DEVELOPING A BETTER UNDERSTANDING OF THE AUSTRALIAN MONSOON

AND WET SEASON ONSET CLIMATOLOGY

A thesis submitted by

Joel Raphael Lisonbee

For the award of

Doctor of Philosophy

2021

# 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.

# ACKNOWLEDGEMENTS

This research has been supported by an Australian Government Research Training Program Scholarship.

I am deeply grateful for the love and support of my wife, Brittany, and our five children, Chloe, Ada Mae, Ezra, Isla and Faye. They have been so patient as I have worked on this project. I love my family; they bring joy and steadiness to my life.

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.

# TABLE OF CONTENTS

# LIST OF FIGURES

# LIST OF TABLES

# 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).

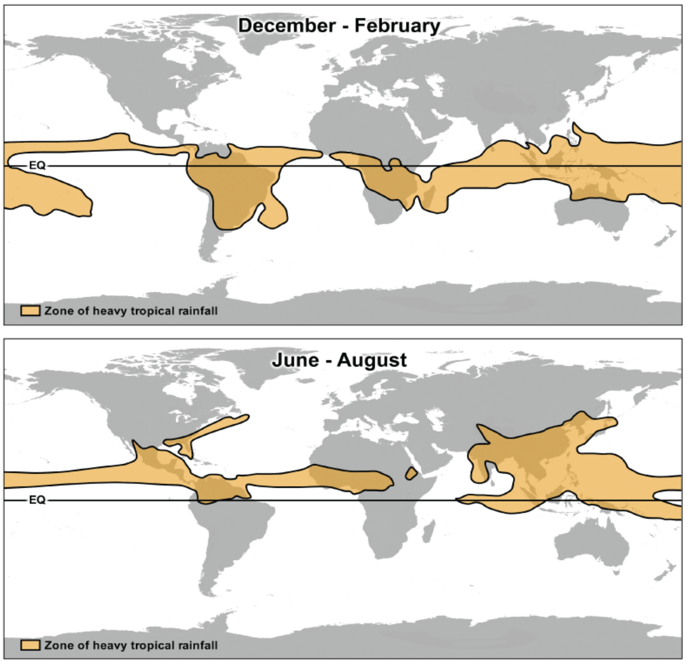



*Figure 1 The locations of the heaviest tropical rainfall from December to February (top) and June to August (bottom). (Source: University Corporation for Atmospheric Research; https://scied.ucar.edu/learning-zone/storms/monsoons accessed 30 Sept 2021)*

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).

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.

# **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.

Weather Clim. Dynam., 2, 489–506, 2021
https://doi.org/10.5194/wcd-2-489-2021


Weather and Climate Dynamics
Open Access
EGU

# Seasonal climate influences on the timing of the Australian monsoon onset

**Joel Lisonbee and Joachim Ribbe**

School of Sciences, University of Southern Queensland, Toowoomba, 4350, Australia

**Correspondence:** Joel Lisonbee (joel.lisonbee@usq.edu.au)

Received: 9 February 2021 – Discussion started: 22 February 2021
Revised: 5 May 2021 – Accepted: 11 May 2021 – Published: 11 June 2021

**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;

Published by Copernicus Publications on behalf of the European Geosciences Union.

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 ($\rho$) 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 ($\tau$) 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 $\pm 0.3$, we considered the monsoon onset to be somewhat influenced by the climate driver, and when the correlation coefficients were larger than $\pm 0.6$, 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<br>NINO 3.4<br>NINO 4 | ERSST5 data from<br>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<br>(last access: 1 September 2020) |
| | Monthly Southern Oscillation Index (SOI) | http://www.bom.gov.au/climate/current/soi2.shtml<br>(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/<br>(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.<br>(adapted from Taschetto et al., 2011) |
| | Indonesian index sea surface temperature (II SST) | ERSST.v5<br>(Verdon and Franks, 2005) |
| Northern Hemisphere monsoons | Indian Monsoon Index (IMI) | http://apdrc.soest.hawaii.edu/projects/monsoon/seasonal-monidx.html<br>(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<br>(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<br>(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)<br>(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/<br>marshall-southern-annular-mode-sam-index-station-based<br>(Marshall and National Center for Atmospheric Research Staff (Eds.), 2018) |
| Quasi-Biennial Oscillation (QBO) | | Standardised westerly 50 hPa winds<br>https://www.cpc.ncep.noaa.gov/data/indices/ (last access: 4 June 2021) |
| North Atlantic Oscillation (NAO) | | https://www.ncdc.noaa.gov/teleconnections/nao/<br>(last access: 4 June 2021) (Barnston and Livezey, 1987) |
| Amundsen Sea Low index (ASLI) | Latitude variations | https://climatedataguide.ucar.edu/climate-data/<br>amundsen-sea-low-indices (last access: 4 June 2021)<br>(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):

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

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

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 $\mathrm{W/m^2}$ 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

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

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 $\mathrm{PW}_n$ was calculated for each day and each grid point, they then define monsoon onset/retreat as follows: first, they assess if the $\mathrm{PW}_n$ 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 $PW_{max}$ and $PW_{min}$ (i.e. whether the $PW_{max}$ and $PW_{min}$ 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-

