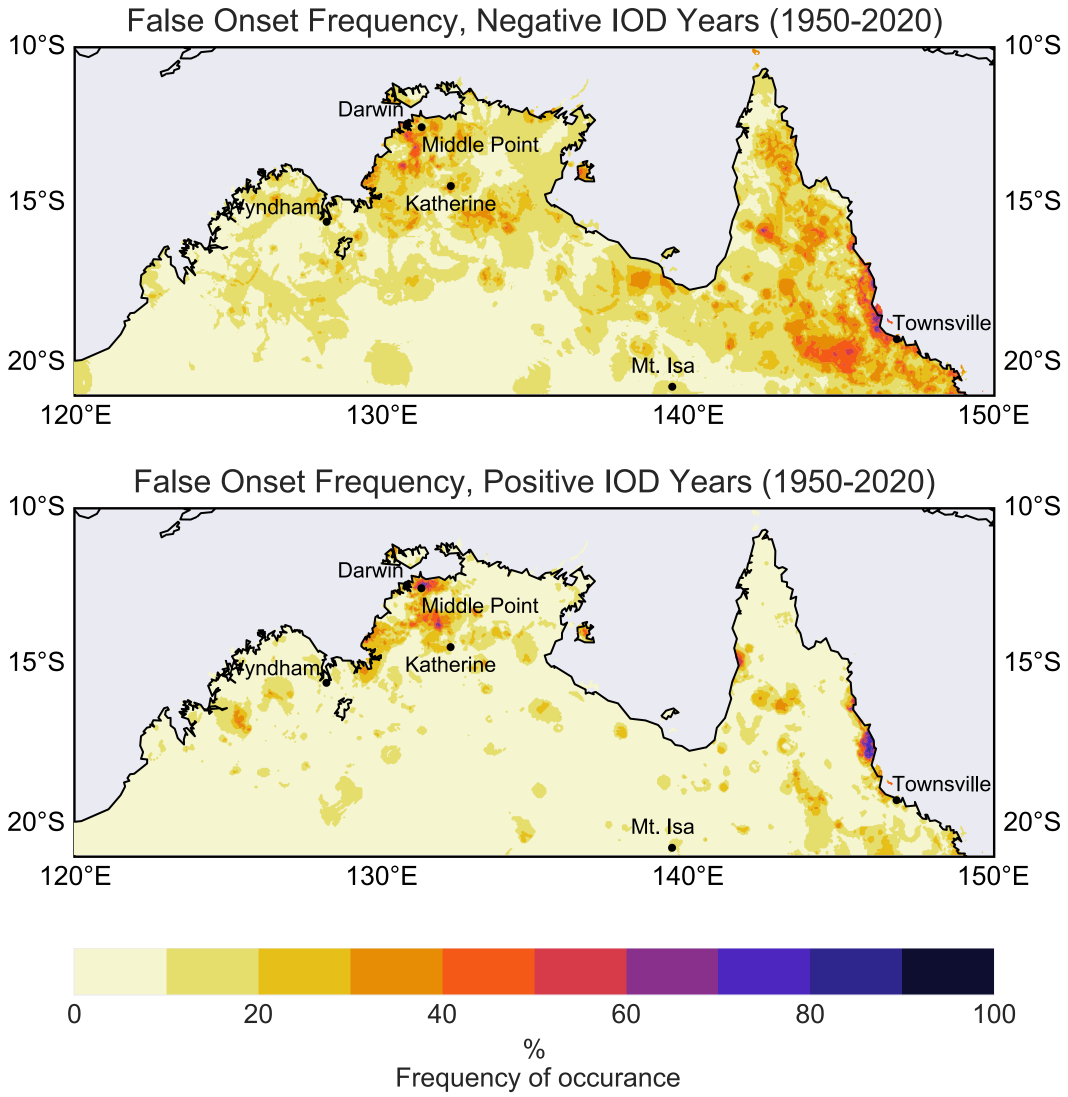
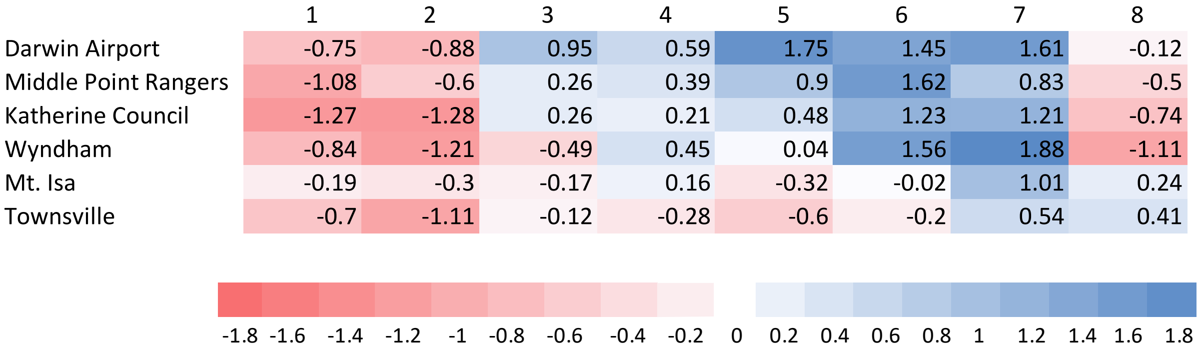


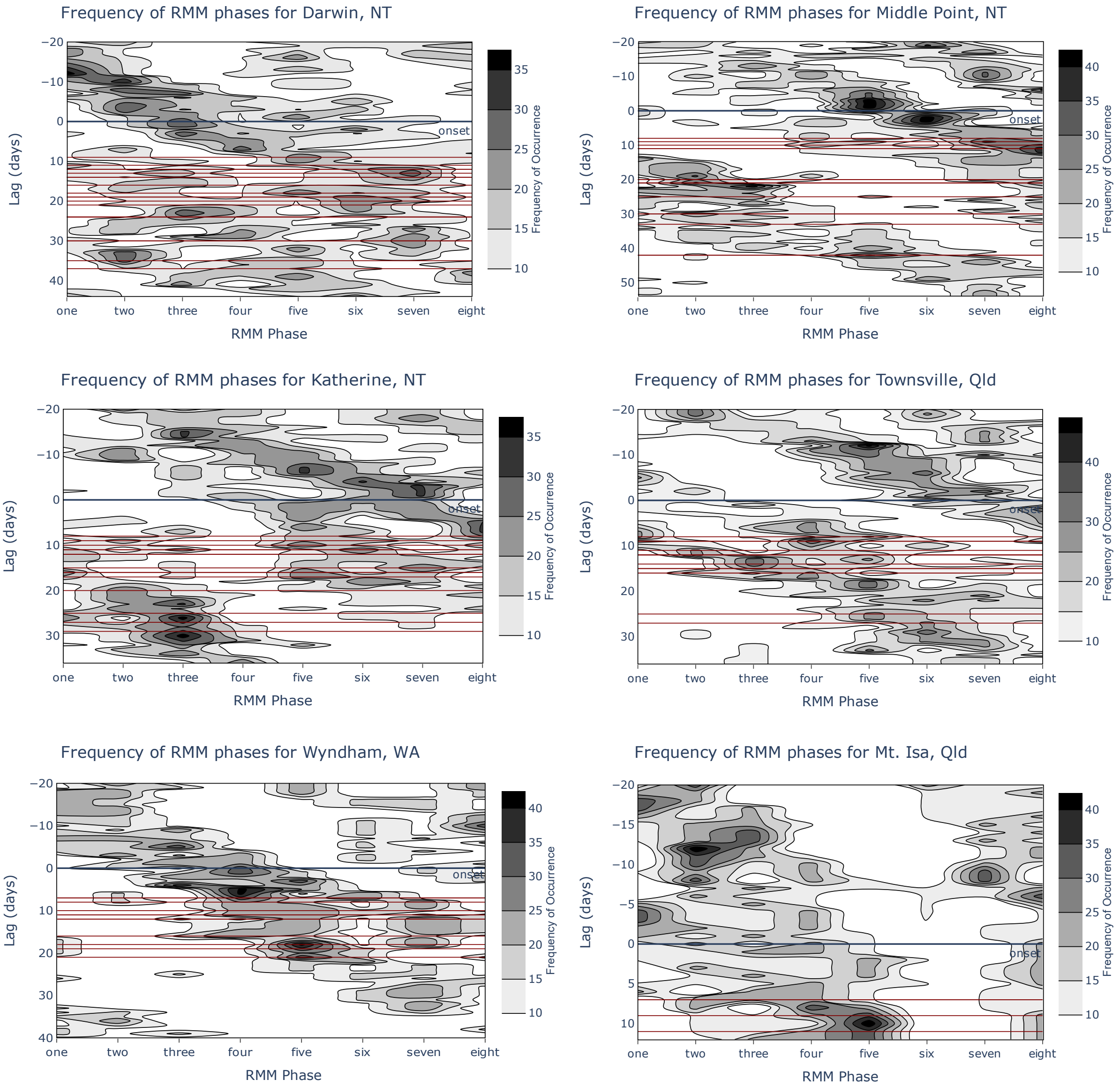
Figure 5 False onset frequency for all negative IOD events (top) and all positive IOD events (bottom) from 1950-2020.

The wet season onset is more likely when the MJO is active over Australian longitudes and the effective rainfall is less likely to return to zero while the MJO is active over Australia but can return to zero during any other phase of the MJO. Figure 6 shows the pre- and early-wet season (September through December) daily rainfall anomaly for each active MJO phase (RMM amplitude is > 1) compared to all days when the MJO is weak or indiscernible (RMM amplitude is < 1) for the six locations considered in Section 4.1, similar to the analysis done by Borges et al. (2018). Consistent with previous studies, we found that periods of increased rainfall are more likely in RMM phases 5—7 while suppressed rainfall is more likely for phases 1—2 with some differences by location. This alone would imply that the early wet season rainfall onset would be more likely when the RMM shows phases 5—7 and that the effective rainfall would be more likely to return to zero in phases 1—2. Figure 7 shows the frequency of RMM phases of any amplitude as a function of composite lag time relative to the wet season rainfall onset date for seasons that included a false onset at the same six location considered earlier, similar to an analysis done by Berry and Reeder (2016). The influence of the MJO on false onsets varies by location. Darwin and Katherine, for example, do not show a clear link between the MJO and false onsets while Townsville usually experiences an onset when the MJO is in phase 7 and then the effective rainfall returns to zero when the MJO is in phases 2—5.



	1	2	3	4	5	6	7	8
Darwin Airport	-0.75	-0.88	0.95	0.59	1.75	1.45	1.61	-0.12
Middle Point Rangers	-1.08	-0.6	0.26	0.39	0.9	1.62	0.83	-0.5
Katherine Council	-1.27	-1.28	0.26	0.21	0.48	1.23	1.21	-0.74
Wyndham	-0.84	-1.21	-0.49	0.45	0.04	1.56	1.88	-1.11
Mt. Isa	-0.19	-0.3	-0.17	0.16	-0.32	-0.02	1.01	0.24
Townsville	-0.7	-1.11	-0.12	-0.28	-0.6	-0.2	0.54	0.41

Figure 6 Daily Rainfall anomaly for RMM active phases and locations for the pre- and early-wet season months of September through December, inclusive. The anomaly is calculated as the difference between the mean daily rainfall during active (RMM amplitude > 1) and inactive or indiscernible (RMM amplitude < 1) periods.



Frequency of RMM phases for Darwin, NT

Frequency of RMM phases for Middle Point, NT

Frequency of RMM phases for Katherine, NT

Frequency of RMM phases for Townsville, Qld

Frequency of RMM phases for Wyndham, WA

Frequency of RMM phases for Mt. Isa, Qld

Figure 7 Frequency of occurrence (shading) of RMM phase (of any amplitude) and lag time in days for seasons that experienced a false onset of wet season rainfall. The zero-line represents the dates when the accumulated effective rainfall reached the 50 mm threshold and each thin, maroon line denotes the dates when the accumulated effective rainfall returned to 0 mm after the onset.

4.4. False onsets and flash drought

Parker et al. (2021) demonstrated that flash drought, as defined by a standardised soil moisture index (Ford and Labosier 2017), occurred over Cape York and the *Top End* during 10-15% of days within their study period, which is relatively high when compared to other parts of the country but consistent with other studies of climate regions that experience high soil moisture variability (Pendergrass et al. 2020). When focusing on just the wet season (October through April) and using pentad data from 2000 to present, we found a similar FOC (Figure 8a) as Parker et al. (2021) for Australia which is also similar to the FOC that Mahto and Mishra (2020) found for the Indian monsoon season. To align with the method used for the FOC for false onsets shown in Section 4.2, Figure 8b shows the FOC of wet seasons that experienced a flash drought at least once within the season. When considering the seasonal frequency of occurrence, the mean across all of northern Australia is 25% of seasons. On the higher end of the distribution, a few rare spots met the soil moisture flash drought criteria in over 60% of wet seasons. The relative high frequency of apparent flash droughts seems to provide some evidence that, despite the use in previous studies (e.g. Mahto and Mishra 2020), changes in soil moisture percentiles may not be a good flash drought indicator in tropical locations. If the flash drought criterion is met so frequently (every second or third year in some locations) then it is not a drought, rather, it is evidence that frequent rapid drops in soil moisture are part of the climatology of that location.

A false wet season onset and a soil moisture flash drought may coincide, but they do not always. Figure 9a-10c show examples from Townsville, Qld, that illustrate three scenarios: (a) flash drought without a false onset, (b) both a flash drought and a false onset, and (c) a false onset without a flash drought. Figure 9a is an example from the 2020-21 wet season when there was a flash drought without a false onset. The wet season rainfall onset was delayed until the end of December, nearly eight weeks later than average (Lo et al. 2007), and the soil moisture dropped from above the 40th percentile on 10 November 2020 to below the 20th percentile by four pentads later on 30 November 2020, and remained low for five pentads in December. Figure 9b shows an example from the 2013-14 season of a false wet season rainfall onset from a rainfall event on 1 November 2011, but without follow-up rainfall the soil moisture declined steadily through November and December followed by a rapid decline in the last two pentads in December that resulted in flash drought conditions through January 2014. Using an accumulated rainfall threshold alone would give the indication that the 2013-14 wet season rainfall began early without any other indication of potential difficulties for agriculture or fire management in the region. The delay of a month or two between the false onset and the development of a flash drought was a common characteristic among all the sites considered in this analysis. Oftentimes the wet season rainfall onset criterion is met, causing high percentile soil moisture, but hot summertime temperatures, high evaporative demand and low follow up rainfall depletes the soil moisture and a flash drought develops several weeks later. Finally, Figure 9c shows an example from the 2011-12 wet season when the rainfall showed a false onset in mid-December 2011, but the soil moisture remained above the 20th percentile.

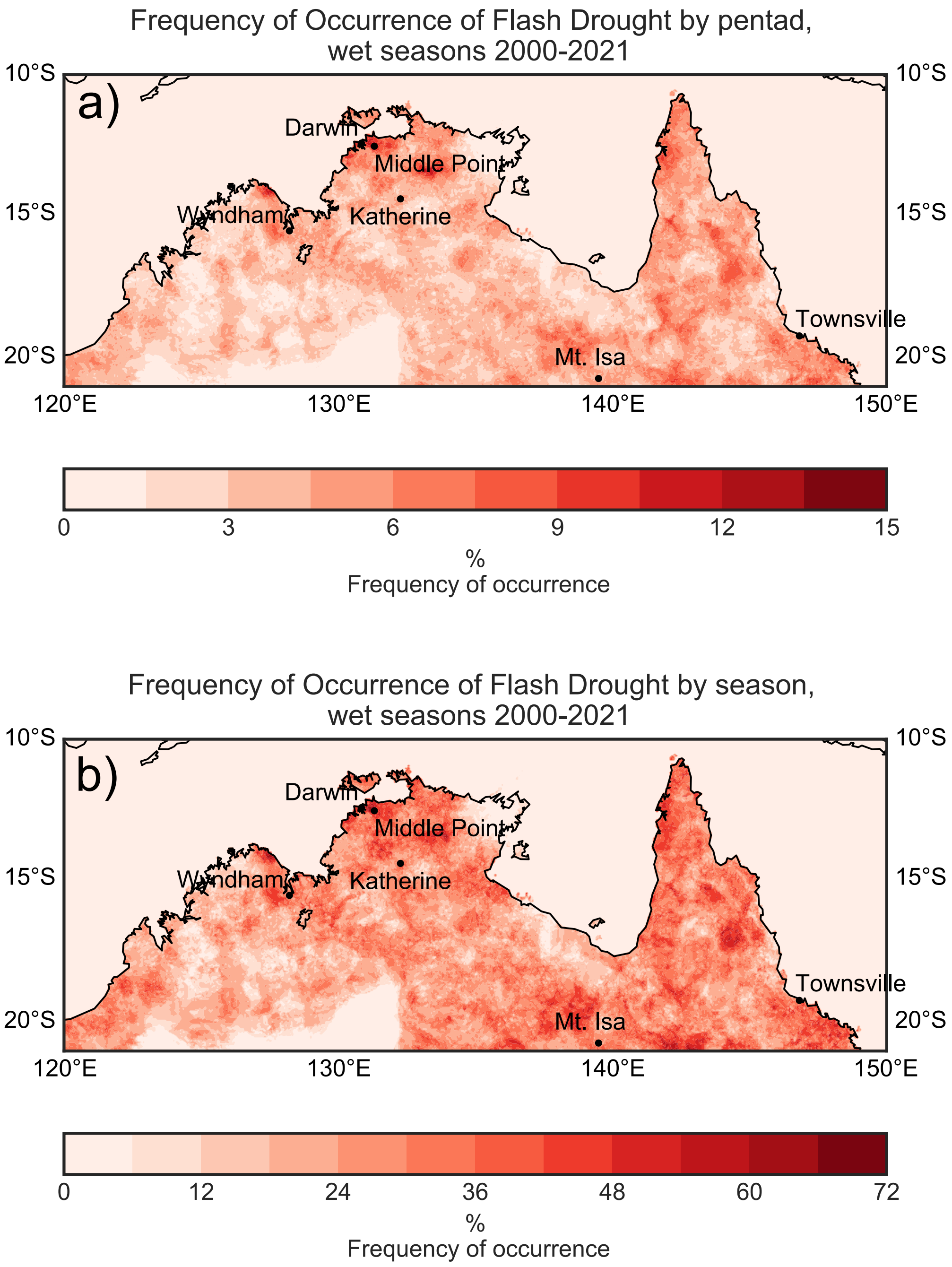


Figure 8 Frequency of occurrence of flash droughts within wet season months of October through April for the years 2000-2021: (a) calculated as the number of pentads that met the flash drought criteria per total pentads; (b) calculated as the number of seasons which met the flash drought criteria at least once per total seasons.