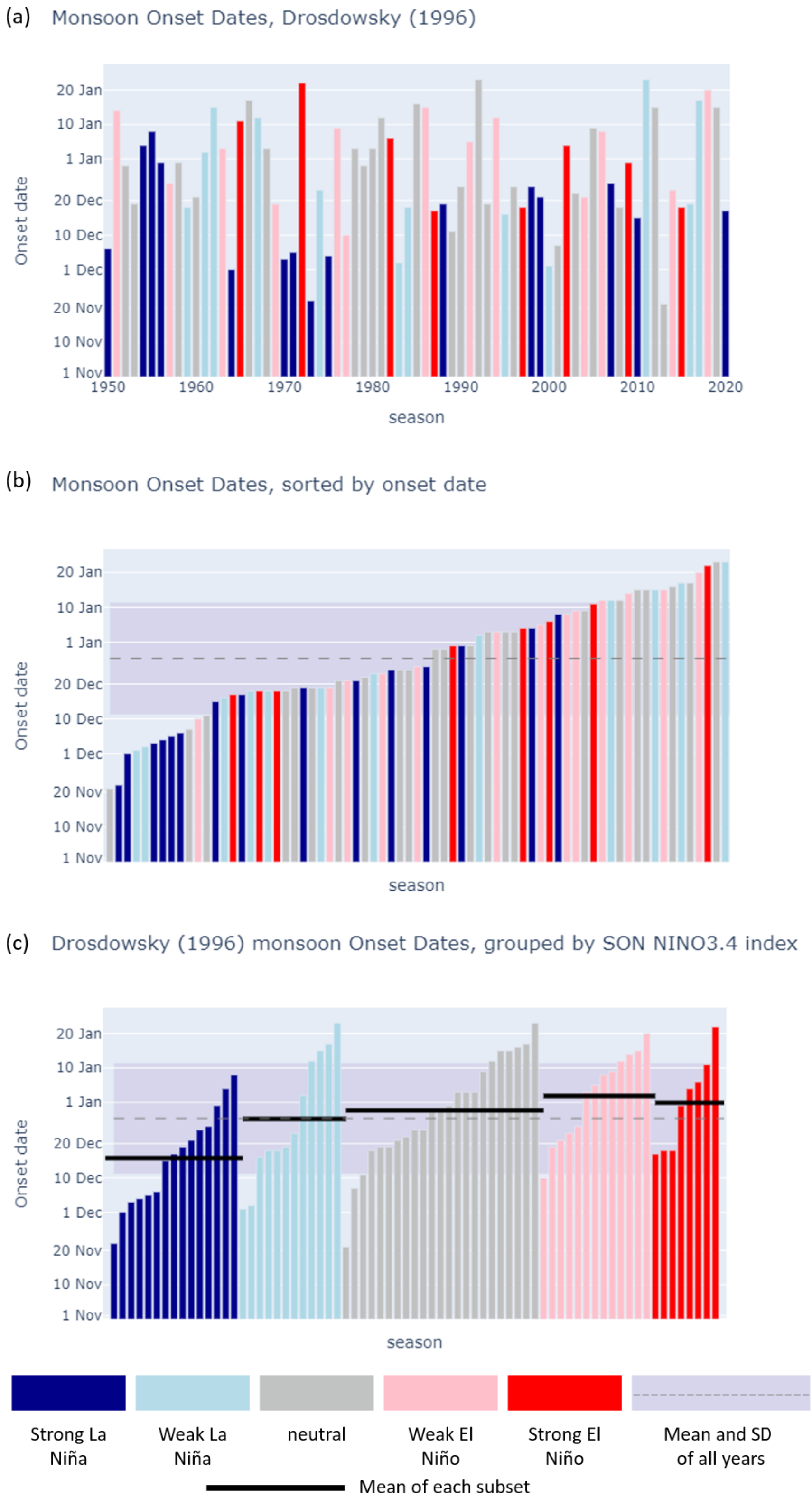



**Figure 2.** Analysis of Drosdowsky (1996) onset dates with NINO3.4 SST anomalies. Colours are as follows: *dark blue* = SST < − 0.99 °C; *light blue* = −0.99 °C ≤ SST < − 0.5 °C; *grey* = −5 °C ≤ SST ≤ +0.5 °C; *pink* = +0.5 °C < SST ≤ +0.99 °C; and *red* = SST > +0.99 °C. **(a)** Monsoon onset dates 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 ($\tau$) 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 ($\rho$) 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) | $\tau=$ **0.35** | $\tau=$ **0.39** | $\rho=$ **0.58** | $\rho=$ **0.63** | $\tau=$ **0.45** | $\rho=$ **−0.61** | $\rho=$ **0.33** |
| Smith et al. (2008) | $\tau=$ **0.17** | $\tau=$ **0.22** | $\rho=$ **0.27** | $\rho=$ **0.25** | $\tau=0.16$ | $\rho=-0.21$ | $\rho=$ **0.25** |
| Holland (1986) | $\tau=0.06$ | $\tau=0.07$ | $\rho=0.16$ | $\rho=$ **0.20** | $\tau=0.14$ | $\rho=-0.20$ | $\rho=0.20$ |
| Murakami and Sumi (1982) | $\tau=0.13$ | $\tau=$ **0.18** | $\rho=$ **0.27** | $\rho=$ **0.33** | $\tau=$ **0.23** | $\rho=$ **−0.30** | $\rho=$ **0.26** |
| Drosdowsky (1996) | $\tau=0.12$ | $\tau=$ **0.17** | $\rho=$ **0.31** | $\rho=$ **0.37** | $\tau=$ **0.31** | $\rho=$ **−0.40** | $\rho=$ **0.32** |
| Hung and Yanai (2004) | $\tau=0.06$ | $\tau=0.11$ | $\rho=0.14$ | $\rho=$ **0.17** | $\tau=$ **0.26** | $\rho=-0.22$ | $\rho=0.21$ |
| Davidson et al. (2007) | $\tau=$ **0.17** | $\tau=$ **0.18** | $\rho=0.23$ | $\rho=$ **0.29** | $\tau=$ **0.26** | $\rho=$ **−0.34** | $\rho=0.14$ |
| Kajikawa et al. 2010 | $\tau=0.16$ | $\tau=$ **0.21** | $\rho=$ **0.36** | $\rho=$ **0.36** | $\tau=$ **0.26** | $\rho=$ **−0.48** | $\rho=$ **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 (< ± 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.

*Acknowledgements.* The authors would like to thank Wassyl Drosdowsky for providing advice on recreating the onset method from his 1996 paper. We also express gratitude to Huqiang Zhang, Yoshiyuki Kajikawa, Bin Wang, and Qiong He for sharing or assisting with data from their original papers. Finally, thanks to the two reviewers who provided very useful suggestions in strengthening the final manuscript.

*Review statement.* This paper was edited by Martin Singh and reviewed by Sugata Narsey and one anonymous referee.

## References

Ali, S., Khalid, B., Kiani, R. S., Babar, R., Nasir, S., Rehman, N., Adnan, M., and Goheer, M. A.: Spatio-Temporal Variability of Summer Monsoon Onset over Pakistan, Asia-Pacific J. Atmos. Sci., 56, 147–172, https://doi.org/10.1007/s13143-019-00130-z, 2020.

Balston, J. and English, B.: Defining and predicting the “break of the season” for north-east Queensland grazing areas, Rangel. J., 31, 151, https://doi.org/10.1071/RJ08054, 2009.

Barnston, A. G. and Livezey, R. E.: Classification, Seasonality and Persistence of Low-Frequency Atmospheric Circulation Patterns, Mon. Weather Rev., 115, 1083–1126, 1987.

Berry, G. J. and Reeder, M. J.: The dynamics of Australian monsoon bursts, J. Atmos. Sci., 73, 55–69, https://doi.org/10.1175/JAS-D-15-0071.1, 2016.

Chang, C.-P. and Li, T.: A Theory for the Tropical Tropospheric Biennial Oscillation, J. Atmos. Sci., 57, 2209–2224, https://doi.org/10.1175/1520-0469(2000)057<2209:ATFTTT>2.0.CO;2, 2000.

Choi, J. and Kim, H.: Relationship of the Southeast Asian summer monsoon and Mascarene High to the tropical cyclone activity in the western North Pacific, Int. J. Climatol., 40, 4067–4081, https://doi.org/10.1002/joc.6441, 2020.

CLIVAR: CLIVAR special monsoons issue: Persistence of Systematic errors in the Asian-Australian monsoon Precipitation in climate models: a way forward H., CLIVAR Exch., 19, 10–15, available at: http://www.clivar.org/documents/exchanges-66 (last access: 4 June 2021), 2015.

Cook, G. D. and Heerdegen, R. G.: Spatial Variation In The Duration Of The Rainy Season In Monsoonal Australia, Int. J. Climatol., 1732, 1723–1732, https://doi.org/10.1002/joc.704, 2001.

Copernicus Climate Change Service (C3S): ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate. Copernicus Climate Change Service Climate Data Store (CDS), available at: https://cds.climate.copernicus.eu/cdsapp#!/home (last access: 28 August 2020), 2017.

Cowan, T., Wheeler, M., and Stone, R.: Prediction of Northern Australian Rainfall Onset Using the ACCESS-Seasonal Model, Proceedings, 36, 189, https://doi.org/10.3390/proceedings2019036189, 2020.

Crook, D. A., Buckle, D. J., Morrongiello, J. R., Allsop, Q. A., Baldwin, W., Saunders, T. M., and Douglas, M. M.: Tracking the resource pulse: Movement responses of fish to dynamic floodplain habitat in a tropical river, J. Anim. Ecol., 89, 795–807, https://doi.org/10.1111/1365-2656.13146, 2020.

Dai, P. and Tan, B.: The nature of the Arctic oscillation and diversity of the extreme surface weather anomalies it generates, J. Clim., 30, 5563–5584, https://doi.org/10.1175/JCLI-D-16-0467.1, 2017.

Davidson, N. E., Hendon, H. H., Davidson, N. E., and Hendon, H. H.: Downstream Development in the Southern Hemisphere Monsoon during FGGE/WMONEX, Mon. Weather Rev., 117, 1458–1470, https://doi.org/10.1175/1520-0493(1989)117<1458:DDITSH>2.0.CO;2, 1989.

Davidson, N. E., Tory, K. J., Reeder, M. J., and Drosdowsky, W. L.: Extratropical–Tropical Interaction during Onset of the Australian Monsoon: Reanalysis Diagnostics and Idealized Dry Simulations, J. Atmos. Sci., 64, 3475–3498, https://doi.org/10.1175/JAS4034.1, 2007.

Drosdowsky, W.: Variability of the Australian summer monsoon at Darwin: 1957–1992, J. Clim., 9, 85–96, https://doi.org/10.1175/1520-0442(1996)009<0085:VOTASM>2.0.CO;2, 1996.

Drosdowsky, W. and Wheeler, M. C.: Predicting the Onset of the North Australian Wet Season with the POAMA Dynamical Prediction System, Weather Forecast., 29, 150–161, https://doi.org/10.1175/WAF-D-13-00091.1, 2014.

Evans, S., Marchand, R., and Ackerman, T.: Variability of the Australian Monsoon and precipitation trends at Darwin, J. Clim., 27, 8487–8500, https://doi.org/10.1175/JCLI-D-13-00422.1, 2014.

Fitzpatrick, R. G. J., Bain, C. L., Knippertz, P., Marsham, J. H., and Parker, D. J.: The West African monsoon onset: A concise comparison of definitions, J. Clim., 28, 8673–8694, https://doi.org/10.1175/JCLI-D-15-0265.1, 2015.

Gochis, D.: Emerging challenges in advancing predictions of the North American Monsoon, CLIVAR Exch., 66, 19, 3–5, 2015.

Grimm, A. M., Cavalcanti, I. F. A., and Berbery, H. E.: The South American Monsoon, CLIVAR Exch., 66, 6–8, 2015.

Hai-Tien, L. and NOAA CDR_Program: NOAA Climate Data Record (CDR) of Daily Outgoing Longwave Radiation (OLR), Version 1.2. NOAA National Climatic Data Center, https://doi.org/10.7289/V5SJ1HH2, 2011.

Hendon, H. H. and Liebmann, B.: A Composite Study of Onset of the Australian Summer Monsoon, J. Atmos. Sci., 47, 2227–2240, https://doi.org/10.1175/1520-0469(1990)047<2227:ACSOOO>2.0.CO;2, 1990a.

Hendon, H. H. and Liebmann, B.: The Intraseasonal (30–50 d) Oscillation of the Australian Summer Monsoon, J. Atmos. Sci., 47, 2909–2924, https://doi.org/10.1175/1520-0469(1990)047<2909:TIDOOT>2.0.CO;2, 1990b.

Hendon, H. H., Davidson, N. E., and Gunn, B.: Australian Summer Monsoon Onset during AMEX 1987, Mon. Weather Rev., 117, 370–390, https://doi.org/10.1175/1520-0493(1989)117<0370:ASMODA>2.0.CO;2, 1989.

Holland, G. J.: Interannual Variability of the Australian Summer Monsoon at Darwin: 1952–82, Mon. Weather Rev., 114, 594–604, https://doi.org/10.1175/1520-0493(1986)114<0594:IVOTAS>2.0.CO;2, 1986.

Hung, C.-W. and Yanai, M.: Factors contributing to the onset of the Australian summer monsoon, Q. J. Roy. Meteor. Soc., 130, 739–758, https://doi.org/10.1256/qj.02.191, 2004.

Gibson, J. K., Kållberg, P., Uppala, S., Hernandez, A., Nomura, A., and Serrano, E.: 1. ERA-15 Description (Version 2 – January 1999), ECMWF Re-Analysis Proj. Rep. Ser., 19, 243–247, 1999.

Jain, M., Naeem, S., Orlove, B., Modi, V., and DeFries, R. S.: Understanding the causes and consequences of differential decision-making in adaptation research: Adapting to a delayed monsoon onset in Gujarat, India, Glob. Environ. Chang., 31, 98–109, https://doi.org/10.1016/j.gloenvcha.2014.12.008, 2015.

Joseph, P. V., Liebmann, B., and Hendon, H. H.: Interannual Variability of the Australian Summer Monsoon Onset: Possible Influence of Indian Summer Monsoon and El Niño, J. Clim., 4, 529–538, https://doi.org/10.1175/1520-0442(1991)004<0529:IVOTAS>2.0.CO;2, 1991.

Kajikawa, Y., Wang, B., and Yang, J.: A multi-time scale Australian monsoon index, Int. J. Climatol., 30, 1114–1120, https://doi.org/10.1002/joc.1955, 2010.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Leetmaa, A., Reynolds, R., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K. C., Ropelewski, C., Wang, J., Jenne, R., and Joseph, D.: The NCEP/NCAR 40-Year Reanalysis Project, B. Am. Meteorol. Soc., 77, 437–471, https://doi.org/10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2, 1996.

Kim, J. and Kim, K. Y.: The tropospheric biennial oscillation defined by a biennial mode of sea surface temperature and its impact on the atmospheric circulation and precipitation in the tropical eastern Indo-western Pacific region, Clim. Dyn., 47, 2601–2615, https://doi.org/10.1007/s00382-016-2987-9, 2016.

Kim, K.-Y., Kullgren, K., Lim, G.-H., Boo, K.-O., and Kim, B.-M.: Physical mechanisms of the Australian summer monsoon: 2. Variability of strength and onset and termination times, J. Geophys. Res., 111, 1–17, https://doi.org/10.1029/2005JD006808, 2006.

Kullgren, K. and Kim, K. Y.: Physical mechanisms of the Australian summer monsoon: 1. Seasonal cycle, J. Geophys. Res.-Atmos., 111, 1–13, https://doi.org/10.1029/2005JD006807, 2006.

Li, T., Zhang, Y., Chang, C. P., and Wang, B.: On the relationship between Indian ocean sea surface temperature and Asian summer monsoon, Geophys. Res. Lett., 28, 2843–2846, https://doi.org/10.1029/2000GL011847, 2001.

Lim, Y., Son, S. W., and Kim, D.: MJO prediction skill of the subseasonal-to-seasonal prediction models, J. Clim., 31, 4075–4094, https://doi.org/10.1175/JCLI-D-17-0545.1, 2018.

Lisonbee, J., Ribbe, J., and Wheeler, M.: Defining the north Australian monsoon onset: A systematic review, Prog. Phys. Geogr. Earth Environ., 44, 398–418, https://doi.org/10.1177/0309133319881107, 2020.

Lo, F., Wheeler, M. C., Meinke, H., and Donald, A.: Probabilistic Forecasts of the Onset of the North Australian Wet Season, Mon. Weather Rev., 135, 3506–3520, https://doi.org/10.1175/MWR3473.1, 2007.

Marshall, G. and National Center for Atmospheric Research Staff (Eds.): The Climate Data Guide: Marshall Southern Annular Mode (SAM) Index (Station-based), available at: https://climatedataguide.ucar.edu/climate-data/marshall-southern-annular-mode-sam-index-station-based (last access: 5 August 2020), 2018.

Martinez, P. P., Mahmud, A. S., Yunus, M., Faruque, A. S. G., Ahmed, T., Pascual, M., and Buckee, C. O.: Tube Well Use as Protection Against Rotavirus Infection During the Monsoons in an Urban Setting, J. Infect. Dis., 221, 238–242, https://doi.org/10.1093/infdis/jiz436, 2020.

Mcbride, J. L.: Satellite observations of the southern hemisphere monsoon during Winter MONEX, Tellus A, 35 A, 189–197, https://doi.org/10.1111/j.1600-0870.1983.tb00196.x, 1983.

Meehl, G. A.: Coupled land-ocean-atmosphere processes and South Asian monsoon variability, Science, 266, 263–267, https://doi.org/10.1126/science.266.5183.263, 1994.

Meehl, G. A. and Arblaster, J. M.: The tropospheric biennial oscillation and Asian-Australian monsoon rainfall, J. Clim., 15, 722–744, https://doi.org/10.1175/1520-0442(2002)015<0722:TTBOAA>2.0.CO;2, 2002.

Misra, V. and Bhardwaj, A.: Defining the northeast monsoon of India, Mon. Weather Rev., 147, 791–807, https://doi.org/10.1175/MWR-D-18-0287.1, 2019.

Misra, V., Bhardwaj, A., and Mishra, A.: Local onset and demise of the Indian summer monsoon, Clim. Dyn., 51, 1609–1622, https://doi.org/10.1007/s00382-017-3924-2, 2018.

Mo, K. C.: Relationships between low-frequency variability in the Southern Hemisphere and sea surface temperature anomalies, J. Clim., 13, 3599–3610, https://doi.org/10.1175/1520-0442(2000)013<3599:RBLFVI>2.0.CO;2, 2000.

Murakami, T. and Sumi, A.: Southern Hemisphere Summer Monsoon Circulation during the 1978–79 WMONEX Part II: Onset, Active and Break Monsoons, J. Meteorol. Soc. Japan, 60, 649–670, 1982.

Nicholls, N.: A system for predicting the onset of the north Australian wet-season, J. Climatol., 4, 425–435, https://doi.org/10.1002/joc.3370040407, 1984.