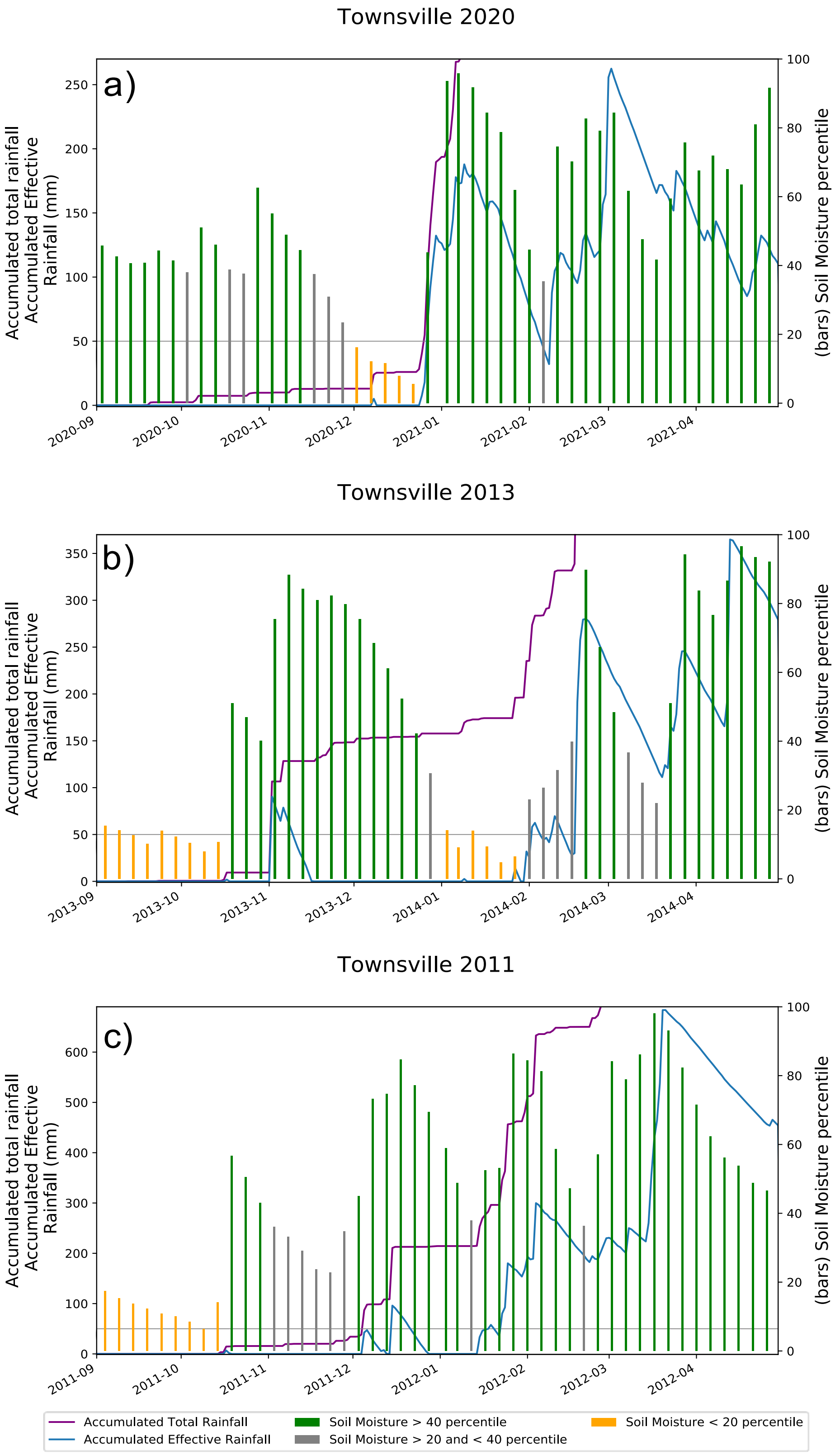


Figure 9 Accumulated effective rainfall (blue), accumulated total rainfall (purple) and root-zone soil moisture percentiles (bars) at Townsville Aero for the following wet seasons: (a) 2020-2021, (b) 2013-2014, (c) 2011-2012. Soil moisture bars are coloured by value with soil moisture above the 40th percentile in green and below the 20th percentile in orange. The 50 mm wet season onset threshold is marked by the horizontal grey line.

From these examples at Townsville, Qld, a FOC can be calculated for how many seasons experienced a false onset, a flash drought and both a false onset and a flash drought within the same season. For all years from 2000 to 2020 (the years with available daily soil moisture data) Townsville experienced a false onset in 29% of the wet seasons considered, a flash drought in 24% of wet seasons, and both a false onset and a flash drought in 10% of wet seasons. Figure 10 shows the frequency of occurrence of seasons that experience both a false onset and a flash drought using gridded data from 2000 to the present for northern Australia. While both false rainfall onsets and soil moisture flash droughts occur with relative frequency across northern Australia, they only occasionally occur within the same season.

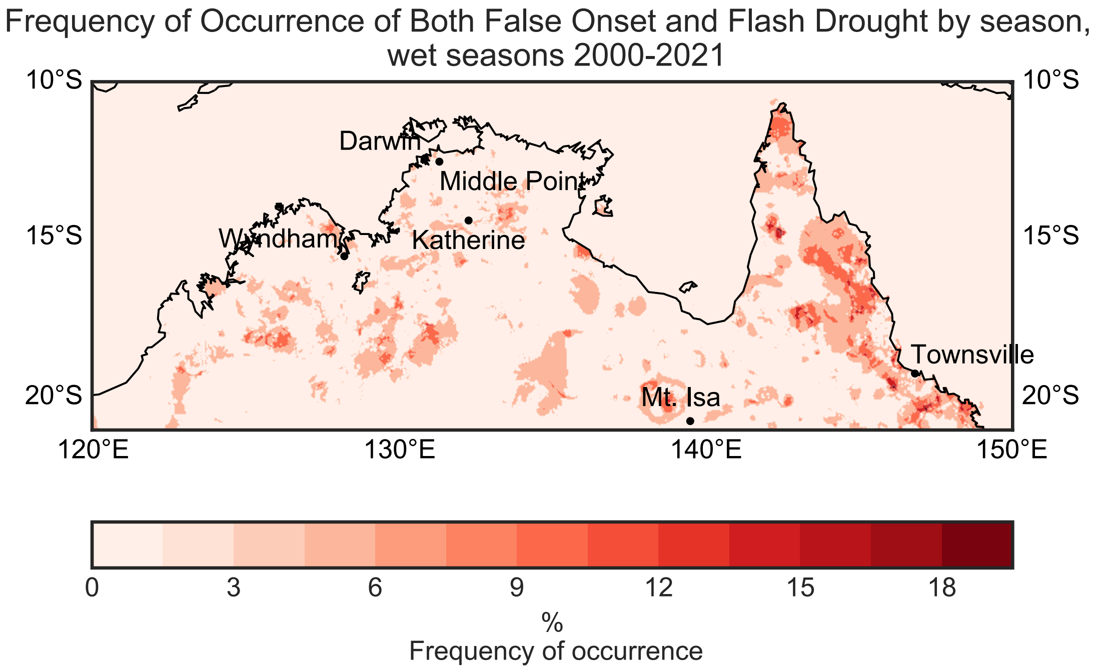


Figure 10 Frequency of occurrence of seasons that experienced both a false onset and a flash drought within the wet season months of October through April for the years 2000-2021.

5. Discussion and Conclusion

This analysis builds on the previously published concept first proposed by Lo et al. (2007) that the northern Australian wet season rainfall onset can be defined using a rainfall threshold of 50 mm accumulated rainfall after 1 September. In this study, we do not dispute the merits of such an onset definition, but rather add to the understanding of the climate and physical characteristics of northern Australia during the early wet season and build-up to the monsoon. We find that there are times when the wet season experiences a “false onset”, i.e. the wet season begins based on the accumulated rainfall criterion but low rainfall or high evaporative demand dries the soil before the monsoon begins. In these seasons, agricultural producers would experience a downward trend in soil moisture at a time of the year when they would expect an increase instead. The likelihood of false onsets is impacted by large-scale climate influences such as ENSO and the IOD, with La Niña and negative IOD patterns often coinciding with false onsets. This then provides the motivation for further analysis to investigate periods of false onset and flash drought and the frequency at which they occur. We find that not all false onsets are associated with or culminate in a flash drought.

In addition to the influence of seasonal-scale climate drivers, we also investigated the influence of the MJO on a sub-seasonal time scale. The literature shows that while the MJO is known to influence the timing of the dynamical monsoon onset, it is less of an influence on early wet season rainfall. Consistent with previous studies, we found that when the MJO is strong over Australian longitudes in October through December that it can also enhance precipitation and influence the timing of the wet season rainfall onset. While it is unlikely for the wet season to experience a false onset while the MJO is active over Australia, false onsets can occur during any other phase of the MJO progression.

Here, we have shown that a false onset to the wet season rainfall can occur frequently over northern Australia. The frequency of occurrence ranges from about 20% of wet seasons at places like Mt. Isa, Qld, up to around 50% of wet seasons near Darwin, NT, and north of Townsville, Qld. The concept of a false onset has not been thoroughly investigated previously, but was introduced by Berry and Reeder (2018). Previous studies have investigated flash droughts in Australia (Parker et al. 2021) and other tropical locations in the context of monsoonal and wet season rainfall variability (Zhang et al. 2019a; Christian et al. 2019a; Zhang et al. 2020; Mahto and Mishra 2020; Yang et al. 2020; Stojanovic et al. 2020). We chose to investigate the concurrence of false onsets and flash droughts over tropical Australia to bridge potential impacts of drought-like conditions in the region. We have also shown that false rainfall onsets occasionally coincide with a soil moisture flash drought, but the two events are usually not related.

There are several limitations to this study that are considered in the interpretation of these results. This study followed previously published studies that used a change in soil moisture percentiles over a short time period to establish the occurrence of a flash drought (Ford and Labosier 2017; Mahto and Mishra 2020; Parker et al. 2021) including studies that applied this method in monsoonal climates (Mahto and Mishra 2020). One of the limitations to using soil moisture percentiles in tropical climates during the wet season is that the soils are typically very wet even when the relative soil moisture percentile shows low values compared to the historical average. Notwithstanding this caveat, we showed that soil moisture flash droughts occur over northern Australia within about 25%

of the seasons, on average. This frequency of occurrence, representing about once every fourth year, raises the question of should these events be considered a drought or are they an inherent characteristic of the natural variability of tropical Australia? It also suggests that in regions with large temporal rainfall variability, that it may be better to use standardized change anomalies that account for the local climatology when determining if changes in absolute value over some period of time are truly unusual for that location (Otkin et al. 2013, 2014, 2015). We used soil moisture as a step between false rainfall onsets and potential agricultural impacts, but from these results, it may be better to use a different indicator. Evapotranspiration (ET)-based drought metrics for flash drought detection have been effective at detecting mid-latitude flash drought because decreases in ET are a more direct indicator of vegetation impacts (Anderson et al. 2007a,b, 2013; Nguyen et al. 2019). However, ET may not be more suitable for tropical locations; Otkin et al. (2018c) and Christian et al. (2019b) both suggest that an evaporative stress index may not work in monsoon regions (both referring to the southwest US monsoon) due to normally rapid changes in evaporative stress during monsoonal rains in the hot summer months. Notwithstanding the difficulty in selecting an appropriate flash drought indicator for tropical locations, we recommend that similar analyses are carried out for other regional monsoon systems where agriculture is often the most important sector of overall economic activity.

A final assumption made in this work is that the connection between false onsets and agricultural impacts can be drawn using soil moisture as an intermediate indicator between rainfall and agriculture (Otkin et al. 2018a), thus the consideration of soil moisture changes is similar to previous research on flash drought (Ford and Labosier 2017; Mahto and Mishra 2020; Parker et al. 2021). Considering that false rainfall onsets and flash droughts are usually not concurrent, it should not be assumed that wet seasons that experience a false rainfall onset will see drought-like impacts to agriculture in northern Australia; this connection should be tested in future research (i.e. the impacts of false wet season rainfall onsets and flash droughts should be documented and quantified).

It is concluded that the time between the wet season onset and the monsoon onset can be highly prone to false wet season rainfall onsets. We further conclude that La Niña and negative IOD—climate patterns that are usually associated with early onset and above average early wet season rainfall—are also associated with seasons with a false onset. We also found that wet seasons that experience a false rainfall onset only occasionally coincide with a rapid depletion of soil moisture and may not always have negative impacts on agriculture.

6. References

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CHAPTER 5: SYNTHESIS AND CONCLUSIONS

Northern Australia's climate can be challenging and the wet season rainfall patterns can seem sporadic and unpredictable. Following five to six months of dry season, and the high temperatures and humidity in the build-up to the wet season, the first burst of monsoonal rains bring life to Australia's tropical north. The motivation for the research documented in this thesis is to better understand the seasonal variability of the north Australian wet season and monsoon, including potential drought conditions that may develop from delayed monsoon onset. Particularly, this research aims to understand the drivers of monsoon and wet season onset variability. Much of this variability has not been quantified before or previously analysed over shorter time periods and with limited data.

As shown in Chapter 1, this aim and motivation underpin two research objectives that were answered over three publications with a fourth supporting publication in Appendix A. These objectives are:

1. Determine which monsoon onset definitions provide the most predictability at seasonal time scales and which seasonal-scale climate influences (drivers) provide the strongest influence on onset timing.

   Lisonbee et al. (2020) and Lisonbee and Ribbe (2021)
2. Understand how often the climate system experiences a "false onset", when an onset criterion is met but follow-up rainfall is not received, and how often do false onsets create a "flash drought" condition.

   Lisonbee et al. (In Review) see also Lisonbee et al. (2021) in Appendix A

The objectives were met, key research questions were answered and the key findings are briefly summarized in the following section.

5.1. Summary of important findings

5.1.1 Monsoon Onset and Drivers of Variations

In the first ever review of monsoon onset definitions, Lisonbee et al. (2020) identified that the Australian monsoon and/or wet season onset has been defined in 25 unique ways within the scientific literature. Lisonbee et al. (2020) showed that each method pins the “onset” to different events throughout the progression of the season. Some capture a wet season onset while others capture the dynamical overturning of the atmosphere, i.e. the monsoon. 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 (Wang et al. 2004; Kim et al. 2006; Smith et al. 2008).

The question of whether a single date should be used to characterize this transition from dry to wet, or from easterly to westerly wind flow, must also be considered. Nevertheless, the concept of an onset date has received widespread use. The monsoon pattern over northern Australia 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 (Troup 1961; Wheeler and McBride 2012); the monsoon onset is defined as the first burst, or active monsoon period, of the season. The concept of an onset has also been applied to the first rainfall of the northern Australian wet season regardless of whether the precipitation was monsoonal or not.

Many studies have introduced monsoon indices that 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 (based on the daily soundings at this location), rather than the broader tropics region and cannot be applied to locations that do not have sounding data available (this issue 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., Nicholls 1984; Kim et al. 2006) can be applied only to seasonal or interannual monsoonal variability at the end of each season but 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, are based on data that is difficult to obtain or are not updated in real-time and therefore cannot be used operationally (Murakami and Matsumoto 1994; Tanaka 1994; Xie and Arkin 1997; Hung and Yanai 2004; Kim et al. 2006; Kajikawa et al. 2010; Zhang 2010; Evans et al. 2014). The quantity and applicability of different onset definitions for the Australian monsoon highlights a known difficulty in this area of research.

Lisonbee et al. (2020) further showed that, regardless of the definition used, the Australian monsoon and wet season onsets experience a large temporal variation. The standard deviation of the wet season onset can range from 10 to 30 days (depending on the region and definition) while the standard deviation of the dynamical monsoon onset is between 16 and 25 days and has a range of between 65 and 122 days (depending on the region and definition).