Nicholls, N., McBride, J. L., and Ormerod, R. J.: On Predicting the Onset of Australian Wet Season at Darwin, Mon. Weather Rev., 110, 14–17, https://doi.org/10.1175/1520-0493(1982)110<0014:OPTOOT>2.0.CO;2, 1982.

Noska, R. and Misra, V.: Characterizing the onset and demise of the Indian summer monsoon, Geophys. Res. Lett., 43, 4547–4554, https://doi.org/10.1002/2016GL068409, 2016.

Parija, P.: India's Monsoon, Bloomberg, available at: https://www.bloomberg.com/quicktake/indias-monsoon (last access: 4 June 2021), 2018.

Pillai, P. A. and Mohankumar, K.: Tropospheric biennial oscillation of the Indian summer monsoon with and without the El Nino-Southern Oscillation, Int. J. Climatol., 27, 2095–2101, https://doi.org/10.1002/joc.1503, 2007.

Pope, M., Jakob, C., and Reeder, M. J.: Regimes of the north Australian wet season, J. Clim., 22, 6699–6715, https://doi.org/10.1175/2009JCLI3057.1, 2009.

Pradhan, M., Rao, A. S., Srivastava, A., Dakate, A., Salunke, K., and Shameera, K. S.: Prediction of Indian Summer-Monsoon Onset Variability: A Season in Advance, Sci. Rep., 7, 1–14, https://doi.org/10.1038/s41598-017-12594-y, 2017.

Pramono, A., Middleton, J. H., and Caponecchia, C.: Civil Aviation Occurrences in Indonesia, J. Adv. Transp., 2020, 1–17, https://doi.org/10.1155/2020/3240764, 2020.

Qian, W., Deng, Y., Zhu, Y., and Dong, W.: Demarcating the Wolrdwide Monsoon, Theor. Appl. Climatol., 71, 1–16, https://doi.org/10.1007/s704-002-8204-0, 2002.

Qiao, Y., Huang, W., and Jian, M.: Impacts of El Niño-Southern Oscillation and local sea surface temperature on moisture source in Asian-Australian monsoon region in boreal summer, Aquat. Ecosyst. Health Manag., 15, 31–38, https://doi.org/10.1080/14634988.2012.649667, 2012.

Ramage, C. S.: Monsoon Meteorology, Academic Press, New York, 1971.

Ramella Pralungo, L., Haimberger, L., Stickler, A., and Brönnimann, S.: A global radiosonde and tracked balloon archive on 16 pressure levels (GRASP) back to 1905 – Part 1: Merging and interpolation to 00:00 and 12:00 GMT, Earth Syst. Sci. Data, 6, 185–200, https://doi.org/10.5194/essd-6-185-2014, 2014.

Raphael, M. N., Marshall, G. J., Turner, J., Fogt, R. L., Schneider, D., Dixon, D. A., Hosking, J. S., Jones, J. M., and Hobbs, W. R.: The Amundsen sea low: Variability, change, and impact on Antarctic climate, B. Am. Meteorol. Soc., 97, 111–121, https://doi.org/10.1175/BAMS-D-14-00018.1, 2016.

Saji, N., Goswami, B., Vinayachandran, P., and Yamagata, T.: A dipole mode in the Tropical Ocean, Nature, 401, 360–363, 1999.

Semazzi, F., Liu, B., Xie, L., Smith, K., Angus, M., Gudoshava, M., Argent, R., Sun, X., Liess, S., and Bhattacharya, A.: Decadal Variability of the East African Monsoon, CLIVAR Exch., 19, 15–18, 2015.

Shaik, H. and Lisonbee, J.: The tropical circulation in the Australian/Asian region – November 2010 to

April 2011, Aust. Meteorol. Oceanogr. J., 62, 51–61, https://doi.org/10.22499/2.6201.006, 2012.

Smith, I. N., Wilson, L., and Suppiah, R.: Characteristics of the Northern Australian Rainy Season, J. Clim., 21, 4298–4311, https://doi.org/10.1175/2008JCLI2109.1, 2008.

Stuecker, M. F., Timmermann, A., Yoon, J., and Jin, F. F.: Tropospheric Biennial Oscillation (TBO) indistinguishable from white noise, Geophys. Res. Lett., 42, 7785–7791, https://doi.org/10.1002/2015GL065878, 2015.

Sumi, A. and Murakami, T.: Large-scale Aspects of the 1978–79 Winter Circulation over the Greater WMONEX Region, J. Meteorol. Soc. Japan. Ser. II, 59, 625–645, https://doi.org/10.2151/jmsj1965.59.5_625, 1981.

Suppiah, R.: The Australian summer: a review, Prog. Phys. Geogr., 16, 283–318, 1992.

Taschetto, A. S., Gupta, A. Sen, Hendon, H. H., Ummenhofer, C. C., and England, M. H.: The contribution of Indian Ocean sea surface temperature anomalies on Australian summer rainfall during EL Niño events, J. Clim., 24, 3734–3747, https://doi.org/10.1175/2011JCLI3885.1, 2011.

Thompson, D. W. J. and Wallace, J. M.: The Arctic oscillation signature in the wintertime geopotential height and temperature fields, Geophys. Res. Lett., 25, 1297–1300, https://doi.org/10.1029/98GL00950, 1998.

Troup, A. J.: Variation in Upper Tropospheric Flow associated with the onset of the Australian Summer Monsoon, Indian J. Meteorol. Geophys., 12, 217–230, 1961.

Troup, A. J.: The "southern oscillation", Q. J. Roy. Meteor. Soc., 91, 490–506, https://doi.org/10.1002/qj.49709139009, 1965.

Verdon, D. C. and Franks, S. W.: Indian Ocean sea surface temperature variability and winter rainfall: Eastern Australia, Water Resour. Res., 41, 1–10, https://doi.org/10.1029/2004WR003845, 2005.

Wang, B. and Ding, Q.: Global monsoon: Dominant mode of annual variation in the tropics, Dyn. Atmos. Ocean., 44, 165–183, https://doi.org/10.1016/j.dynatmoce.2007.05.002, 2008.

Wang, B. and Fan, Z.: Choice of South Asian Summer Monsoon Indices, B. Am. Meteorol. Soc., 80, 629–638, https://doi.org/10.1175/1520-0477(1999)080<0629:COSASM>2.0.CO;2, 1999.

Wang, B., Wu, R., and Lau, K. M.: Interannual variability of the asian summer monsoon: Contrasts between the Indian and the Western North Pacific-East Asian monsoons, J. Clim., 14, 4073–4090, https://doi.org/10.1175/1520-0442(2001)014<4073:IVOTAS>2.0.CO;2, 2001.

Wang, B., Wu, R., and Li, T.: Atmosphere-warm ocean interaction and its impacts on Asian-Australian monsoon variation, J. Clim., 16, 1195–1211, https://doi.org/10.1175/1520-0442(2003)16<1195:AOIAII>2.0.CO;2, 2003.

Wang, B., Ho, L., Zhang, Y., and Lu, M.-M.: Definition of South China Sea Monsoon Onset and Commencement of the East Asia Summer Monsoon, J. Clim., 17, 699–710, 2004.

Wang, B., Lee, J. Y., Kang, I. S., Shukla, J., Kug, J. S., Kumar, A., Schemm, J., Luo, J. J., Yamagata, T., and Park, C. K.: How accurately do coupled climate models predict the leading modes of Asian-Australian monsoon interannual variability?, Clim. Dyn., 30, 605–619, https://doi.org/10.1007/s00382-007-0310-5, 2008a.

Wang, B., Yang, J., Zhou, T., and Wang, B.: Interdecadal changes in the major modes of Asian-Australian monsoon variability: Strengthening relationship with ENSO since the late 1970s, J. Clim., 21, 1771–1789, https://doi.org/10.1175/2007JCLI1981.1, 2008b.

Webster, P. J. and Yang, S.: Monsoon and Enso: Selectively Interactive Systems, Q. J. Roy. Meteor. Soc., 118, 877–926, https://doi.org/10.1002/qj.49711850705, 1992.

Webster, P. J., Magaña, V. O., Palmer, T. N., Shukla, J., Tomas, R. A., Yanai, M., and Yasunari, T.: Monsoons: Processes, predictability, and the prospects for prediction, J. Geophys. Res.-Ocean., 103, 14451–14510, https://doi.org/10.1029/97JC02719, 1998.

Wheeler, M. C. and Hendon, H. H.: An All-Season Real-Time Multivariate MJO Index: Development of an Index for Monitoring and Prediction, Mon. Weather Rev., 132, 1917–1932, https://doi.org/10.1175/1520-0493(2004)132<1917:AARMMI>2.0.CO;2, 2004.

Wheeler, M. C. and McBride, J. L.: Australasian monsoon, in Intraseasonal Variability in the Atmosphere-Ocean Climate System (2nd edition), 147–198, Springer-Verlag Berlin Heidelberg, 2011.

Wheeler, M. C. and McBride, J. L.: Australasian monsoon, Intraseasonal Var. Atmos. Clim. Syst., 1814, 147–197, https://doi.org/10.1007/978-3-642-13914-7_5, 2012.

Wu, M. C. and Chan, J. C. L.: Observational relationships between summer and winter monsoons over East Asia. Part II: Results, Int. J. Climatol., 25, 453–468, https://doi.org/10.1002/joc.1153, 2005.

Yancheva, G., Nowaczyk, N. R., Mingram, J., Dulski, P., Schettler, G., Negendank, J. F. W., Liu, J., Sigman, D. M., Peterson, L. C., and Haug, G. H.: Influence of the intertropical convergence zone on the East Asian monsoon, Nature, 445, 74–77, https://doi.org/10.1038/nature05431, 2007.

Yu, J. Y., Weng, S. P., and Farrara, J. D.: Ocean roles in the TBO transitions of the Indian-Australian monsoon system, J. Clim., 16, 3072–3080, https://doi.org/10.1175/1520-0442(2003)016<3072:ORITTT>2.0.CO;2, 2003.

Zeng, X. and Lu, E.: Notes and Correspondence: Globally unified monsoon onset and retreat indexes, J. Clim., 17, 2241–2248, https://doi.org/10.1175/1520-0442(2004)017<2241:GUMOAR>2.0.CO;2, 2004.

Zhang, H.: Diagnosing Australia-Asian monsoon onset / retreat using large-scale wind and moisture indices, Clim. Dyn., 35, 601–618, https://doi.org/10.1007/s00382-009-0620-x, 2010.

Zhang, S. and Wang, B.: Global summer monsoon rainy seasons, Int. J. Climatol., 28(12), 1563–1578, https://doi.org/10.1002/joc.1659, 2008.

Zhou, W. and Chan, J. C. L.: ENSO and the South China Sea summer monsoon onset, Int. J. Climatol., 27, 157–167, https://doi.org/10.1002/joc.1380, 2007.

# **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.

*This is the peer reviewed version of the following article: Lisonbee, J., Ribbe, J., Otkin, J., Pudmenzky, C., 2002. Wet Season Rainfall Onset and Flash Drought: The Case of the Northern Australian Wet Season. International Journal of Climatology. DOI: 10.1002/joc.7609, which at the time of thesis submission is in production by Wiley Publishing and will be published at the DOI listed here. This article may be used for non-commercial purposes in accordance with Wiley Terms and Conditions for Use of Self-Archived Versions.*

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

Authors: Joel Lisonbee[1, 4], Joachim Ribbe[1], Jason A. Otkin[2], Christa Pudmenzky[3]
Affiliations:

1. School of Sciences, University of Southern Queensland, Toowoomba, Australia
2. Cooperative Institute for Meteorological Satellite Studies, Space Science and Engineering Center, University of Wisconsin-Madison, USA
3. School of Sciences, Centre for Applied Climate Sciences (CACS), University of Southern Queensland, Toowoomba, Queensland, Australia
4. NOAA/National Integrated Drought Information System, and Cooperative Institute for Research in the Environmental Sciences (CIRES), University of Colorado Boulder, Boulder, Colorado, USA

Corresponding author: Joel Lisonbee, joel.lisonbee@noaa.gov. 325 Broadway, Boulder, CO, USA 80305

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".

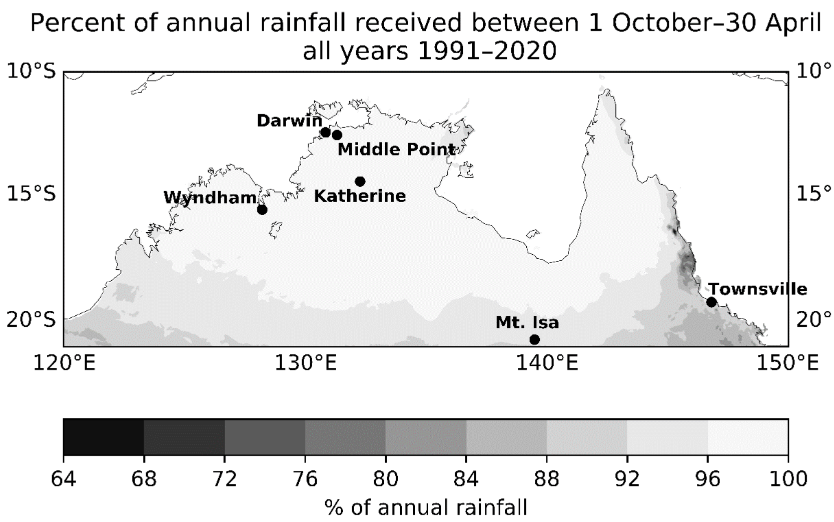



*Figure 1 Locations used in this study and percentage of annual precipitation that falls within the wet season (October–April).*

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.

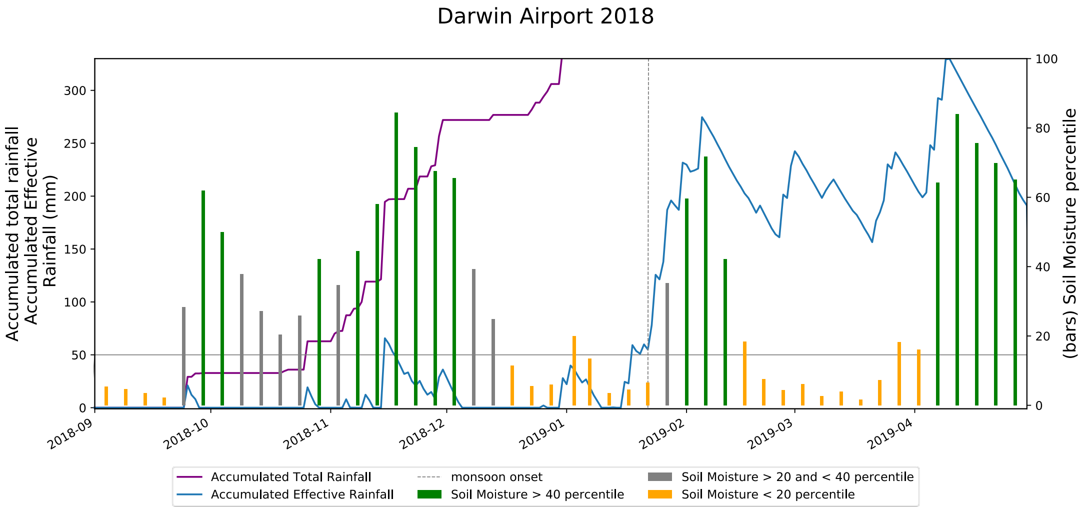



*Figure 2 Accumulated effective rainfall (mm, blue), accumulated total rainfall (mm) for the same season (purple) and root-zone soil moisture (bars) at Darwin Airport for the 2018 wet season. Soil moisture bars are coloured by value with soil moisture above the 40th percentile in green and below the 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.