Lisonbee and Ribbe (2021) show the different monsoon onset criteria for a consistent period in a true side-by-side comparison. Not only do the authors demonstrate that each definition has its own strengths and weaknesses, but also that some provide more predictability than others on a seasonal time scale. One of the key conclusions of this thesis is that the beginning of the wet season is relatively predictable, the onset of the monsoon is not. When considering only the dynamical monsoon, physical mechanisms within the climate system such as El Niño–Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD) and the Southern Annular Mode, have only a weak and somewhat limited influence on monsoon onset timing on a seasonal timescale. This provides a partial answer to the question of “why do some monsoons start late while others start early?”. Lisonbee and Ribbe (2021) demonstrate that ENSO has a non-linear relationship with monsoon onset timing and that only a strong La Niña pattern (NINO3.4 < 1 standard deviation) had a statistically significant relationship with an expedited onset. A weak La Niña, neutral or El Niño pattern did not have a statistically significant correlation with either an early or late onset.

Similarly, with the IOD as measured with the Dipole Mode Index (DMI); only a strongly positive DMI (> 1 standard deviation) correlated with a delayed onset of the dynamical monsoon. A neutral and negative DMI value did not show a statistically significant correlation.

This lack of correlation with seasonal drivers suggests that subseasonal variability on the dynamical monsoon onset exerts a stronger influence on onset timing than seasonal influences (Wheeler and Hendon 2004). Thus, agricultural producers, fire managers, water managers, operational weather forecasters and others in tropical northern Australia should pay close attention to sub-seasonal drivers, such as the Madden-Julian Oscillation, in seasons when the central Pacific Ocean (NINO3.4) does not show a strong La Niña pattern or the Indian Ocean does not show a strong positive IOD pattern.

The review by Lisonbee et al. (2020) pointed to research that demonstrated the influence of ENSO on the timing of the wet season rainfall onset, which occurs earlier in the wet season before the influence of the dynamical monsoon (Nicholls et al. 1982; McBride and Nicholls 1983; Lo et al. 2007; Drosdowsky and Wheeler 2014). Lisonbee and Ribbe (2021) showed that ENSO has only a weak, and sometimes non-existent, link with the onset timing of the dynamical monsoon, which occurs later in the wet season. In considering the application of this research, there are times when the wet season rainfall onset criteria are met (indicating a normal onset of the wet season) but follow up rainfall is not received and even the dynamical monsoon onset is delayed. These circumstances create a type of false wet season rainfall onset and drought that are unique to monsoonal climates. The second research objective of this thesis is based upon this scenario with the findings summarised in the next section.

5.1.2 False Onsets and Flash Droughts

A literature review was undertaken to determine the use of the term “flash drought” in connection with drought (Appendix A; Lisonbee et al. 2021). The results showed that the term flash drought has gained acceptance in the literature over the past two decades, but really gained popularity following the rapid onset of drought in the American Great Plains in 2012. While the review focuses on the general use of the term “flash drought”, it showed that there is precedence in the published literature to use rapid decline in soil moisture as an indication of rapid onset drought events, even flash drought events, in tropical locations.

In drawing from the flash drought literature review, Yang et al. (2020) is a good example of how short periods of drought (less than or equal to 6-month) are more common than longer-duration droughts (more than 6 months) in tropical locations—southern China, in this case (Yang et al. 2020). Notwithstanding this usage, Lisonbee et al. (2021) also showed that the term “flash drought” is more appropriately applied to the rapid onset of drought events regardless of their duration. This is important when considering the possibility of a flash drought near the end of the wet season with impacts that would last through the dry season due to the stark seasonality of the precipitation. Thus, the second research objective, regarding whether delayed monsoon onsets display characteristics of a flash drought, chose to focus on the rate of the onset rather than the duration of the dry periods.

This approach proved beneficial as it showed that the rapid drop in soil moisture during the hot wet season months was relatively common in northern Australia. In fact, rapid depletion of root-zone soil moisture is such a common feature of the northern Australian wet season that it should not be considered a drought (meaning a climatological extreme) but should be considered a standard feature of the climate.

Lisonbee et al. (**In Review**) showed that false wet season rainfall onsets are:

- relatively common across northern Australia, occurring on average about once every three years for most of the region, but as common as about once every other year near Darwin, Northern Territory, and north of Townsville, Queensland.
- more common during La Niña years and negative IOD years when mesoscale wet season rainfall is prone to begin early.
- less common during El Niño and positive IOD events when the wet season rainfall onset criteria are not met until later in the season and the monsoon is able to follow shortly thereafter.
- not usually coinciding with flash droughts.

A final finding from Lisonbee et al. (**In Review**), is that even in times of low percentile soil moisture, compared to the historical record, the actual soil saturation values are relatively modest (30-50% saturation). Despite the use of the metric in previous publications (e.g. Mahto and Mishra, 2020), the results from Lisonbee et al. (**In Review**) demonstrate the limitation of using soil moisture percentiles as a drought indicator during the wet season and it may not be suitable to other monsoonal climates.

5.2. Significance and scientific contribution of the study

Northern Australia provides a difficult climate to live and work in. Research and projects aimed at improving economic development in northern Australia frequently arise on the agenda of government and businesses (e.g., https://www.regional.gov.au/regional/northernaustralia/; https://www.nacp.org.au/about). One of the limiting factors in successful agriculture in northern Australia is the uncertainty around the timing of useful rainfall. It is generally understood that pasture, crop, and horticulture productivity is water limited during the dry season and nitrogen limited in the wet season. Variability in the transition from one season to the next is one of the factors that make productivity in tropical northern Australia very unpredictable. Therefore, any accurate information regarding the seasonal transitions would be valuable (CSIRO 2009). The robust statistical analysis shown in this research provides more certainty in the predictability of the monsoon onset.

Within the “onset” literature, there seems to be a subtle debate about the usefulness of an onset definition that captures the onset of the north Australian wet season as opposed to the onset of the dynamical monsoonal weather system. For example, Nicholls et al. (1982) point out that "many users…are primarily interested in rainfall rather than any large-scale rearrangement of the troposphere". Holland (1986, p. 596) explicitly rejects using a rainfall-based monsoon definition “because of the need to account for the large and variable proportion [of rain] that falls in the transition season (i.e. before any large-scale circulation change occurs)”. Most authors clearly differentiate the wet season from the monsoon (e.g. Nicholls et al. 1982; Lo et al. 2007; Smith et al. 2008; Drosdowsky and Wheeler 2014), while some do not (e.g. Kim et al. 2006; Berry and Reeder 2016). This research project recognises the utility of both for different applications. For example, information on a wet season onset would be most valuable for agricultural applications (CSIRO 2009), while a monsoon onset definition could be quite valuable for water storage, emergency services and transport applications. This research used both definitions to better understand some of natural variability of northern Australia’s climate.

While the wet season and monsoon are two different phenomena, for research on seasonal predictability perhaps the wet-season/monsoon demarcation has not been beneficial; since the predictability of precipitation can change over the course of the season (Hendon et al. 2012). Perhaps early studies such as Nicholls et al. (1982) were following a better path, and that the monsoon should be defined in terms of the annual seasonal march of the ITCZ and/or Outgoing Longwave Radiation, or other parameters, and not by the wind circulation alone.

This research focuses on the north Australian monsoon, which adds to similar research being done in the international scientific community on other monsoonal systems (for example, see http://www.clivar.org/clivar-panels/monsoons, last accessed 4 October 2021). The variability of monsoon onset is a challenge in other regions (Wang et al. 2004; Kim et al. 2006; Smith et al. 2008; Fitzpatrick et al. 2015; Noska and Misra 2016), and this research will contribute to that global conversation.

5.3. Recommendation for future works

This thesis focused on northern Australia’s wet season, including the seasonal monsoon pattern. The analysis presented in this thesis identified that the precipitation between the first rains of the wet season and the monsoon onset can be highly variable and unreliable at times and that the timing of the dynamical monsoon onset can be expedited during strong La Niña patterns and delayed during strong positive IOD patterns. It is recommended that similar analysis be done for other monsoon regions around the world.

Improved understanding of the north Australian climate is important for residents, land and natural resource managers, water management, fire management and businesses of that region. While this research will help improve the understanding of northern Australia's climate, it is acknowledged that there are still unresolved questions that were not addressed in this research. Therefore, the following future research recommendations are proposed:

Australian monsoon research:

1. This thesis focused on the timing of the start of the wet season. More could be ascertained about the monsoon through additional analysis of the onset, including a regression analysis as mentioned in Chapter 3. Additionally, the timing of the retreat of the monsoon and the end of the wet season rainfall was not addressed here nor has it received much attention in the literature (Tanaka 1994; Pope et al. 2009; Zhang 2010). Future research could focus on why some seasons end earlier than others.

2. This thesis helps quantify the propensity for rapid onset (i.e. flash) drought during the wet season. The high frequency of soil moisture flash drought events suggests that these regular occurrences may not be considered a drought but should be considered a regular feature of northern Australia’s climate. Future research should focus on understanding thresholds of extreme drought events in a way that is relevant to the north Australian tropics.
3. This research included an analysis of false wet season onsets over northern Australia in relation to ENSO and IOD. Similar analysis could be done using other climate drivers, including ENSO Modoki patterns. This could include examining the dynamics as to why mesoscale weather patterns may start and then stop within the early wet season?

Research with an international context:

4. Another significant limitation of this thesis is the lack of sub-seasonal to seasonal scale, physics-based, dynamical modelling of the monsoon onset. An earlier conceptualization of this work included a dynamical modelling component, but the authors could not find an objective monsoon onset criterion that would not produce a large amount of false positive onset signals from the seasonal model output. Therefore, it was decided to remove this focus from the scope of the present work. Future research should revisit this problem and search for monsoon signals in dynamical model monthly and seasonal forecasts/outlooks. This may include considering rainfall-based monsoon onset definitions, maintaining the distinction between wet season and monsoon, but looking for the snap change in the location of the ITCZ, and the tie in with the Indonesian monsoon onset.
5. The application of this research was discussed only briefly in this thesis. Future research should be done that aims to integrate management and planning decisions to wet season and monsoon onset thresholds, false

onsets and/or flash drought in the region. This can include planning for the length of the bushfire season, water storage management, weed control for agricultural practices, etc.

6. As mentioned above, similar assessments could be carried out for other monsoonal climates around the world. This should include efforts to relate this present work to the body of work on spatial coherence of rainfall in monsoon environments (e.g., Haylock and McBride 2001; McBride et al. 2003; Moron et al. 2009, 2017).

5.4 Final Conclusions

The aim of this research has been to provide further understanding of north Australia's climate and to determine if the onset timing of the north Australian wet season and the monsoonal weather pattern can be predicted on a seasonal timescale using seasonal-scale climate drivers. This aim and the associated research objectives have been achieved.

This thesis concludes that the dynamical monsoon onset experiences high temporal variability and is not easily predictable on seasonal timescales by traditional seasonal climate influences. Only a strong La Niña pattern (<-1 standard deviation in NINO3.4 sea surface temperatures) shows a statistically significant correlation with an early onset. A weak La Niña, ENSO-neutral, and a weak or strong El Niño pattern showed only a weak or non-statistically significant correlation and should not be used to make monsoon onset predictions. A negative and neutral IOD do not have a statistically significant correlation with monsoon onset dates, but a strong positive IOD correlates with a delayed monsoon onset and could be used in monsoon onset predictions.

It is further concluded that some wet seasons experience a false onset. These are seasons when a wet season onset criterion is met, but follow up rainfall is not received for several weeks, and sometimes not until the onset of the dynamical monsoons, which may be several months. These false wet season onsets are more common when a La Niña or a negative IOD pattern is in place. These false onsets sometimes, but not always, coincide with a rapid onset of soil moisture drought conditions, which are found to be relatively common across northern Australia in the wet season.

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APPENDIX A: SUPPORTING PUBLICATION

Lisonbee et al. (2021). Making sense of flash drought: definitions, indicators, and where we go from here

This literature review was prepared in preparation for the first International Flash Drought Workshop, held virtually on 2-3 December 2020 and hosted by the National Oceanic and Atmospheric Administration's National Integrated Drought Information System. The key takeaways from this review strongly supported the inclusion of a flash drought analysis for northern Australia, included in this Thesis as Chapter 4, and the overall conclusions about wet season and monsoonal variability included as Chapter 5.

One of the key takeaways is that there has been precedence within the scientific literature to apply the concept of a *flash drought* to monsoonal climates, but not all flash drought definitions can work at lower latitudes. Nguyen et al. (2019) used an evaporation stress index to identify flash drought in Australia’s Murray-Darling Basin, but Otkin et al. (2018) and Christian et al. (2019b) both suggested that the standardised evaporative stress index may not work in monsoon regions (both referring to the southwest US monsoon) due to normally rapid changes in evaporative stress during monsoonal rains in the hot summer months. Mahto and Mishra (2020) was published shortly after the literature review was submitted, and therefore was not included therein, but it provided a precedent for using changes in soil moisture percentiles (Ford and Labosier 2017) to identify flash drought events during the Indian monsoon season. We apply this criterion to identify flash droughts during the north Australian wet season in Chapter 4.

Making sense of flash drought: definitions, indicators, and where we go from here

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ABSTRACT

The topic of "Flash Drought" is rapidly gaining attention within both the research and drought management communities. This literature review aims to synthesize the research to-date and provide a basis for future research on the topic. Specifically, our review is focused on documenting the range of definitions of "flash drought" being proposed in the research community. We found that the term first appeared in the peer-reviewed literature in 2002, and by 2020 has become an area of active research. Within that 18-year span, "flash drought" has been given 29 general descriptions, and 20 papers have provided measurable, defining criteria used to distinguish a flash drought from other drought. Of these papers, 11 distinguish flash drought as a rapid-onset drought event while eight distinguish flash drought as a short-term or short-lived, yet severe, drought event and one paper considers flash drought as both a short-lived and rapid onset event. Of the papers that define a flash drought by its rate of onset, the rate proposed ranges from 5 days to 8 weeks. Currently, there is not a universally accepted definition or criteria for "flash drought," despite recent research that has called for the research community to adopt the principle of rapid-intensification of drought conditions.

1. Motivation and Methodology

Flash drought has been the topic of scientific research since 2002. Research on this topic has recently increased, with a significant rise in the number of publications starting about 2013 (Figure 1). As of July 2020, there have been over 50 publications wholly devoted to the topic and at least 142 others that mention the term "flash drought" in relation to other topics.[1] Within these publications, unique defining criteria have been applied to flash drought at least 20 times. Currently, there is not a universally accepted definition or criteria for flash drought, though the principle of rapid onset or intensification that ends in drought is generally applied (Otkin et al. 2018a).

The motivation for this paper is to synthesize this broad range of research, highlight some of the questions and incongruities that exist within the literature to date, and provide a basis for future research on flash drought. We hope this paper will serve as a resource for other researchers as they frame research questions to improve our physical understanding of this phenomenon. We do not attempt to critique the flash drought definitions provided in the literature thus far. Instead, our intent for this paper is to support more discussion within the literature—and the research community more broadly—regarding what are the "right" ways, and perhaps more importantly, most useful ways, to characterize flash drought.

We have focused this literature review of flash drought research on the use and definition of the term "flash drought" in the literature to date. Following the methodology of Pickering and Byrne (2014), this review began with an online search via Scopus (www.scopus.com) for any peer-reviewed journal publications that included the words "flash drought" in the article title, abstract, or keywords. This

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[1] *As detailed below, we are only including 86 of these publications in the reference list herein.*

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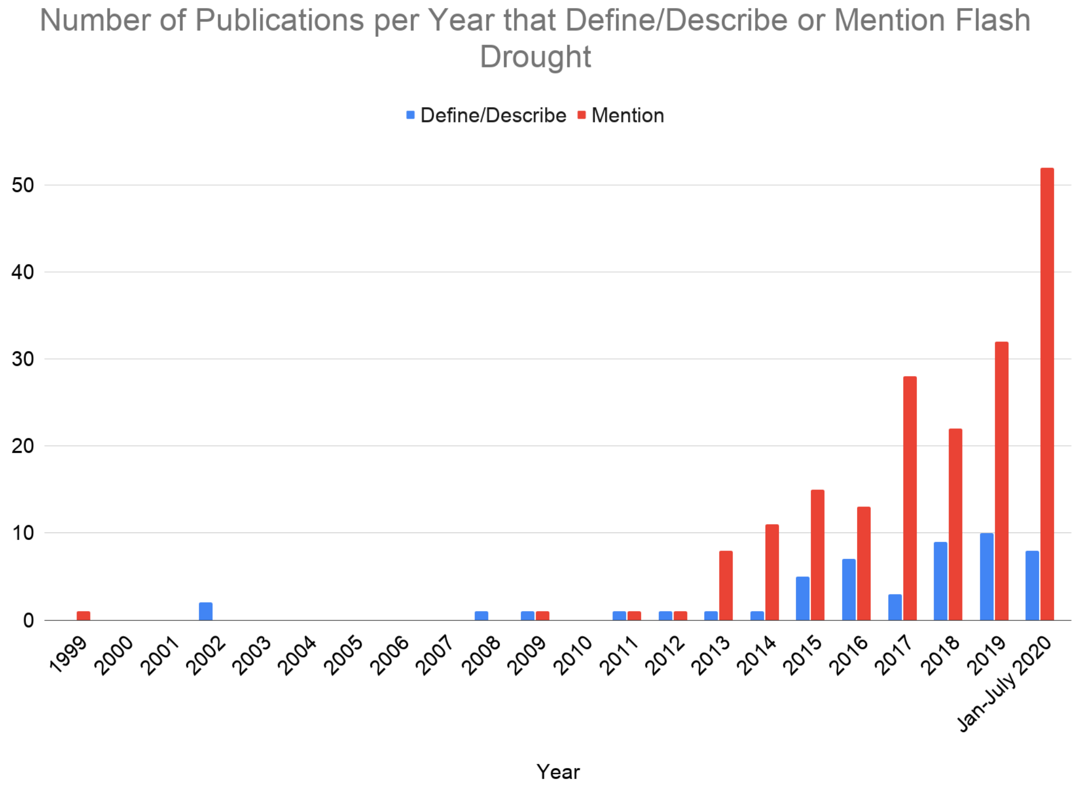

Figure 1: Number of publications each year that either provided a definition or description of flash drought (blue) or that simply mentioned the term "flash drought" without providing a description or definition (red).

search produced 52 unique results (as of July 2020). Twenty more papers were added to these results based on papers referenced within any of the articles identified (including each newly-added paper) and further input from subject matter experts. Of these 72 total publications, nine simply mentioned the term "flash drought" without providing any further description or definition and are not included herein. The remaining 63 citations included 60 refereed journal publications, one magazine article, one book chapter, and one conference paper.

One of the motivations for limiting a search to the article title, abstract and keywords is to identify articles that are dedicated to the topic of flash drought. However, one limitation to this approach is that it overlooks articles that use the term "flash drought" within the text but may not have been dedicated to the topic. Since we are interested in the use and definitions of the term, whether the paper was devoted to the topic or not, we chose to supplement our Scopus search with an online search using Google Scholar.[2] This produced 644 search results (through July 2020), which we then refined to include only peer-reviewed journal publications (374 results). The results were further filtered to remove spurious search results—those that did not actually include the term "flash drought" in the text (148 results), papers that simply mention the term "flash drought" but do not provide any further description or definition (142 results), or papers that had already been referenced from the Scopus search (59 results). This left us with 23 articles that were added to the literature review, giving a total of 86 articles.

These results were then sorted according to how the term "flash drought" was used. We looked for whether they provided a general description or a measurable definition based on set criteria and if they focused on a specific drought event (e.g., Central U.S. 2012 or Northern Great Plains U.S. 2017). After identifying some general patterns in the definitions used, for perspective and completeness we performed one final search in Scopus for papers that - while not using the term "flash drought" per se, were focused on concepts or events that share similar physical characteristics with those considered "flash droughts." This final search (using Scopus in early August 2020) combined the terms "rapid onset" + "drought," "rapid development" + "drought," "rapid intensification" + "drought," "short-term" + "drought,"[3] and "short-duration" + "drought." This produced 203 total results, including 167 irrelevant results (e.g., economics, engineering, botany, etc.), 32 duplicate results to the "flash

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[2] *Google scholar picks up any journal, university or research organization publications that contains the search phrase, which includes theses, newsletters, curriculum vitae, etc.*

[3] *The search "short-term" + "drought," produced 2,541 results, so in this case we refined our search to also include "flash drought" somewhere in the text.*

drought" search, and three papers that are included in the final literature review.

This study contains a few limitations that should be noted. One limitation is that the search results were not sorted by region or location. Therefore, the regional differences of flash drought definitions will not be explored here. We also did not compare definitions by the authors' intent (e.g., was a definition intended to measure an event or predict an event, etc.). Both of these are topics for future research. Another key limitation includes the timeliness of the search results: this literature review reflects a snapshot in time as of July/August 2020. Given that flash drought is a very active topic of research, it is likely that several more papers have been published on the topic since our searches were conducted; any such papers would not be included herein.

2. A Brief Timeline of Flash Drought Research Highlights

2.1 First References

In 1999, R. Showstack authored a piece for *EOS, Transactions*[4] titled, US Federal Government Tries to Get Ahead of the Curve with Drought Planning, in which prominent physical scientists were interviewed about drought. Showstack (1999) points to the slow onset of drought compared to more dramatic and sudden weather events and states "Droughts receive less attention because they are slow-moving disasters… There is no such thing as a flash drought, for instance, and droughts edge up without lightning bolts or tremors that people experience directly" (Showstack, 1999, p. 365).

Showstack (1999) notwithstanding, the term "flash drought" began showing up in the published literature only three years later. First, in January 2002 by Peters et al. (2002)—a paper on the derivation and utility of the Standardized Vegetation Index (SVI)—that points to the rapid intensification of drought across the southern High Plains in August and September 2000 and says, "the term to describe this was 'flash drought' because of the combination of no precipitation and very high temperatures" (Peters et al. 2002, p. 73), likely alluding to discussions about the event that were occurring outside of the published literature at the time. The term appeared again in August 2002 in the foundational paper on the U.S. Drought Monitor by Svoboda et al. (2002), where "flash drought" was mentioned in a general reference to rapidly intensifying drought conditions.

Both Svoboda et al. (2002) and Peters et al. (2002)[5] have been referenced as the first use of the term "flash drought." Ten papers specifically cite the Svoboda et al. (2002) study in reference to the term "flash drought" (see Appendix 1 for a list of these papers).[6] Peters et al. (2002) was referenced twice, these were by Twidwell et al. (2014) and Lee and Gill (2015).

2.2 First General Definitions

The earlier references to flash drought were general in their description. For example, Svoboda et al. (2002) describes flash drought as "rapid crop deterioration due to the adverse effects of a severe heat wave and short-term dryness, leading to a rapid onset of drought and associated impacts…" (Svoboda et al. 2002, p. 1184). The first place to offer a definition of flash drought (and specifically call it a definition) was a conference presentation at the AMS 22nd Conference on Hydrology in 2008. Here Senay et al. (2008) defined flash drought as "a short-term, yet severe [drought] event, characterized by moisture deficits and abnormally high temperatures" (Senay et al. 2008, Abstract). The Senay et al. (2008) drought definition has been referenced directly five times by subsequent authors (See Appendix 1) in the use or definition of the term "flash drought."

2.3 First Paper to Define Flash Drought Using Indicator Values and a Defining Criterion

Hunt et al. (2009) was the first paper to use a set of criteria to objectively determine a flash drought. With a reference to Senay et al. (2008), they defined a flash drought as "a severe, short-term [drought] event characterized by moisture deficits and abnormally high temperatures" (Hunt et al. 2009, p. 757). Hunt et al. (2009) further add that "a flash drought is the result of a synoptic meteorological pattern where potential ET (evapotranspiration) greatly exceeds precipitation for a period no less than 3 weeks such that available water in a previously moist (0–50 cm) soil profile decreases by more than 50%" (Hunt et al. 2009, p. 757). This definition has been cited at least four times, including by Mo and Lettenmaier (2015) before they proposed a flash drought definition based on heat waves (see Sections 3.2 and 3.4).

2.4 First Paper to Solely Focus on Flash Drought

The first paper solely devoted to the topic of flash drought was Otkin et al. (2013), which examined the characteristics of the following four "rapid-onset droughts": Oklahoma and Arkansas in late summer 2000; Indiana and Ohio in early summer 2007; Southeast Wisconsin in summer 2002; and Oklahoma and Arkansas in summer 2011. This paper used the terms "rapid-onset drought" and "flash

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[4] *EOS, Transactions was a weekly magazine of Earth science published by John Wiley & Sons for the American Geophysical Union (now available online only at eos.org).*

[5] *Svoboda was also a co-author on the Peters et al. (2002) paper.*

[6] *It should be noted that a total of 63 of the papers included in this review reference Svoboda et al. 2002, but usually in reference to the US Drought Monitor, rather than to the term "flash drought."*

drought" interchangeably. This paper demonstrated that the Evaporative Stress Index (ESI) is effective in providing early warning of flash drought events. While they did not explicitly define flash drought, they referred to Mozny et al. (2012) in their description of flash drought.[7]

2.5 Flash Drought Research and the 2012 Drought

Between 2002 and 2012 the literature was relatively quiet on the topic of flash drought. It is possible that there were papers published on the topic during this time that simply did not use the term "flash drought" but rather stayed within the accepted terminology of the time. Two possible examples of this are Fowler and Kilsby (2002) and Illston et al. (2004). Fowler and Kilsby (2002) mention rapid onset of drought in the Yorkshire region of the UK, but do not use the term "flash drought." This paper was the only one found between 2002 and 2012 using any of the additional search terms ("rapid onset" + "drought" in this case). Illston et al. (2004) was found as a reference in Hunt et al. (2014). This paper examines rapid changes in the soil moisture profile in Oklahoma, USA, before and after the 2000 drought, but they do not call it a "flash drought." Any other similar papers using slightly different terms than those we searched for might not have shown up in our literature search and would not be included in this review.

The rate of flash drought publications increased after 2012 (see Figure 1). One reason for this increase is the extreme drought over the central US during 2011 and 2012. During this time, the term seemed to be picked up by both the media and the scientific community in the United States (Otkin et al. 2018a). According to many publications, the 2012 drought in the US Central Plains was a quintessential flash drought[8] and has been used as a case study by many (Hoerling et al. 2013, 2014; Kumar et al. 2013; AghaKouchak 2014; Otkin et al. 2014, 2015b; Behrangi et al. 2015; Mo and Lettenmaier 2015; Wang et al. 2015; Sun et al. 2015; McNider et al. 2015; PaiMazumder and Done 2016; Otkin et al. 2016; Lorenz et al. 2017a,b; Hao et al. 2017; Rupp et al. 2017; Yang et al. 2018; Yan et al. 2018; Jin et al. 2019; Sun et al. 2019; Basara et al. 2019) or as a flash drought standard against which to compare other droughts (He et al. 2019). While the literature shows there had been droughts prior to 2012 that are now considered to be flash droughts [e.g., 1988 in the north central US (Trenberth et al. 1988), 1999 in Nebraska (Hunt et al. 2009), Southeast Wisconsin in summer 2002 (Otkin et al. 2013), 2000 in the Southern US (Peters et al. 2002; Otkin et al. 2013), Indiana and Ohio in early summer 2007 (Otkin et al. 2013), and Oklahoma and Arkansas in summer 2011 (Otkin et al. 2013)], the 2012 event certainly attracted researchers' attention to the topic.

3. Definitions

Flash drought has been defined or described in at least 49 different ways, although several definitions[9] are closely related or add qualifiers to previously proposed definitions. This section documents all of these definitions or descriptions and the criteria used by each definition. Where a definition is used in multiple papers, we include only its first instance, and note who refers to that definition in subsequent research,[10] although we include those papers where the definitions were adapted in some way. We chose to group these definitions into the following categories: (1) general definitions that provide a qualitative description of flash drought but provide neither criteria nor thresholds to measure or distinguish flash drought events; (2) definitions based on the rate of onset; (3) definitions based on duration of the drought event or that, by nature of the criteria used, can distinguish a flash drought as one with a short duration; (4) definitions based on both the duration and the rate of onset to identify a flash drought (one paper).

3.1 General Definitions or Descriptions

Twenty-nine papers provided a general description of flash drought (Appendix 1). While some papers may describe flash drought in terms of rate of onset/intensification or duration, they do not provide specific thresholds that could be used to distinguish flash droughts.

One notable inclusion here is Otkin et al. (2018a), which provided a review and assessment of flash drought science up to 2018. The authors proposed that flash drought is "a subset of all droughts that are distinguished… by their unusually rapid rate of intensification" (Otkin et al. 2018a, p. 914). However, it did not specify how rapid the rate must be to be considered "unusual;" i.e., they did not provide a definition based on thresholds of an indicator(s). Rather, the authors proposed a set of guiding principles that should be considered when examining flash drought. A criteria-based definition was proposed by Christian et al. (2019a) based on the recommendations made by Otkin et al. (2018a) and will be discussed briefly in the next section.

The 29 general definitions listed in Appendix 1 can be categorized in the following way:

- 15 described flash drought as a rapid onset or

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[7] In their description of flash drought, Mozny et al. (2012) in turn drew from Hunt et al. (2009) and referred to Senay et al. (2008), which was the first research to offer a definition of the term, as noted above in Section 2.2.

[8] One exception is McEvoy et al. (2016) which demonstrates the application of the Evaporative Demand Drought Index (EDDI) for detecting and monitoring flash drought and challenges the notion that 2012 should be considered a flash drought, at least over central Iowa.

[9] While we use the word "definition," in some instances the authors only provide a description of the term "flash drought." We are including these papers here for completeness.

[10] A full list of the papers identified are included in the references section.

intensification drought event (Anderson et al. 2011; Otkin et al. 2014; Sun et al. 2015; Anderson et al. 2016; Brown et al. 2016; Hobbins et al. 2016, 2017; Cook et al. 2018; Yao et al. 2018; Otkin et al. 2018a; Lorenz et al. 2018; Gerkin et al. 2018; Hoell et al. 2019; Jin et al. 2019; Trnka et al. 2020).

- Ten described flash drought as a short-term drought event (Senay et al. 2008; Hunt et al. 2014; Yuan et al. 2015; Cammalleri et al. 2016; Orbringer et al. 2016; Sanchez et al. 2016; Vogt et al. 2018; Haile et al. 2020; H. Zhang et al. 2019; Zhang et al. 2020).
- A few hard-to-categorize papers include:
    - Stojanovic et al. (2020) which described flash drought as having both a sudden onset and a short duration
    - Svoboda et al. (2002) which describes "...short-term dryness, leading to a rapid onset of drought" (p. 1184)
    - Peters et al. (2002) and Han et al. (2019) both describe flash drought as a combination of no precipitation and very high temperatures without any indication of the rate or duration of the event

3.2 Rate vs. Duration

As mentioned above, we could have grouped these definitions in various ways, but the literature includes a subtle debate about whether flash drought should be defined by the rate of onset/intensification or the duration of the drought event, and we have chosen this grouping to bring this debate to the forefront.

The Senay et al. (2008) definition references "short-term, yet severe" events that last at least three weeks but are not required to last longer than that. This idea of a "short-term" drought was supported by Mo and Lettenmaier (2015, 2016) who proposed that there are two types of flash drought, a "heat wave flash drought" and a "precipitation deficit flash drought." While the precise definitions proposed by Mo and Lettenmaier (2015, 2016) do not have a duration requirement, the nature of their proposed definition relying on a heat wave means that these events will be short-lived. Therefore, they conclude, "One feature that distinguishes flash droughts from longer meteorological and agricultural droughts is that flash droughts generally do not persist because T_{air} anomalies tend not to be persistent. For heat wave flash droughts, most events only last for one to two pentads." (Mo and Lettenmaier 2016, p. 1173).

The Otkin et al. (2018a) review paper on the topic weighed in heavily on this debate, stating: "Here, we have proposed that the definition for 'flash drought' should inherently focus on its rate of intensification rather than its duration, with droughts that develop much more rapidly than normal being identified as flash droughts" (Otkin et al. 2018a, p. 914) Under this definition, even droughts that persist for several years may be considered a flash drought, (e.g., Southeast Australia 2017-2020 drought, see Nguyen et al. 2019).

Table 1. Comparison of onset rates from papers that defined flash drought as a "rapid-onset" event.

Onset rate	References(s)
5 days	Park et al. (2018)
1 week	Liu et al. (2020a)
2 weeks	Pendergrass et al. (2020)
15 days	Yuan et al. (2019)
20 days	Ford and Labosier (2017); Koster et al. (2019)
4 weeks	Anderson et al. (2013); Chen et al. (2019); Noguera et al. (2020)
30 days	Christian et al. (2019a)
8 weeks	Ford et al. (2015)

3.3 Rate of Onset/Intensification Definitions

Eleven papers in our review define flash drought by its rate of onset or intensification that are tied to specific thresholds of various indicators (Appendix 2).

The rate of flash drought development depends on the definitions and criteria used in the publications, with onset rates ranging from five days to eight weeks. Table 1 compares the onset rates for each of the definitions listed in Appendix 2.

3.4 Short-Duration Drought Events

Eight papers provided a set of criteria that defined a flash drought to be one that is short-lived (Appendix 3). While only two of the definitions listed in Appendix 3 includes short-duration as a defining criteria of a flash drought (Hunt et al. 2009; Li et al. 2020c), they all consider flash drought to be short-term drought events by nature of the criteria used. Two examples illustrate this: M. Zhang et al. (2019) defined flash drought in terms of rainfall deficit at a specific time of the year at Shanchuan, China; a "flash-drought event is defined as when the monthly (July or August) rainfall is less than 100 mm" (M. Zhang et al. 2019, p. 2). The second example is from Mo and Lettenmaier (2015, 2016) where they require a flash drought to be associated with a heat wave. Mo and Lettenmaier (2016) acknowledge that "Because heat waves do not persist, most flash droughts only last one or two pentads" (Mo and Lettenmaier 2016, p. 1183). Hence, we have included these, and similar definitions (Zhang et al. 2017; Yuan et al. 2018; Wang and Yuan 2018) in the short-duration drought event category.