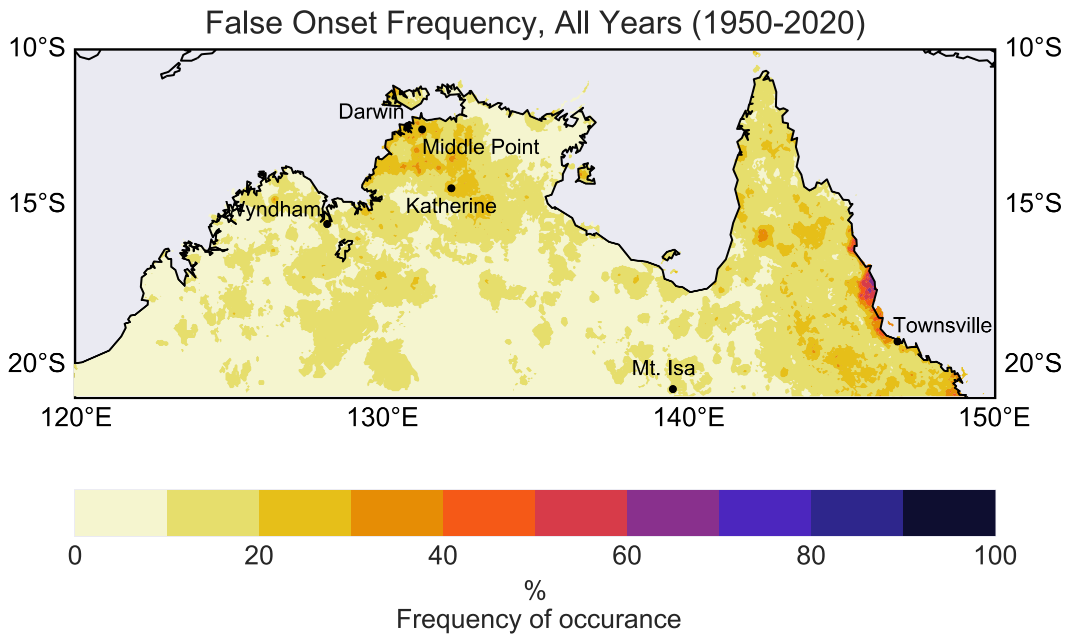



*Figure 3 False onset frequency for all years from 1950 to 2020.*

## 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.

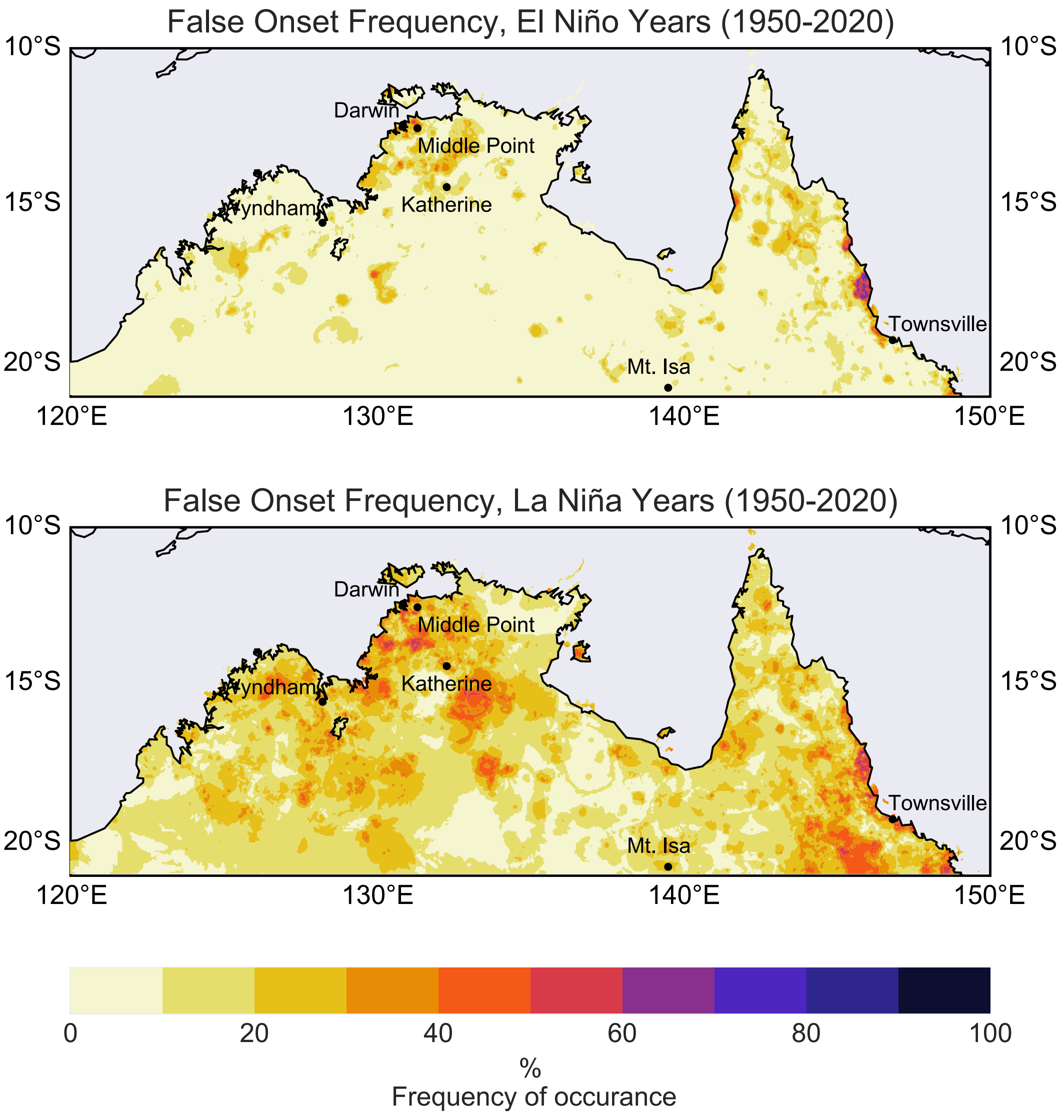



*Figure 4 False onset frequency for all El Niño years (top) and all La Niña years (bottom) from 1950-2020.*

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.