As an aside, most authors who considered flash drought to be a short-term drought event also considered flash drought to be a subset of agricultural droughts. Hunt et al. (2014) and Svoboda et al. (2002) both mention agricultural impacts in their description of flash drought, especially when the short-term dryness corresponds with sensitive times in a crops' development. Mo and Lettenmaier (2015) described a Heat Wave Flash Drought (see Appendix 3 for a description) as agricultural drought in nature. Mo and Lettenmaier

(2016), when comparing the Heat Wave Flash Drought and the Precipitation Deficit Flash Drought (see Appendix 3) explain, "Both are manifested by [soil moisture] deficits that cause damage to crops. In that sense, both are agricultural droughts" (Mo and Lettenmaier 2016, p. 1181). Zhang et al. (2017) state that "soil moisture deficit is an important indicator of flash drought, and soil moisture is the proximate determinant of agricultural drought, therefore, flash drought is the category of agricultural drought" (p. 167). Wang and Yuan (2018) cite Mo and Lettenmaier (2015) when they write "flash drought is an agricultural drought in nature" (Wang and Yuan, 2018, p. 1480).

3.5 Rapid Onset and Short Duration Drought Definition

There was one paper that included both a rate of onset and short-duration criteria to identify a flash drought (Appendix 4). Li et al. (2020a) used a standardized evapotranspiration deficit index (SEDI) to identify flash drought using the following three criteria: (1) the duration is longer than five pentads but shorter than twelve pentads; (2) the instantaneous intensification rate of the cumulative SEDI is at or below the 25% of cumulative distribution frequency of the change in the cumulative SEDI during flash drought development; (3) the average instantaneous intensification rate during flash drought development phase is at or below the 40% of cumulative distribution frequency of the change in the cumulative SEDI during flash drought development.

4. Indicators Used in Flash Drought Definitions

The indicators used in flash drought definitions vary by paper. In this section we have grouped flash drought criteria by indicator used, which also may give an indication of the type of drought described (meteorological, agricultural, hydrological, socioeconomic and ecological; see Otkin et al. 2018a). We will first look at which papers rely upon the US Drought Monitor changes (Svoboda et al. 2002), as the US Drought Monitor is produced through expert examination of a myriad of data sources. We then will look at the indicators used by other papers.

4.1 The US Drought Monitor in Flash Drought Definitions

There were four papers that defined flash drought using category changes in the US Drought Monitor as a way to identify a flash drought. These are included in Table 2 (these are also listed among the definitions grouped in Appendices 1, 2 and 3). Even among these papers, the rate of change differs by definition. Pendergrass et al. (2020) proposed a two-category change in two weeks, while Chen et al. (2019) also proposed a two-category change but over four weeks. Lorenz et al. (2018), through some experimentation, considered "rapid onset" to mean any change toward drought within 2, 4, or 6 weeks. Ford et al. (2015) looked for a three-category change toward drought in eight-weeks or less.

Not included in Table 2, but still notable, are Anderson et al. (2013) and Otkin et al. (2015b). Anderson et al. (2013) did not use the US Drought Monitor in their definition of flash drought but used the US Drought Monitor as a "standard of truth" as they compared hydrologic indicators during drought periods. Otkin et al. (2015b) did not use the USDM to define flash drought, but observed that "...according to the U.S. Drought Monitor (USDM), many locations across the central United States during the 2011 and 2012 flash droughts experienced up to a three-category increase in drought severity in only one month, meaning that areas that were drought free at the beginning of the month were characterized by severe to extreme drought conditions by the end of the month" (Otkin et al. 2015b, p. 1073).

4.2 Other Indicators Used

We have documented the types of indicators that have been used to define and measure flash drought (Appendix 5). Out of brevity, we have limited our list of indicators to only those used to define flash drought (i.e., not considering other drought analysis that may have been done in those papers or subsequent research that referenced those definitions, see Appendices 2, 3, and 4). Soil moisture data is used in 11 definitions, evapotranspiration is used eight times, precipitation is used seven times and air temperature is used in six definitions. Three definitions use an index for atmospheric evaporative demand (EDDI, ESI and ESR), satellite-based vegetation land-surface temperature, and precipitation-evaporation-based drought indices (SPEI) are each used once (see Appendix 5). Some of the indicators

Table 2. Papers that use the US Drought Monitor to identify flash drought.

Reference	Specific criteria
Pendergrass et al. (2020)	Flash drought definition 2 (application: US operations): two-category change in the USDM in 2 weeks, sustained for at least another 2 weeks
Chen et al. (2019)	"[W]e define a flash drought event as a drought event with greater than or equal to two categories degradation in a four-week period based on USDM." (p. 2)
Lorenz et al. (2018)	Generally: if the USDM is more intense in 2, 4, or 6 weeks, then they consider this a rapid-onset to the drought situation.
Ford et al. (2015)	"We define a flash drought event in the US Drought Monitor record as three category or more increase in drought severity over 8 or less weeks."(p. 9793)

used to identify flash drought are composite-indices that are formed from multiple elements (e.g. the SPEI). When considering only the base elements of indicators and indices (e.g. SPEI is separated into precipitation and evaporation), Figure 2 shows that evaporation/evapotranspiration (12 times) and soil moisture (11 times) are the most frequently used indicators of flash drought. These seem logical metrics when measuring flash drought considering that by most of the definitions considered, flash drought represents a rapid change in the available water in the landscape (whether those changes persist or not).

Only one study used SPEI (Noguera et al. 2020) and none of the definitions use the Standardized Precipitation Index (SPI) to define flash drought. Zhang et al. (2017, p. 163) claim that these indices are not appropriate for flash drought measurement "due to the relatively untimely response to monthly input data versus immediate prevailing weather conditions" [note that Zhang et al. (2017) considered flash drought to be those that persist for a short duration—days to weeks]. Otkin et al. (2013) explains that precipitation-based drought indices, such as the SPI, can miss a flash drought because precipitation deficits are only one factor contributing to their development. Flash droughts can occur even when the SPI indicates only moderate precipitation deficits. Otkin et al. (2013) further explains that the Palmer Drought Severity Index (Palmer 1965) also may not be appropriate for flash drought detection. While it uses both precipitation and temperature observations, it is more effective at identifying long-term drought conditions developing over a period of several months and may be overly sensitive to temperature effects (Otkin et al. 2013). However, both the SPI and SPEI were used by Hunt et al. (2014) in their analysis of "rapid onset drought" which demonstrated that both the 1-month SPI and the 1-month SPEI were quite sensitive to the onset of the flash drought. Hunt et al. (2014) used the Svoboda et al. (2002) description as their definition of flash drought.

There were a few studies that used indicators and indices to examine some characteristics of flash drought but did not use these as defining criteria nor categorical thresholds for flash drought identification. Most of the indicators used were also used by the papers listed in Appendix 5. A few other indicators, not listed above, include: crop condition data, cloud cover, 10-m wind speed, dewpoint depression (Otkin et al. 2013), a rapid change index for ESI, the SPI and total column soil moisture (Otkin et al. 2015a), a vegetative drought response index, dew point temperature (Otkin et al. 2016), a lower tropospheric humidity index, a convective triggering potential—similar to CAPE (Gerken et al. 2018), various remote sensing techniques including NASA's Soil Moisture Active Passive (SMAP) mission data and Satellite Solar-induced chlorophyll fluorescence (Yan

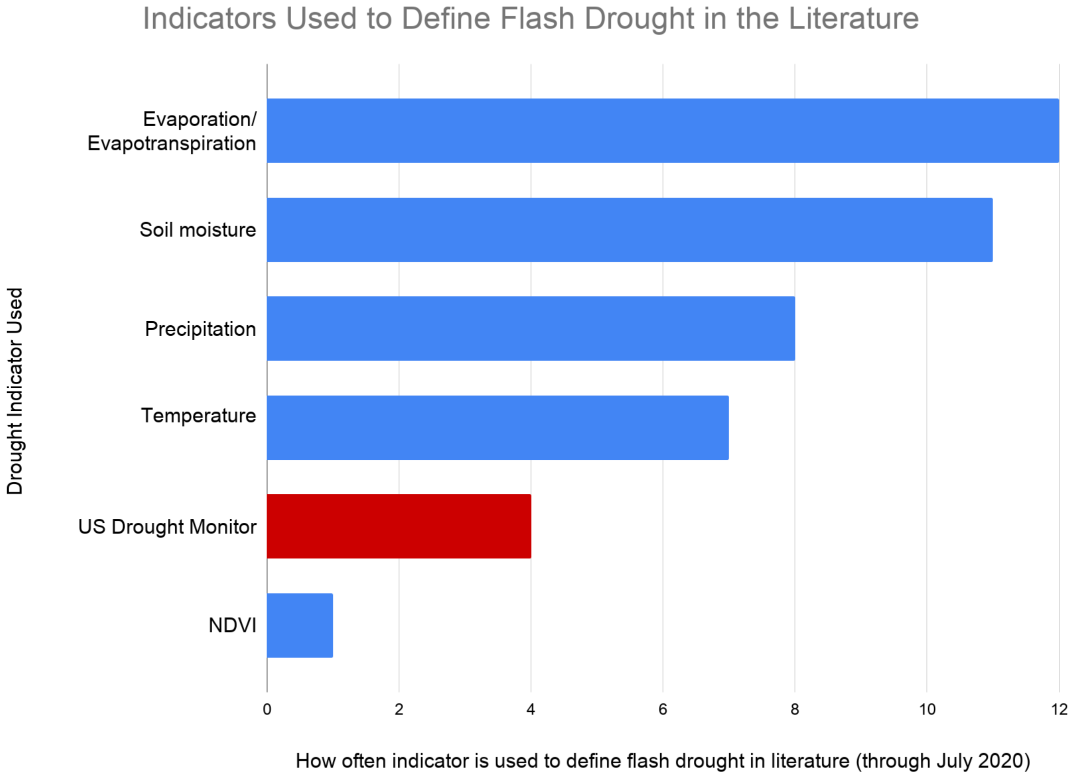

Figure 2: How often a climate indicator was used in a flash drought definition. The base elements from composite indices were counted separately. For example, the Standardized Precipitation Evaporation Index (SPEI) was used in one definition, but here evaporation and precipitation were counted as separate indicators that were combined for that definition. The US Drought Monitor is highlighted (red) because this represents a synthesis of indicators (as opposed to a single indicator) and is, therefore, different from the others on this chart.

et al. 2018; Kimball et al. 2019; and He et al. 2019). While not an exhaustive list, these papers demonstrate that flash drought can be looked at in a myriad of ways, using various indicators within the climate system, without necessarily setting terms or thresholds to diagnose a flash drought event (Zhang et al. 2020).

When considering the indicators used to define flash drought, we also considered the studies that used multiple indicators to define the phenomena (see Appendix 5 and Figure 3). Of the 20 papers cited here that defined flash drought using a set of criteria, One included four indicators, five used a combination of three indicators, five used a combination of two indicators and the remaining nine papers used a single indicator (counting the SPEI as a single indicator in this case). Of the total 20 papers, three used the US Drought Monitor, which represents a synthesis of indicators.

5. Summary and Conclusions

Given how active the flash drought research field has become, we were motivated to conduct this literature review as a way to synthesize the current research, highlight some of the questions and incongruities that exist within the literature, and provide a basis for future research on flash drought.

Since flash drought first appeared in the scientific literature in 2002 there have been 29 general descriptions and 20 papers providing defining criteria across 86 papers and 325 authors/co-authors (as of July 2020). We reviewed these definitions and grouped them by papers that provide only a general description (29 papers), papers that define flash drought by the rate of onset or intensification (11 papers), papers that consider flash droughts to be short-term drought events (8 papers), and one paper that considers both rate of onset and short-term duration. We have made these definitions available so that they can be utilized in future research.

While we have not assessed the merits or demerits of any individual criteria or method, we have noted the variety of ways that flash drought has been measured. For example, definitions that consider flash drought as a rapid-onset event include a range of onset rates from five days to eight weeks. Four papers used changes in the US Drought Monitor to define flash drought. The most common indicators of flash drought have been evaporation/evapotranspiration (12 times), soil moisture (used 11 times), precipitation (8 times) and temperature (7 times). It is clear from reviewing these papers that flash drought can be identified using a variety of indices. Despite a call in 2018 for flash drought definitions to be based on the principle of rapid-intensification (Otkin et al. 2018a), new definitions calling short-duration events a “flash drought” continue to be published. Thus, within the current understanding, the term “flash drought” could be used to mean either a drought that formed or intensified rapidly, or a drought that was intense (usually associated with a heatwave) but relatively short-lived.

Upon completing this review it is clear that there are many differences among the way the term “flash drought” has

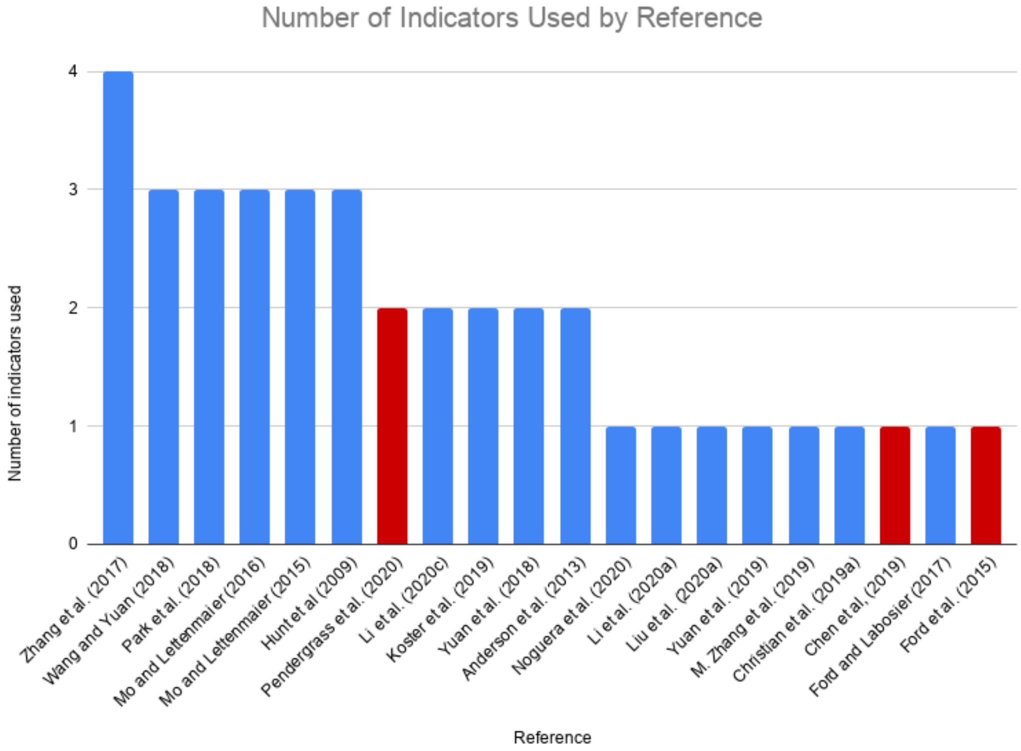

Figure 3: Number of indicators used in each flash drought definition. Red bars indicate if that definition used the US Drought Monitor, which represents a synthesis of indicators.

been used in the literature, but there are also some common themes. The first commonality being that a flash drought represents a rapid change in the available water in the landscape, whether those changes persist or not or whether those changes occur at the beginning of the drought (rapid onset) or at some point throughout the event (rapid intensification). Another theme that was sometimes explicitly stated (e.g. Anderson et al. 2015; Cook et al. 2018; Zheng et al. 2019) and other times implied (e.g. Otkin et al. 2015a; Mo and Lettenmaier 2016) is that flash drought often hits without (or with very little) warning and is often not picked up in seasonal climate forecast (e.g. PaiMazumder and Done 2016; Pendergrass et al. 2020) or by the US Drought monitor (e.g. Basara et al. 2019; Jin et al. 2019). In other words, the research commonly notes that flash drought can have dire impacts with little-to-no warning.

Given that flash drought has real relevance and implications for a wide range of resource managers, we call on flash drought researchers to be mindful that as they work to define this phenomenon they should think beyond their particular research interests to the broader societal relevance. Given the impact of flash drought on various sectors of society, this is not just a technical physical science issue.

We are not sure it is necessary (or possible) to limit flash drought to a single rigid definition with an immutable set of criteria because the methodology used should be appropriate for the question asked. However, a clear set of guidelines to distinguish flash drought events from other droughts should be agreed upon. It is the opinion of the authors that when the term "flash drought" is used, its intended meaning should be stated explicitly. We further encourage researchers to explicitly engage in discussion of how to characterize and define flash drought, both within the literature and at workshops and conferences, such as the one held by NOAA's National Integrated Drought Information System (NIDIS) in late 2020. We expect this discourse will continue within future publications, and we call on the ever-growing flash drought research community to consider methodologies and definitions that are robust, reproducible, and useful to those impacted by future flash drought events.

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APPENDICES

Appendix 1. List of generalized flash drought descriptions in chronological order.

Reference	Generic Descriptions
Peters et al. (2002)	"flash drought...combination of no precipitation and very high temperatures…" (p. 73) *Referenced by Lee and Gill (2015); Twidwell et al. (2014)*
Svoboda et al. (2002)	"flash drought...refers to rapid crop deterioration due to the adverse effects of a severe heat wave and short-term dryness, leading to a rapid onset of drought and associated impacts in agriculture, fire potential, livestock health, and other areas." (p. 1184) *Referenced by Hunt et al. (2014); Otkin et al. (2014); McEvoy et al. (2016); Cammalleri et al. (2016); Lorenz et al. (2017a); Cook et al. (2018); Bollasina and Messori (2018); Otkin et al. (2018a); Jin et al. (2019); Heim et al. (2020); Noguera et al. (2020)*
Senay et al. (2008)	"A flash drought is considered to be a short-term, yet severe event, characterized by moisture deficits and abnormally high temperatures." (Abstract) *Referenced by Hunt et al. (2009); Mozny et al. (2012) [Mozny et al. (2012) is then referenced by Otkin et al. (2013)]; Potop et al. (2014); Krueger et al. (2015); Sanchez et al. (2016)*
Anderson et al. (2011)	"…the so-called flash drought events, where prolonged hot, dry, and windy conditions lead to rapid water loss and the potential for catastrophic crop yield loss." (p. 2041)
Hunt et al. (2014)	"Short-term drought, sometimes referred to as flash drought, is a rapid onset of drought often accompanied by high temperatures and winds that lead to rapid soil moisture depletion during a critical time in the growing season (Svoboda et al. 2002)." (p. 2)
Otkin et al. (2014)	"…the term 'flash drought' has been used to better distinguish rapid-onset drought events from those that develop more slowly (e.g., Otkin et al. 2013; Svoboda et al. 2002). This Terminology captures the distinguishing characteristic of these droughts, namely, their unusually rapid rate of intensification." (p. 939)
Sun et al. (2015)	"...the 2012 drought in the central Great Plains was preceded by relatively normal precipitation and warmer surface temperature in spring followed by an abrupt rainfall reduction and abnormally high temperatures in summer, typifying a "flash" drought (Hoerling et al. 2014; Mo and Lettenmaier, 2015)." (p. 2430)
Yuan et al. (2015)	Drought (general) "is defined as the monthly soil moisture percentile is lower than 20% or the SPI-1 is less than 0.8 [Svoboda et al. 2002]." (p. 4396) Flash drought is considered a "short-term (monthly to seasonal) drought" (p. 4394)
Anderson et al. (2016)	"rapid onset – or 'flash' – drought events" (p. 83)
Brown et al. (2016)	"rapid onset droughts known as 'flash drought'...evolve in a matter of weeks and are usually characterized by a relatively short period of low rainfall combined with an extended period of anomalously high temperatures." (p. 166)
Cammalleri et al. (2016)	"rapidly occurring events of dryness that last less than 1 year" (p. 289)
Hobbins et al. (2016)	" 'Flash Drought'...i.e., fast-developing drought driven by strong, transient meteorological/radiative changes—such as increases in T_{air}, wind, or radiation, or decreases in humidity—with no substantive change in Prcp." (p. 1747)
Obringer et al. (2016)	A flash drought is a drought that occurs over a small temporal scale, often for the length of a season." (p. 750)
Sanchez et al. (2016)	"flash drought, defined as a severe, short-term event characterized by soil moisture deficit and abnormally high temperatures, thus negatively impacting vegetation conditions." (p. 1)
Hobbins et al. (2017)	"flash (or rapid onset) drought" (p. 265)
Cook et al. (2018)	"This term [Flash drought] is typically used to refer to soil moisture droughts that develop and intensify rapidly (especially over the summer), with often little or no advance warning." (p. 170)
Yao et al. (2018)	Generally: flash drought is a rapid-onset drought event

Appendix 1 Continued

Otkin et al. (2018a)	Flash Drought: "a subset of all droughts that are distinguished from more conventional slowly developing droughts by their unusually rapid rate of intensification." (p. 914) *Referenced by Otkin et al. 2018b, 2019; Basara et al. 2019; Nguyen et al. 2019; He et al. 2019; Haigh et al. 2019; Christian et al. 2019a, b)*
Lorenz et al. (2018)	Generally: if the US Drought Monitor is more intense in 2, 4, or 6 weeks then the authors considered this a rapid onset to the drought situation.
Gerken et al. (2018)	Described "rapid onset" droughts, and in the case study used the Northern Great Plains 2017 drought which set in over 2-to-4 months depending on the location.
Vogt et al. (2018)	Describes flash drought as one that lasts less than 3 months
Hoell et al. (2019)	Described the 2017 Northern Great Plains drought as a "rapid" decrease in soil moisture, leading to agricultural drought that ended only three months after it began.
Jin et al. (2019)	"short-term drought events with a rapid on-set and intensification rate (Svoboda et al. 2002)." (p. 769)
Han et al. (2019)	"The concurrent drought and heatwave events with low soil moisture...and high ET are recently termed as 'flash drought' (Yuan et al. 2015)." (p. 7)
Zheng et al. (2019)	"Flash drought refers to relatively short periods of warm surface temperature and anomalously low and rapid decreasing soil moisture (Mo and Lettenmaier 2016). Compared with traditional slow-onset and long-term droughts, flash droughts are unexpected and bring a grand challenge for early warning due to limited prior external signals, as well as lead to devastating impacts on crop yields and water supply (Wang et al. 2016)." (p. 441)
Haile et al. (2020)	"Flash droughts are short term, rapidly evolving drought events during crop growing seasons, occurring simultaneously with unusually high temperature (Yuan, Ma, Pan, & Shi, 2015)." (p. 8)
H. Zhang et al. (2020)	"Flash drought is a short-term drought event that develops rapidly in association with a high-temperature heat wave. It occurs suddenly with fast development and high intensity, posing a serious threat to crop yield and water supply." (p. 470)
Stojanovic et al. (2020)	Flash droughts: "episodes with sudden onset and a short duration, e.g., 1 or 2 months" (p. 12)
Trnka et al. (2020)	"flash drought events, that is, sharp intensification of lower intensity droughts occurring in the space of days or weeks" (p. 5942)

Appendix 2. List of flash drought definitions based on the rate of onset, in chronological order.

Reference	Onset rate criteria
Anderson et al. (2013)	*Flash drought* was not explicitly defined, but the authors looked for periods when changes in Evaporative Stress Index (ESI) and Soil Moisture (SM) occurring over a 4-week interval were strong (>1.5 standard deviations).
Ford et al. (2015)	"We define a flash drought event in the USDM record as three category or more increase in drought severity over 8 or less weeks." (p. 9793)
Ford and Labosier (2017)	Flash Drought is when "the pentad-average 0–40 cm soil moisture percentile at a station declines from at or above the 40th percentile to at or below the 20th percentile in 4 pentads or less." (p. 417)
Park et al. (2018)	Examined three satellite-based drought indices (details given in the paper): 1) The scaled drought condition index (SDCI) 2) Microwave integrated drought index (MIDI) 3) Very short-term drought index (VSDI), When any of these three indices dropped below 0.4 for even only one pentad (5 day period), the authors considered this a "dry period." While the authors did not define "flash drought," they conclude that the VSDI would be good for identifying "flash droughts caused by a rapid rate of intensification."

APPENDIX 2 CONTINUED

Koster et al. (2019)	Based on Ford and Labosier (2017) definition but with the following additional constraints: 1) “A drought event has to lead to at least a nominal reduction in ET and thereby reflect some moisture stress on the land system…The ‘nominal reduction’ enforced here focuses on ET in the 20 days prior and in the 20 days after the 20-day soil moisture reduction period—ET in the prior period must lie at or above four-fifths of the climatological mean value for that time of year..., and ET in the latter period must lie at or below three-fifths of the climatological mean value for that later time of year.” 2) “Independence of drought events is ensured by not allowing identified drought events...to overlap in time.” 3) “The final constraint is that the climatological ET during the 20-day soil moisture reduction period lies above 0.5 mm/day. This condition is imposed because ... soil moisture percentile in dry regions is overly sensitive to meteorological drivers.” (p. 1245)
Christian et al. (2019a)	Based on the principles outlined in (Otkin et al. 2018a): The data used include pentad values of Standardized Evaporative Stress Ratio: SESR = ET/PET which is standardized for each grid point and pentad using the z-score minus the mean and the difference divided by the standard deviation. In this methodology, flash drought events are required to have: 1) a minimum length of five SESR changes (ΔSESR), equivalent to a length of six pentads (30 days); 2) a final SESR value below the 20th percentile of SESR values; 3) pentad-to-pentad changes toward drought development: a) ΔSESR must be at or below the 40th percentile between individual pentads, and b) no more than one ΔSESR above the 40th percentile following a ΔSESR that meets criterion 3a; 4) development through the entirety of the flash drought event...[i.e.] the mean change in SESR during the entire length of the flash drought must be less than the 25th percentile of the climatological changes in SESR for that grid point and time of year. *Referenced by Christian et al. (2019b); Basara et al. (2019)*
Chen et al. (2019)	“[W]e define a flash drought event as a drought event with greater than or equal to two categories degradation in a four-week period based on USDM." (p. 2)
Yuan et al. (2019)	Flash Drought is identified when "the pentad (5 days) mean root-zone (top 1 m) soil moisture decreases from above 40th percentile to 20th percentile, with an average decline rate of no less than 5% in percentile for each pentad...if the declined soil moisture rises up to 20th percentile again, the drought terminates... the drought should last for at least 3 pentads (15 days)." (p. 2)
Liu et al. (2020a)	A drought event (of any kind) is identified when the soil moisture falls below the 40th percentile, and at some point, within the drought event the soil moisture must fall below the 20th percentile (as in Ford and Labosier 2017). A flash drought event is identified using a Rate of Intensification index (RI), which is the rate of change in soil moisture percentiles (P) per week. RI is measured during the onset-development phase of any drought. A flash drought is defined as: mean RI > 6.5 P/week, or max RI > 10 P/week *Referenced by Liu et al. (2020b)*
Pendergrass et al. (2020)[11]	• **Flash drought definition 1** (applications: international operations, prediction, research): 50% increase in EDDI (toward drying) over two weeks, sustained for at least another two weeks • **Flash drought definition 2** (application: US operations): two-category change in the U.S. Drought Monitor (USDM) in 2 weeks, sustained for at least another 2 weeks

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[11] *These proposed definitions were developed by the attendees of the Aspen Global Change Institute (AGCI) workshop that took place in September 2018.*

Appendix 2 Continued

Noguera et al. (2020)	Using the Standardised Precipitation Evaporation Index (SPEI; Vicente-Serrano et al. 2010), they stated: "...the criteria selected to record the occurrence of a flash drought were: 1. A minimum length of 4 weeks in the development phase. 2. A ΔSPEI value equal to or less than –2 z-units. 3. A final SPEI value equal to or less than –1.28 z-units." (p. 157)

Appendix 3. List of flash drought definitions that consider only short-term drought events, in chronological order.

Reference	Short-duration criteria
Hunt et al. (2009)	"...a severe, short-term event characterized by moisture deficits and abnormally high temperatures...a flash drought is the result of a synoptic meteorological pattern where potential ET greatly exceeds precipitation for a period no less than 3 weeks such that available water in a previously moist (0–50 cm) soil profile decreases by more than 50%." (p. 757) *Referenced by: Mozny et al. (2012); Mo and Lettenmaier (2015); Krueger et al. (2015); Sanchez et al. (2016)*
Mo and Lettenmaier (2015)	**Heat wave flash droughts**: T_{air} anomaly > one standard deviation computed from the base period for that pentad, ET anomaly > 0, and Soil Moisture %ile < 40. *Referenced by Mo and Lettenmaier (2016); Zhang et al. (2017); Koster et al. (2017); Rupp et al. 2017; Wang and Yuan (2018); Poshtiri et al. (2018); H. Zhang et al. (2019); Kim et al. 2019; Ran et al. (2020); Zhang et al. (2020)*
Mo and Lettenmaier (2016)	**Precipitation deficit flash drought**: T_{air} anomaly > one standard deviation; ET anomaly < 0, Precip %ile < 40% Applies only to grid points with pentad Precip climatology greater than 0.2 mm/day to distinguish P-deficit flash droughts from monsoon onset conditions. *Referenced by Zhang et al. (2017); Wang and Yuan (2018); Cook et al. (2018); Ran et al. (2020); Zhang et al. (2020)*
Zhang et al. (2017)	Adapted from Mo and Lettenmaier (2015, 2016) For each grid and pentad: • a *Heat Wave Flash Drought* event is defined as the conditions under which the maximum temperature anomaly is greater than one standard deviation, the evapotranspiration anomaly is in positive phase, and the soil moisture percentile is lower than 40%; • a *Precipitation Deficit Flash Drought* event is defined by maximum temperature anomaly greater than one standard deviation, evapotranspiration anomaly in negative phase, and precipitation percentile below 40%. *Referenced by Zhang et al. (2018); Li et al. (2020b)*
Yuan et al. (2018)	For each grid point and each pentad, a flash drought is defined as pentad-mean surface air temperature anomaly is larger than one standard deviation, the percentile of target pentad-mean soil moisture is lower than 40%, and the soil moisture percentile of target pentad is at least 10% lower than the preceding pentad.

Appendix 3 Continued

Wang and Yuan (2018)	Adapted from Mo and Lettenmaier (2015, 2016) Defined two types of flash drought: (1) FD Type I : $T_{ano} > T_{std}$, $ET_{ano} > 0$, $q(\theta_{pentad}) < 30\%$ (2) FD Type II : $T_{ano} > T_{std}$, $ET_{ano} < 0$, $q(\theta_{pentad}) < 30\%$ Where: T_{ano} (∘C) = anomaly for the pentad-mean surface air temperature T_{std} (∘C) = standard deviation of the T_{ano} time series ET_{ano} (mm/d) = anomaly for the pentad-mean ET $q(\theta_{pentad})$ = pentad-mean soil moisture quantile values (%)
M. Zhang et al. (2019)	This definition was created specifically for Shanchuan town, Anji County, Zhejiang Province, China, based on the local seasonality and climatology of rainfall at that location. It provides an example of a locally adapted definition of flash drought. "A flash-drought event is defined as when the monthly [July or August] rainfall is less than 100 mm." (p. 2)
Li et al. (2020c)	While not using the term “flash drought” this paper references other flash drought papers to define “... short-term droughts lasting a few weeks or even days (Mo and Lettenmaier 2015, 2016; Ford et al. 2015; Otkin et al. 2015, 2016, 2018).”(p. 892) Using the standardized antecedent precipitation evapotranspiration index (SAPEI) this paper defines a “short-term drought” during the growing season (April–September) as: 1) grid points with daily SAPEI <-1 2) The area with SAPEI <-1 covers at least 1.6% of the study region 3) Drought patches that overlap from one day to the next were considered one event 4) The total event lasts for 2–4 weeks

Appendix 4. List of flash drought definitions that require a flash drought event to have both a rapid-onset and a short-duration.

Reference	Rapid-onset and short-duration criteria
Li et al. (2020a)	Using a standardized evapotranspiration deficit index (SEDI) flash drought identification follows three criteria: • The duration is longer than five pentads but shorter than twelve pentads. • The instantaneous intensification rate of the cumulative SEDI is at or below the 25% of cumulative distribution frequency of the change in the cumulative SEDI during flash drought development. • Average instantaneous intensification rate during flash drought development phase is at or below the 40% of cumulative distribution frequency of the change in the cumulative SEDI during flash drought development.

Appendix 5. List of indicator or indicator-types used in each flash drought definition.

Reference	Indicator Used
Noguera et al. (2020)	SPEI
Pendergrass et al. (2020)	EDDI US Drought Monitor
Li et al. (2020a)	Evapotranspiration
Li et al. (2020c)	Precipitation Evapotranspiration
Liu et al. (2020a)	Soil moisture
Koster et al. (2019)	Soil moisture Evapotranspiration

Appendix 5 Continued

Yuan et al. (2019)	Soil moisture
M. Zhang et al. (2019)	Precipitation
Christian et al. (2019a)	Standardized Evaporative Stress Ratio: ESR = ET/PET
Chen et al, (2019)	US Drought Monitor
Wang and Yuan (2018)	Air temperature Evapotranspiration Soil moisture
Park et al. (2018)	Three satellite-based drought indices use the combinations of the following data: • Land surface temperature • Normalized difference vegetation index • Tropical Rainfall Measuring Mission precipitation • Soil moisture
Yuan et al. (2018)	Air temperature Soil moisture
Ford and Labosier (2017)	Soil moisture
Zhang et al. (2017)	Air temperature Evapotranspiration Soil moisture Precipitation
Mo and Lettenmaier (2016)	Air temperature Evapotranspiration Precipitation
Mo and Lettenmaier (2015)	Air temperature Evapotranspiration Soil moisture
Ford et al. (2015)	US Drought Monitor
Anderson et al. (2013)	Soil moisture changes Evaporative Stress Index (ESI=ET/F_{ref} , where F_{ref} is a scaling flux)
Hunt et al (2009)	PET precipitation soil moisture

APPENDIX B: CORRELATION TABLE

The table included in this appendix shows the calculated correlation coefficients of 11 monsoon onset definitions and various large-scale climate influences. This was used in the analysis for Lisonbee and Ribbe (2021), but was not included in that publication due to length restrictions. The table rows are labelled as: “abbreviated index_time period”. The index abbreviations are shown in Chapter 3, Table 2 (Lisonbee and Ribbe 2021) and the time period represents the first letter of each month included (e.g., JJA = June, July, August; JAS = July, August, September and so forth). Single months are abbreviated using the first three letters of the month. Detrended datasets are noted by the abbreviation “dt”. The suffix “4max”, “4min”, and “gen” indicates the 4-month (SOND) maximum, minimum, and an indication of if a threshold was met at least once within the 4-month period, respectively. The values labelled with “ρ” signify a Pearson Correlation Coefficient while values labelled with “τ” signify a Kendall’s Tao Correlation Coefficient. Bolded values signify correlations with statistical significance at the 95% confidence interval.