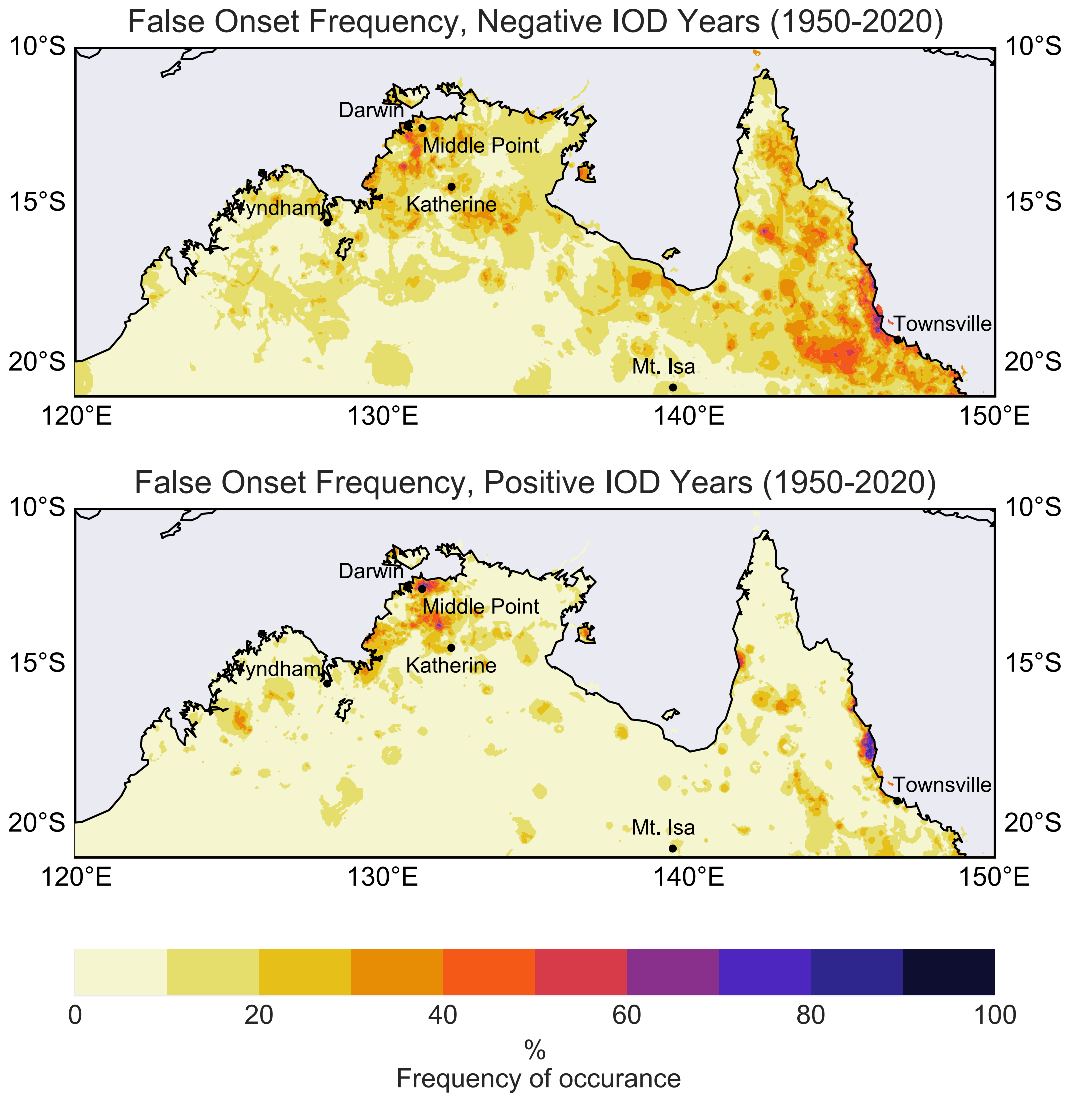



*Figure 5 False onset frequency for all negative IOD events (top) and all positive IOD events (bottom) from 1950-2020.*

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 |

-1.8 -1.6 -1.4 -1.2 -1 -0.8 -0.6 -0.4 -0.2 0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8

*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.*

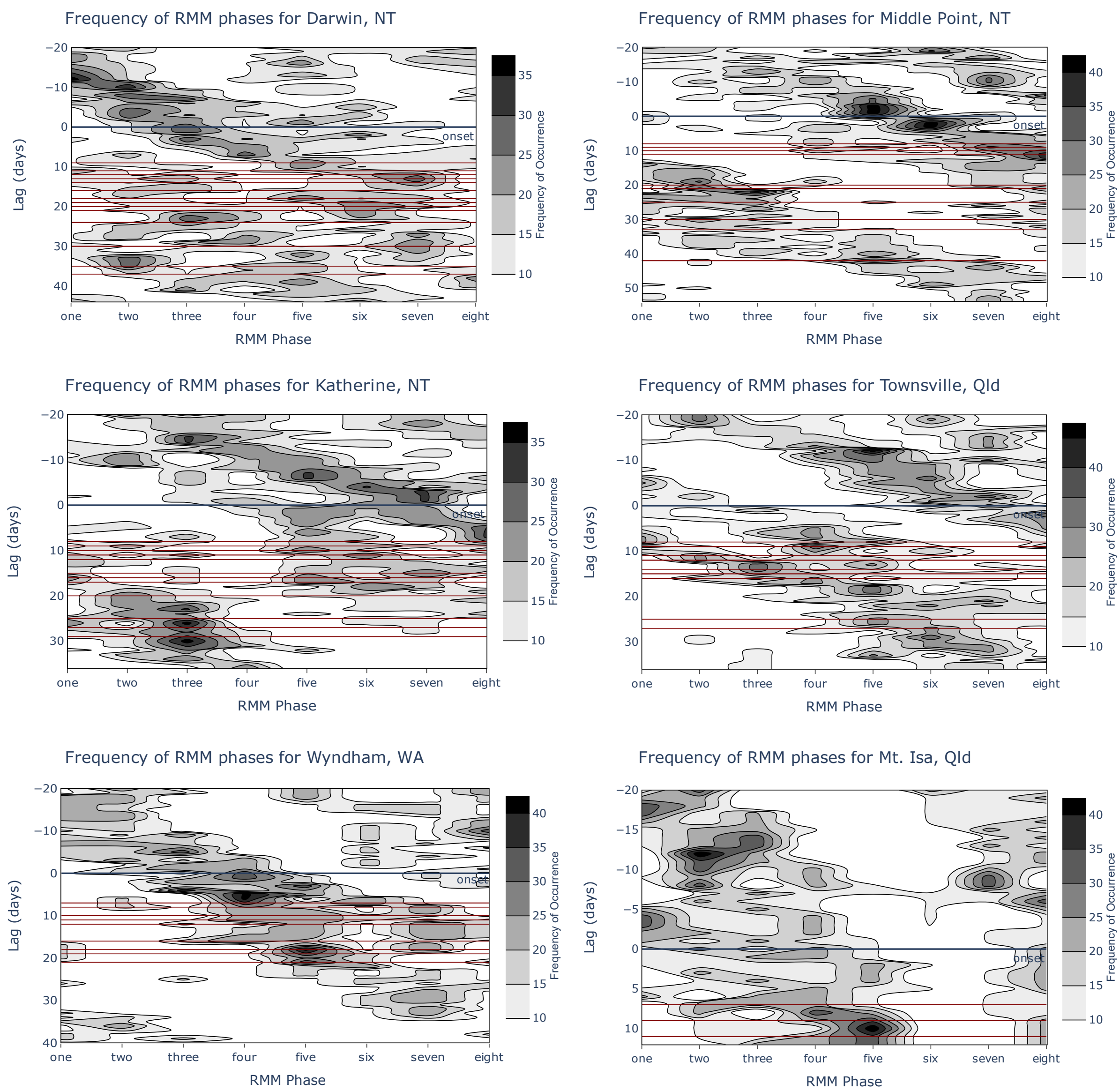



*Figure 7 Frequency of occurrence (shading) of RMM phase (of any amplitude) and lag time in days for seasons that experienced a false onset of wet season rainfall. The zero-line represents the dates when the accumulated effective rainfall reached the 50 mm threshold and each thin, maroon line denotes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