Table 1 Calculated correlation coefficients of 11 monsoon onset definitions and various large-scale climate influences which was used in the analysis for Lisonbee and Ribbe (2021).

	Troup (1961) RAIN	Troup (1961) WIND	Troup (1961)	Hendon and Liebmann (1990)	Nichols (1984)	Smith et al. (2008)	Holland (1986)	Murakami and Sumi (1982)	Drosdowsky (1996)	Hung and Yanai (2004)	Davidson et al. (2007)	Kajikawa et al. 2010	Zhang et al. (2010)
NINO1.2_JJA	τ = 0.060	**τ = 0.182**	τ = 0.080	τ = 0.114	τ = 0.148	τ = 0.138	τ = 0.033	τ = 0.052	τ = 0.123	τ = 0.027	τ = 0.137	τ = 0.071	τ = -0.05
NINO1.2_JAS	τ = 0.032	τ = 0.134	τ = 0.093	τ = 0.121	**τ = 0.201**	τ = 0.156	τ = 0.035	τ = 0.053	τ = 0.112	τ = 0.047	τ = 0.138	τ = 0.099	τ = -0.02
NINO1.2_ASO	τ = 0.030	τ = 0.104	τ = 0.060	τ = 0.128	**τ = 0.270**	**τ = 0.184**	τ = 0.041	τ = 0.089	τ = 0.103	τ = 0.064	τ = 0.153	τ = 0.118	τ = 0.027
NINO1.2_SON	τ = 0.052	τ = 0.115	τ = 0.042	τ = 0.134	**τ = 0.352**	**τ = 0.174**	τ = 0.063	τ = 0.128	τ = 0.119	τ = 0.058	**τ = 0.165**	τ = 0.160	τ = 0.058
NINO3_JJA	ρ = 0.116	ρ = 0.192	ρ = 0.116	ρ = 0.226	**ρ = 0.433**	**ρ = 0.295**	ρ = 0.113	ρ = 0.186	**ρ = 0.249**	ρ = 0.065	**ρ = 0.244**	ρ = 0.231	ρ = 0.035
NINO3_JAS	τ = 0.090	τ = 0.138	τ = 0.103	**τ = 0.192**	**τ = 0.354**	**τ = 0.227**	τ = 0.074	τ = 0.152	**τ = 0.168**	τ = 0.096	**τ = 0.202**	**τ = 0.185**	τ = 0.124
NINO3_ASO	τ = 0.095	τ = 0.123	τ = 0.064	**τ = 0.180**	**τ = 0.362**	**τ = 0.230**	τ = 0.067	τ = 0.160	**τ = 0.163**	τ = 0.094	**τ = 0.191**	**τ = 0.175**	τ = 0.138
NINO3_SON	τ = 0.088	τ = 0.125	τ = 0.033	**τ = 0.170**	**τ = 0.393**	**τ = 0.220**	τ = 0.073	**τ = 0.176**	**τ = 0.172**	τ = 0.106	**τ = 0.178**	**τ = 0.205**	τ = 0.175
NINO3.4_JJA	ρ = 0.091	ρ = 0.102	ρ = 0.029	**ρ = 0.274**	**ρ = 0.577**	**ρ = 0.279**	ρ = 0.172	**ρ = 0.241**	**ρ = 0.316**	ρ = 0.123	**ρ = 0.266**	**ρ = 0.358**	ρ = 0.201
NINO3.4_JAS	ρ = 0.081	ρ = 0.121	ρ = 0.046	**ρ = 0.281**	**ρ = 0.572**	**ρ = 0.286**	ρ = 0.154	**ρ = 0.240**	**ρ = 0.294**	ρ = 0.124	ρ = 0.231	**ρ = 0.340**	ρ = 0.180
NINO3.4_ASO	ρ = 0.108	ρ = 0.145	ρ = 0.060	**ρ = 0.283**	**ρ = 0.571**	**ρ = 0.287**	ρ = 0.148	**ρ = 0.247**	**ρ = 0.291**	ρ = 0.128	ρ = 0.222	**ρ = 0.335**	ρ = 0.160
NINO3.4_SON	ρ = 0.136	ρ = 0.163	ρ = 0.070	**ρ = 0.287**	**ρ = 0.582**	**ρ = 0.274**	ρ = 0.156	**ρ = 0.264**	**ρ = 0.305**	ρ = 0.143	ρ = 0.230	**ρ = 0.357**	ρ = 0.189
NINO3.4_dt_JJA	ρ = 0.087	ρ = 0.114	ρ = 0.017	**ρ = 0.291**	**ρ = 0.623**	**ρ = 0.250**	ρ = 0.188	**ρ = 0.265**	**ρ = 0.326**	ρ = 0.157	**ρ = 0.310**	**ρ = 0.414**	ρ = 0.260
NINO3.4_dt_JAS	ρ = 0.076	ρ = 0.133	ρ = 0.037	**ρ = 0.296**	**ρ = 0.612**	**ρ = 0.259**	ρ = 0.165	**ρ = 0.260**	**ρ = 0.301**	ρ = 0.154	**ρ = 0.269**	**ρ = 0.388**	ρ = 0.233
NINO3.4_dt_ASO	ρ = 0.106	ρ = 0.156	ρ = 0.052	**ρ = 0.295**	**ρ = 0.606**	**ρ = 0.263**	ρ = 0.158	**ρ = 0.265**	**ρ = 0.297**	ρ = 0.155	**ρ = 0.255**	**ρ = 0.377**	ρ = 0.207
NINO3.4_dt_SON	ρ = 0.135	ρ = 0.174	ρ = 0.064	**ρ = 0.298**	**ρ = 0.613**	**ρ = 0.252**	ρ = 0.166	**ρ = 0.280**	**ρ = 0.311**	ρ = 0.167	**ρ = 0.259**	**ρ = 0.395**	ρ = 0.231
NINO4_JJA	ρ = 0.124	ρ = 0.007	ρ = -0.04	**ρ = 0.261**	**ρ = 0.553**	ρ = 0.175	ρ = 0.203	ρ = 0.195	**ρ = 0.317**	ρ = 0.084	ρ = 0.213	**ρ = 0.335**	ρ = 0.145
NINO4_JAS	ρ = 0.101	ρ = 0.039	ρ = 0.000	**ρ = 0.310**	**ρ = 0.575**	ρ = 0.203	ρ = 0.208	**ρ = 0.259**	**ρ = 0.341**	ρ = 0.116	**ρ = 0.236**	**ρ = 0.334**	ρ = 0.145
NINO4_ASO	ρ = 0.103	ρ = 0.068	ρ = 0.025	**ρ = 0.322**	**ρ = 0.600**	**ρ = 0.237**	ρ = 0.199	**ρ = 0.298**	**ρ = 0.352**	ρ = 0.141	**ρ = 0.263**	**ρ = 0.336**	ρ = 0.164
NINO4_SON	ρ = 0.122	ρ = 0.094	ρ = 0.033	**ρ = 0.332**	**ρ = 0.633**	**ρ = 0.253**	ρ = 0.202	**ρ = 0.325**	**ρ = 0.371**	ρ = 0.165	**ρ = 0.290**	**ρ = 0.356**	ρ = 0.199
NINO4_dt_JAS	ρ = 0.102	ρ = 0.065	ρ = -0.02	**ρ = 0.366**	**ρ = 0.702**	ρ = 0.150	**ρ = 0.252**	**ρ = 0.324**	**ρ = 0.383**	ρ = 0.192	**ρ = 0.337**	**ρ = 0.465**	ρ = 0.265
NINO4_dt_ASO	ρ = 0.052	ρ = 0.038	ρ = 0.091	ρ = 0.080	ρ = 0.121	**ρ = 0.258**	ρ = 0.008	ρ = 0.099	ρ = 0.115	ρ = -0.01	ρ = 0.001	ρ = -0.05	ρ = -0.18
NINO4_dt_SON	τ = 0.138	τ = 0.094	τ = 0.002	**τ = 0.230**	**τ = 0.490**	**τ = 0.194**	τ = 0.156	**τ = 0.218**	**τ = 0.234**	**τ = 0.180**	**τ = 0.233**	**τ = 0.289**	**τ = 0.296**
modoki_JJA	**τ = 0.164**	**τ = -0.18**	τ = -0.02	τ = 0.065	**τ = 0.322**	τ = 0.043	τ = 0.096	τ = 0.074	τ = 0.151	τ = 0.159	τ = 0.111	**τ = 0.237**	**τ = 0.277**
modoki_JAS	**τ = 0.172**	τ = -0.14	τ = -0.00	τ = 0.133	**τ = 0.352**	τ = 0.056	τ = 0.109	τ = 0.135	**τ = 0.201**	**τ = 0.189**	**τ = 0.181**	**τ = 0.228**	**τ = 0.281**
modoki_ASO	τ = 0.146	τ = -0.08	τ = -0.01	**τ = 0.181**	**τ = 0.401**	τ = 0.114	τ = 0.143	**τ = 0.194**	**τ = 0.274**	**τ = 0.227**	**τ = 0.236**	**τ = 0.264**	**τ = 0.347**
modoki_SON	τ = 0.125	τ = -0.05	τ = -0.00	**τ = 0.199**	**τ = 0.449**	τ = 0.161	τ = 0.144	**τ = 0.226**	**τ = 0.308**	**τ = 0.257**	**τ = 0.259**	**τ = 0.262**	**τ = 0.404**
SOI_JJA	ρ = -0.18	ρ = -0.21	ρ = -0.16	**ρ = -0.28**	**ρ = -0.51**	**ρ = -0.35**	ρ = -0.16	ρ = -0.17	**ρ = -0.24**	ρ = -0.15	**ρ = -0.24**	**ρ = -0.36**	ρ = -0.04
SOI_JAS	ρ = -0.21	ρ = -0.21	ρ = -0.09	**ρ = -0.32**	**ρ = -0.58**	**ρ = -0.33**	ρ = -0.17	ρ = -0.22	**ρ = -0.29**	ρ = -0.22	**ρ = -0.28**	**ρ = -0.41**	ρ = -0.14
SOI_ASO	ρ = -0.19	ρ = -0.22	ρ = -0.09	**ρ = -0.33**	**ρ = -0.59**	**ρ = -0.28**	ρ = -0.18	**ρ = -0.29**	**ρ = -0.32**	ρ = -0.23	**ρ = -0.33**	**ρ = -0.42**	ρ = -0.17

	Troup (1961) RAIN	Troup (1961) WIND	Troup (1961)	Hendon and Liebmann (1990)	Nichols (1984)	Smith et al. (2008)	Holland (1986)	Murakami and Sumi (1982)	Drosdowsky (1996)	Hung and Yanai (2004)	Davidson et al. (2007)	Kajikawa et al. 2010	Zhang et al. (2010)
SOI_SON	ρ = -0.20	ρ = -0.18	ρ = -0.07	**ρ = -0.34**	**ρ = -0.60**	ρ = -0.20	ρ = -0.20	**ρ = -0.29**	**ρ = -0.39**	ρ = -0.22	**ρ = -0.34**	**ρ = -0.48**	ρ = -0.28
IOD_JJA	ρ = 0.109	ρ = 0.230	ρ = 0.244	ρ = 0.161	ρ = 0.155	**ρ = 0.279**	ρ = 0.152	ρ = 0.063	ρ = 0.201	ρ = 0.126	ρ = -0.00	ρ = 0.141	ρ = 0.017
IOD_JAS	ρ = 0.130	ρ = 0.181	ρ = 0.210	**ρ = 0.244**	ρ = 0.229	**ρ = 0.264**	ρ = 0.186	ρ = 0.158	**ρ = 0.261**	ρ = 0.186	ρ = 0.073	ρ = 0.201	ρ = 0.084
IOD_ASO	ρ = 0.128	ρ = 0.139	ρ = 0.135	**ρ = 0.275**	**ρ = 0.305**	**ρ = 0.274**	ρ = 0.200	ρ = 0.223	**ρ = 0.306**	ρ = 0.205	ρ = 0.117	**ρ = 0.260**	ρ = 0.136
IOD_SON	ρ = 0.145	ρ = 0.161	ρ = 0.087	**ρ = 0.275**	**ρ = 0.331**	**ρ = 0.254**	ρ = 0.204	**ρ = 0.261**	**ρ = 0.320**	ρ = 0.208	ρ = 0.140	**ρ = 0.271**	ρ = 0.123
IOD_dt_JJA	ρ = 0.109	**ρ = 0.274**	ρ = 0.246	ρ = 0.191	ρ = 0.214	**ρ = 0.235**	ρ = 0.183	ρ = 0.097	ρ = 0.221	ρ = 0.192	ρ = 0.055	ρ = 0.233	ρ = 0.109
IOD_dt_JAS	ρ = 0.133	ρ = 0.221	ρ = 0.211	**ρ = 0.285**	**ρ = 0.300**	ρ = 0.219	ρ = 0.222	ρ = 0.203	**ρ = 0.289**	**ρ = 0.262**	ρ = 0.146	**ρ = 0.303**	ρ = 0.182
IOD_dt_ASO	ρ = 0.131	ρ = 0.177	ρ = 0.129	**ρ = 0.322**	**ρ = 0.388**	ρ = 0.231	**ρ = 0.239**	**ρ = 0.279**	**ρ = 0.341**	**ρ = 0.285**	ρ = 0.196	**ρ = 0.373**	ρ = 0.235
IOD_dt_SON	τ = 0.108	τ = 0.120	τ = 0.022	**τ = 0.225**	**τ = 0.314**	**τ = 0.172**	**τ = 0.167**	**τ = 0.208**	**τ = 0.237**	**τ = 0.228**	**τ = 0.235**	**τ = 0.264**	τ = 0.192
IOD_Sep	ρ = 0.154	ρ = 0.120	ρ = 0.136	**ρ = 0.303**	**ρ = 0.334**	**ρ = 0.258**	ρ = 0.212	**ρ = 0.243**	**ρ = 0.331**	ρ = 0.212	ρ = 0.146	**ρ = 0.279**	ρ = 0.134
IOD_dt_Sep	ρ = 0.162	ρ = 0.153	ρ = 0.128	**ρ = 0.355**	**ρ = 0.432**	ρ = 0.210	**ρ = 0.255**	**ρ = 0.296**	**ρ = 0.368**	**ρ = 0.295**	ρ = 0.229	**ρ = 0.396**	ρ = 0.249
IOD_Oct	ρ = 0.130	ρ = 0.130	ρ = 0.078	**ρ = 0.253**	**ρ = 0.352**	**ρ = 0.293**	ρ = 0.188	**ρ = 0.249**	**ρ = 0.316**	ρ = 0.180	ρ = 0.133	**ρ = 0.258**	ρ = 0.123
IOD_dt_Oct	τ = 0.105	τ = 0.091	τ = 0.008	**τ = 0.199**	**τ = 0.332**	**τ = 0.192**	τ = 0.149	**τ = 0.198**	**τ = 0.221**	**τ = 0.200**	**τ = 0.200**	**τ = 0.254**	τ = 0.196
IOD_Nov	τ = 0.096	τ = 0.146	τ = -0.00	τ = 0.147	**τ = 0.204**	τ = 0.135	τ = 0.113	**τ = 0.163**	**τ = 0.175**	**τ = 0.205**	τ = 0.157	τ = 0.160	τ = 0.090
IOD_dt_Nov	τ = 0.098	τ = 0.155	τ = -0.05	τ = 0.151	**τ = 0.195**	τ = 0.082	τ = 0.118	**τ = 0.174**	**τ = 0.177**	**τ = 0.207**	**τ = 0.186**	**τ = 0.202**	τ = 0.105
IOD_Dec	ρ = -0.05	ρ = 0.091	ρ = -0.21	ρ = -0.03	ρ = 0.178	ρ = 0.077	ρ = -0.03	ρ = 0.060	ρ = 0.036	ρ = 0.027	ρ = -0.10	ρ = -0.02	ρ = -0.02
IOD_dt_Dec	τ = -0.06	τ = 0.010	τ = -0.15	τ = -0.05	**τ = 0.172**	τ = 0.007	τ = -0.05	τ = 0.045	τ = 0.023	τ = 0.022	τ = -0.02	τ = 0.004	τ = -0.00
IOD_4max	τ = 0.022	τ = 0.074	τ = -0.00	τ = 0.116	**τ = 0.195**	τ = 0.125	τ = 0.080	τ = 0.131	**τ = 0.176**	τ = 0.139	τ = 0.103	τ = 0.138	τ = 0.049
IOD_4min	ρ = 0.113	ρ = 0.170	ρ = 0.058	**ρ = 0.256**	**ρ = 0.352**	ρ = 0.233	ρ = 0.164	**ρ = 0.264**	**ρ = 0.280**	**ρ = 0.252**	ρ = 0.136	**ρ = 0.236**	ρ = 0.135
IOD_gen	τ = 0.117	τ = 0.121	τ = 0.107	**τ = 0.187**	**τ = 0.274**	**τ = 0.198**	τ = 0.121	**τ = 0.175**	**τ = 0.193**	**τ = 0.194**	τ = 0.139	**τ = 0.205**	ρ = 0.109
IO_BASIN_JJA	ρ = 0.053	ρ = -0.05	ρ = 0.048	ρ = -0.10	ρ = -0.11	ρ = 0.159	ρ = -0.01	ρ = -0.12	ρ = -0.07	ρ = -0.19	ρ = -0.17	ρ = -0.22	**ρ = -0.53**
IO_BASIN_JAS	ρ = 0.017	ρ = -0.05	ρ = 0.053	ρ = -0.10	ρ = -0.12	ρ = 0.176	ρ = -0.03	ρ = -0.12	ρ = -0.10	ρ = -0.19	ρ = -0.20	**ρ = -0.25**	**ρ = -0.56**
IO_BASIN_ASO	ρ = -0.00	ρ = -0.02	ρ = 0.057	ρ = -0.07	ρ = -0.08	ρ = 0.199	ρ = -0.01	ρ = -0.07	ρ = -0.08	ρ = -0.16	ρ = -0.19	**ρ = -0.23**	**ρ = -0.53**
IO_BASIN_SON	ρ = 0.013	ρ = 0.010	ρ = 0.074	ρ = -0.00	ρ = -0.00	ρ = 0.226	ρ = 0.022	ρ = 0.006	ρ = -0.04	ρ = -0.10	ρ = -0.14	ρ = -0.17	**ρ = -0.44**
IO_BASIN_OND	ρ = 0.054	ρ = 0.057	ρ = 0.087	ρ = 0.091	ρ = 0.096	**ρ = 0.253**	ρ = 0.084	ρ = 0.082	ρ = 0.036	ρ = -0.02	ρ = -0.06	ρ = -0.06	**ρ = -0.30**
QBO_JJA	τ = -0.01	τ = 0.202	τ = 0.163	τ = 0.091	τ = -0.04	τ = 0.022	τ = 0.110	τ = 0.146	τ = 0.011	τ = 0.139	τ = 0.172	τ = 0.031	τ = -0.04
QBO_JAS	τ = 0.005	τ = 0.210	τ = 0.133	τ = 0.091	τ = -0.01	τ = 0.071	τ = 0.110	τ = 0.132	τ = -0.03	τ = 0.155	τ = 0.125	τ = 0.031	τ = -0.00
QBO_ASO	τ = 0.025	τ = 0.182	τ = 0.089	τ = 0.060	τ = 0.016	τ = 0.076	τ = 0.084	τ = 0.092	τ = -0.08	τ = 0.111	τ = 0.071	τ = -0.02	τ = 0.023
QBO_SON	τ = 0.052	τ = 0.165	τ = 0.054	τ = 0.052	τ = -0.01	τ = 0.097	τ = 0.078	τ = 0.063	τ = -0.09	τ = 0.089	τ = 0.056	τ = -0.02	τ = -0.00
QBO1_JJA	τ = -0.01	τ = 0.189	τ = 0.163	τ = 0.067	τ = -0.04	τ = 0.022	τ = 0.100	τ = 0.113	τ = -0.01	τ = 0.111	τ = 0.144	τ = -0.00	τ = -0.04
QBO1_JAS	τ = 0.005	τ = 0.207	τ = 0.133	τ = 0.082	τ = -0.01	τ = 0.071	τ = 0.110	τ = 0.122	τ = -0.04	τ = 0.141	τ = 0.113	τ = 0.019	τ = -0.00
QBO1_ASO	τ = 0.025	τ = 0.210	τ = 0.089	τ = 0.084	τ = 0.016	τ = 0.076	τ = 0.105	τ = 0.129	τ = -0.05	τ = 0.144	τ = 0.108	τ = 0.015	τ = 0.023
QBO1_SON	τ = 0.059	τ = 0.202	τ = 0.064	τ = 0.074	τ = -0.00	τ = 0.095	τ = 0.098	τ = 0.101	τ = -0.05	τ = 0.127	τ = 0.099	τ = 0.010	τ = -0.00

	Troup (1961) RAIN	Troup (1961) WIND	Troup (1961)	Hendon and Liebmann (1990)	Nichols (1984)	Smith et al. (2008)	Holland (1986)	Murakami and Sumi (1982)	Drosdowsky (1996)	Hung and Yanai (2004)	Davidson et al. (2007)	Kajikawa et al. 2010	Zhang et al. (2010)
AO_JJA	ρ = 0.085	ρ = -0.14	ρ = 0.086	ρ = -0.12	ρ = -0.02	ρ = -0.06	ρ = -0.12	ρ = -0.08	ρ = -0.07	ρ = 0.065	ρ = -0.08	ρ = -0.14	ρ = -0.02
AO_JAS	ρ = 0.141	ρ = -0.17	ρ = 0.083	ρ = -0.09	ρ = -0.09	ρ = -0.06	ρ = -0.15	ρ = -0.12	ρ = -0.08	ρ = 0.042	ρ = -0.10	ρ = -0.08	ρ = -0.24
AO_ASO	ρ = 0.146	ρ = -0.21	ρ = 0.057	ρ = -0.13	ρ = -0.16	ρ = -0.16	ρ = -0.22	ρ = -0.15	ρ = -0.11	ρ = 0.019	ρ = -0.15	ρ = -0.16	ρ = -0.16
AO_SON	ρ = 0.173	ρ = -0.12	ρ = -0.00	ρ = -0.04	ρ = -0.14	ρ = -0.21	ρ = -0.04	ρ = -0.06	ρ = -0.14	ρ = 0.044	ρ = -0.06	ρ = -0.11	ρ = 0.092
M_SAM_JJA	ρ = 0.066	ρ = 0.111	ρ = 0.105	ρ = 0.168	ρ = 0.072	**ρ = 0.376**	ρ = 0.106	**ρ = 0.279**	ρ = 0.020	ρ = 0.226	ρ = 0.215	ρ = -0.05	ρ = -0.24
M_SAM_JAS	ρ = 0.191	ρ = 0.110	ρ = 0.010	ρ = 0.200	ρ = 0.067	**ρ = 0.262**	ρ = 0.163	**ρ = 0.254**	ρ = 0.061	ρ = 0.150	ρ = 0.218	ρ = 0.017	ρ = -0.17
M_SAM_ASO	**τ = 0.192**	τ = 0.023	τ = 0.059	τ = 0.065	τ = -0.04	τ = 0.066	τ = 0.002	τ = 0.006	τ = 0.051	τ = 0.006	τ = 0.035	τ = 0.008	τ = 0.092
M_SAM_SON	ρ = 0.248	ρ = -0.02	ρ = 0.090	ρ = -0.03	ρ = -0.17	ρ = -0.17	ρ = -0.14	ρ = -0.02	ρ = 0.012	ρ = -0.00	ρ = 0.097	ρ = -0.10	ρ = -0.07
AAO_JJA	ρ = 0.027	ρ = 0.097	ρ = 0.014	ρ = 0.085	ρ = -0.08	ρ = 0.296	ρ = -0.16	ρ = 0.277	ρ = -0.23	ρ = 0.001	ρ = -0.00	ρ = 0.007	ρ = -0.07
AAO_JAS	ρ = 0.183	ρ = 0.085	ρ = -0.03	ρ = 0.181	ρ = -0.02	ρ = 0.258	ρ = -0.04	ρ = 0.218	ρ = -0.04	ρ = 0.125	ρ = 0.042	ρ = 0.128	ρ = -0.01
AAO_ASO	**ρ = 0.327**	ρ = 0.088	ρ = 0.039	ρ = 0.137	ρ = -0.15	ρ = 0.218	ρ = -0.05	ρ = 0.019	ρ = -0.05	ρ = 0.094	ρ = -0.01	ρ = 0.125	ρ = 0.076
AAO_SON	**ρ = 0.313**	ρ = -0.04	ρ = 0.019	ρ = -0.05	ρ = -0.25	ρ = -0.05	ρ = -0.14	ρ = 0.007	ρ = -0.10	ρ = 0.016	ρ = -0.03	ρ = -0.20	ρ = -0.15
PDO_JJA	ρ = -0.01	ρ = 0.006	ρ = 0.075	ρ = 0.066	ρ = 0.167	ρ = 0.105	ρ = 0.124	ρ = 0.112	ρ = 0.054	ρ = -0.19	ρ = 0.201	ρ = 0.054	ρ = -0.12
PDO_JAS	ρ = -0.03	ρ = 0.017	ρ = 0.061	ρ = 0.031	**ρ = 0.264**	ρ = 0.182	ρ = 0.054	ρ = 0.078	ρ = 0.093	ρ = -0.15	ρ = 0.148	ρ = 0.081	ρ = -0.09
PDO_ASO	ρ = -0.06	ρ = 0.082	ρ = 0.054	ρ = 0.040	**ρ = 0.330**	ρ = 0.141	ρ = 0.038	ρ = 0.087	ρ = 0.113	ρ = -0.15	ρ = 0.137	ρ = 0.091	ρ = -0.03
PDO_SON	ρ = -0.06	ρ = 0.073	ρ = 0.058	ρ = 0.030	**ρ = 0.342**	ρ = 0.044	ρ = 0.045	ρ = 0.086	ρ = 0.106	ρ = -0.16	ρ = 0.125	ρ = 0.074	ρ = -0.00
ismidx-JJAS	ρ = 0.104	ρ = -0.05	ρ = 0.104	ρ = -0.23	ρ = -0.20	ρ = -0.13	ρ = -0.08	ρ = -0.17	ρ = -0.22	ρ = -0.11	ρ = -0.05	ρ = -0.14	ρ = -0.15
wymidx-JJAS	ρ = 0.034	ρ = -0.03	ρ = 0.070	ρ = -0.10	ρ = -0.05	ρ = -0.19	ρ = 0.007	ρ = -0.03	ρ = -0.05	ρ = 0.051	ρ = 0.052	ρ = 0.000	ρ = 0.131
wnpmidx-JAS	ρ = 0.217	ρ = 0.093	ρ = 0.027	ρ = 0.212	**ρ = 0.427**	ρ = 0.102	ρ = 0.124	ρ = 0.229	**ρ = 0.366**	**ρ = 0.235**	ρ = 0.199	**ρ = 0.292**	**ρ = 0.418**
ASLI_lat_JJA	ρ = 0.008	ρ = -0.14	ρ = 0.055	ρ = 0.043	ρ = 0.090	ρ = -0.08	ρ = 0.042	ρ = -0.08	ρ = 0.130	ρ = 0.201	ρ = 0.036	ρ = 0.023	ρ = 0.283
ASLI_lat_JAS	ρ = 0.037	ρ = -0.06	ρ = 0.056	ρ = 0.119	ρ = 0.012	ρ = -0.01	ρ = 0.149	ρ = -0.22	ρ = 0.165	ρ = 0.085	ρ = -0.02	ρ = 0.068	ρ = 0.071
ASLI_lat_ASO	ρ = -0.10	ρ = 0.112	ρ = -0.08	ρ = 0.171	ρ = -0.08	ρ = 0.028	ρ = 0.237	ρ = -0.05	ρ = 0.162	ρ = -0.01	ρ = 0.061	ρ = -0.04	ρ = -0.14
ASLI_lat_SON	ρ = -0.03	**ρ = 0.365**	ρ = 0.280	ρ = 0.029	ρ = 0.045	ρ = 0.111	ρ = 0.048	ρ = 0.049	ρ = -0.07	ρ = -0.04	ρ = 0.064	ρ = -0.05	ρ = -0.09
ASLI_lat_OND	ρ = 0.050	**ρ = 0.448**	ρ = 0.344	ρ = 0.030	ρ = 0.161	ρ = 0.225	ρ = 0.157	ρ = -0.01	ρ = 0.130	ρ = -0.29	ρ = -0.03	ρ = 0.072	ρ = -0.28
ASLI_lon_JJA	ρ = -0.07	**ρ = -0.39**	ρ = -0.21	ρ = -0.10	ρ = 0.020	ρ = -0.29	ρ = -0.12	ρ = 0.059	ρ = 0.020	ρ = 0.039	ρ = 0.000	ρ = -0.12	ρ = 0.175
ASLI_lon_JAS	τ = -0.06	**τ = -0.30**	τ = -0.18	τ = -0.11	τ = 0.044	τ = -0.15	τ = -0.11	τ = 0.055	τ = -0.07	τ = 0.016	τ = -0.01	τ = -0.10	τ = 0.150
ASLI_lon_ASO	ρ = 0.036	**ρ = -0.41**	ρ = -0.30	ρ = -0.07	ρ = 0.004	ρ = -0.10	ρ = -0.02	ρ = -0.07	ρ = -0.04	ρ = 0.023	ρ = -0.01	ρ = -0.03	ρ = 0.304
ASLI_lon_SON	ρ = 0.012	ρ = -0.11	ρ = -0.12	ρ = -0.12	ρ = -0.05	ρ = -0.17	ρ = -0.17	ρ = -0.06	ρ = -0.20	ρ = -0.04	ρ = -0.04	ρ = -0.09	ρ = 0.263
ASLI_lon_OND	ρ = 0.259	ρ = 0.078	ρ = 0.137	ρ = -0.18	ρ = -0.06	ρ = -0.01	ρ = -0.11	ρ = -0.19	ρ = -0.08	ρ = -0.18	ρ = -0.13	ρ = -0.13	ρ = -0.11
ASLI_RelCP_JJA	ρ = -0.21	ρ = -0.07	ρ = -0.12	ρ = -0.15	ρ = -0.06	ρ = 0.036	ρ = -0.18	ρ = -0.08	ρ = -0.09	ρ = 0.203	ρ = 0.114	ρ = -0.07	ρ = 0.275
ASLI_RelCP_JAS	ρ = -0.06	ρ = -0.07	ρ = -0.04	ρ = -0.04	ρ = -0.03	ρ = -0.01	ρ = -0.01	ρ = 0.143	ρ = 0.064	ρ = 0.235	**ρ = 0.350**	ρ = -0.01	ρ = 0.289
ASLI_RelCP_ASO	ρ = -0.14	ρ = -0.08	ρ = -0.07	ρ = 0.007	ρ = -0.06	ρ = -0.00	ρ = 0.040	ρ = 0.079	ρ = 0.054	ρ = 0.068	ρ = 0.290	ρ = -0.16	ρ = 0.053
ASLI_RelCP_SON	ρ = -0.14	ρ = -0.07	ρ = -0.13	ρ = 0.077	ρ = -0.00	ρ = 0.005	ρ = 0.117	ρ = 0.037	ρ = 0.087	ρ = -0.00	ρ = 0.086	ρ = -0.15	ρ = -0.34

	Troup (1961) RAIN	Troup (1961) WIND	Troup (1961)	Hendon and Liebmann (1990)	Nichols (1984)	Smith et al. (2008)	Holland (1986)	Murakami and Sumi (1982)	Drosdowsky (1996)	Hung and Yanai (2004)	Davidson et al. (2007)	Kajikawa et al. 2010	Zhang et al. (2010)
ASLI_RelCP_OND	**ρ = -0.36**	ρ = -0.21	ρ = -0.29	ρ = 0.061	ρ = 0.065	ρ = -0.08	ρ = 0.001	ρ = 0.042	ρ = 0.028	ρ = -0.01	ρ = 0.084	ρ = -0.12	ρ = -0.08
IIsst_JJA	ρ = -0.15	ρ = -0.15	ρ = -0.21	ρ = -0.19	**ρ = -0.40**	ρ = -0.18	ρ = -0.17	ρ = -0.13	**ρ = -0.23**	ρ = -0.20	**ρ = -0.23**	**ρ = -0.35**	ρ = -0.21
IIsst_JAS	ρ = -0.17	ρ = -0.16	ρ = -0.16	ρ = -0.21	**ρ = -0.44**	ρ = -0.22	ρ = -0.19	ρ = -0.16	**ρ = -0.23**	ρ = -0.20	**ρ = -0.27**	**ρ = -0.38**	ρ = -0.21
IIsst_ASO	ρ = -0.17	ρ = -0.20	ρ = -0.11	**ρ = -0.25**	**ρ = -0.46**	ρ = -0.20	**ρ = -0.24**	**ρ = -0.24**	**ρ = -0.25**	ρ = -0.21	**ρ = -0.32**	**ρ = -0.42**	ρ = -0.27
IIsst_SON	ρ = -0.15	ρ = -0.18	ρ = -0.07	**ρ = -0.25**	**ρ = -0.43**	ρ = -0.13	**ρ = -0.24**	**ρ = -0.27**	**ρ = -0.26**	ρ = -0.20	**ρ = -0.34**	**ρ = -0.42**	**ρ = -0.35**
IIsst_OND	ρ = -0.06	ρ = -0.08	ρ = -0.07	ρ = -0.11	ρ = -0.22	ρ = 0.010	ρ = -0.15	ρ = -0.15	ρ = -0.12	ρ = -0.11	**ρ = -0.24**	**ρ = -0.27**	**ρ = -0.38**