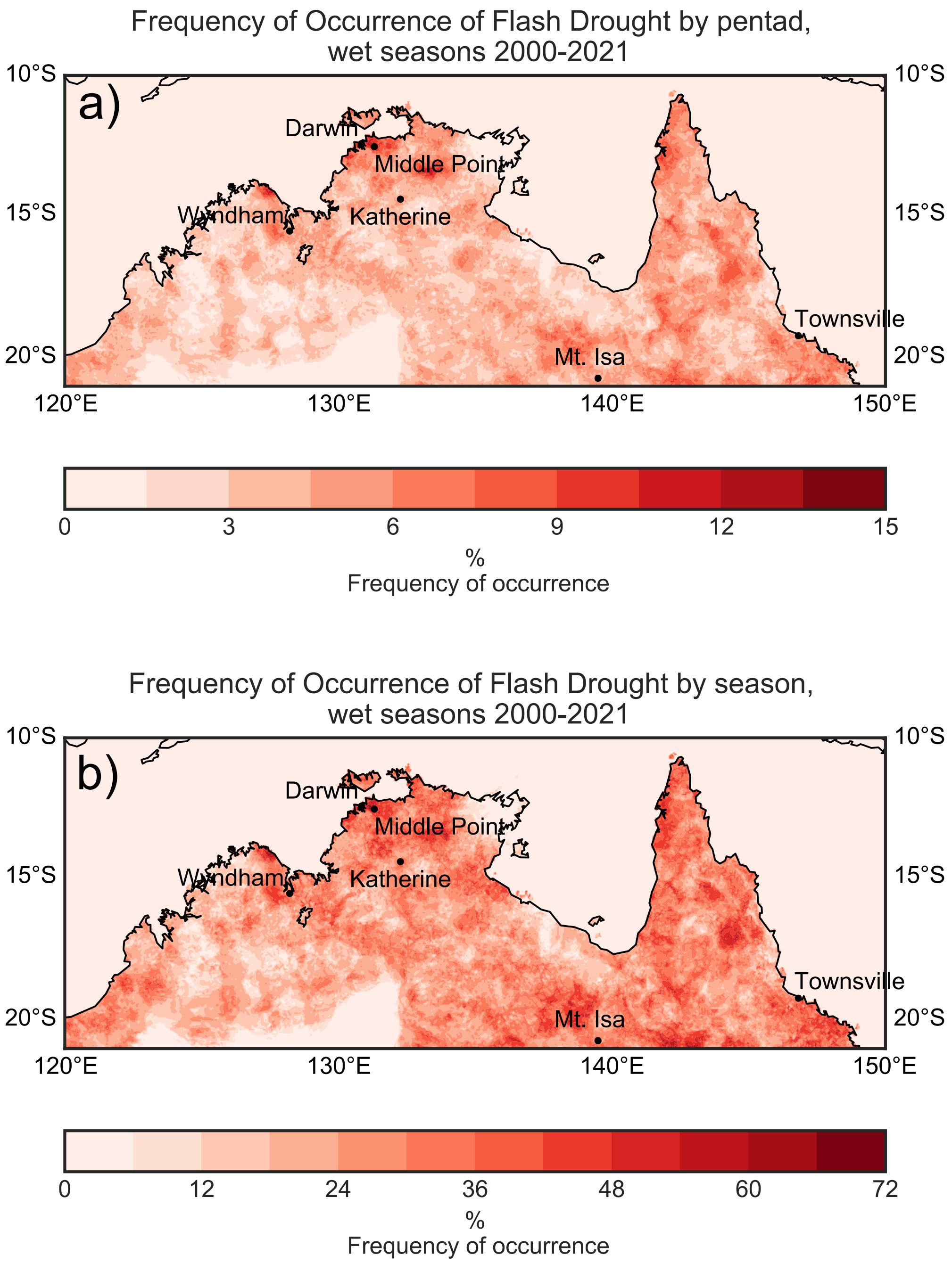
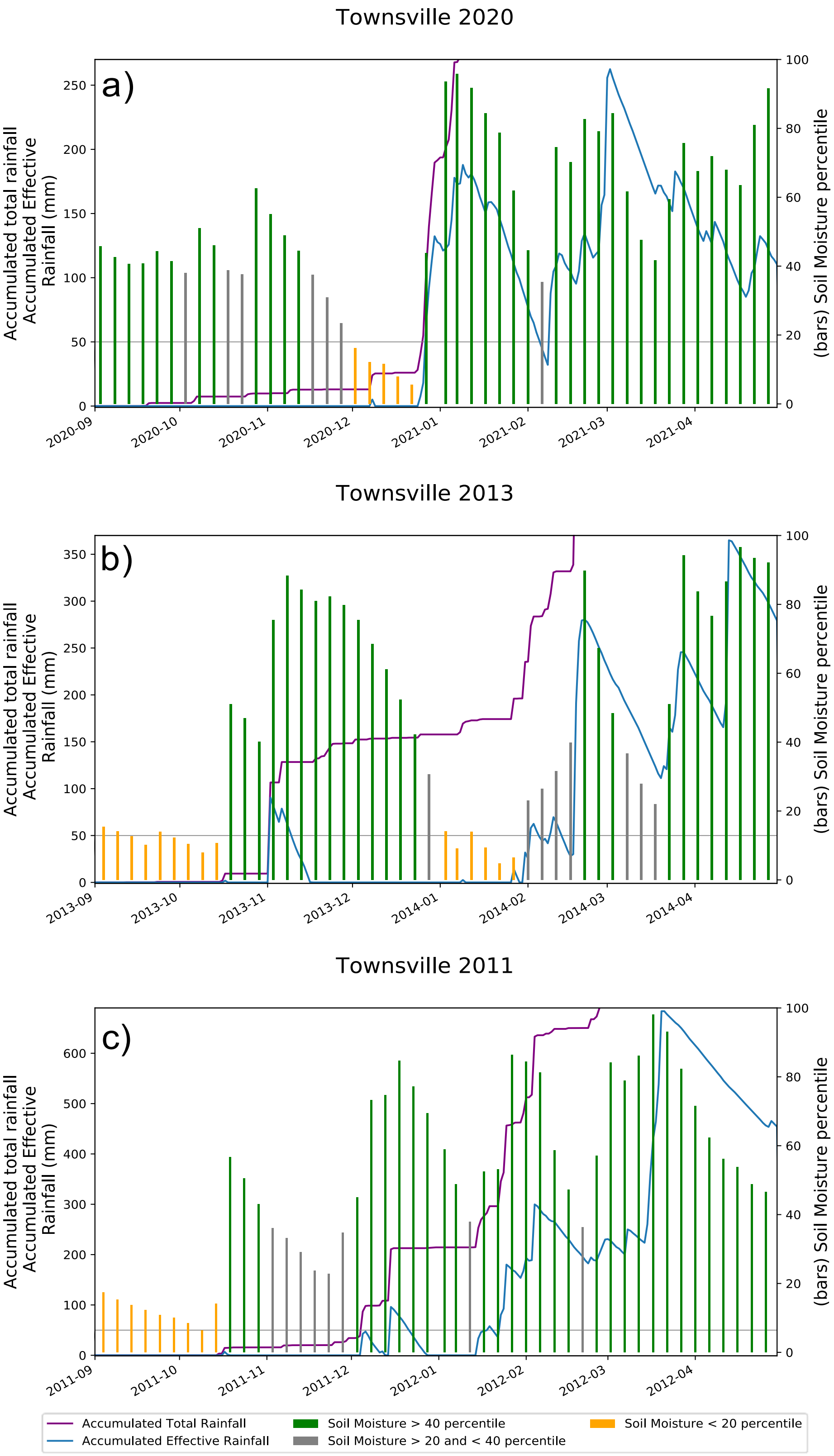



*Figure 8 Frequency of occurrence of flash droughts within wet season months of October through April for the years 2000-2021: (a) calculated as the number of pentads that met the flash drought criteria per total pentads; (b) calculated as the number of seasons which met the flash drought criteria at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




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

463

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.

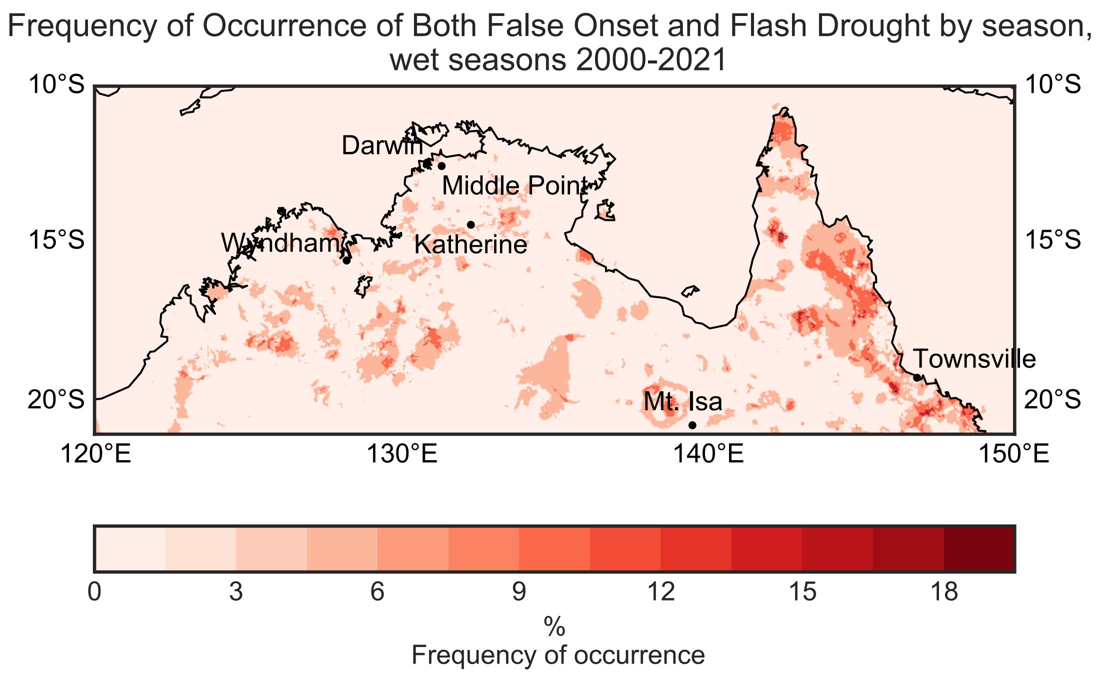



*Figure 10 Frequency of occurrence of seasons that experienced both a false onset and a flash drought within the wet season months of October through April for the years 2000-2021.*

## 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


Ali, S., B. Khalid, R. S. Kiani, R. Babar, S. Nasir, N. Rehman, M. Adnan, and M. A. Goheer, 2020: Spatio-Temporal Variability of Summer Monsoon Onset over Pakistan. *Asia-Pacific J. Atmos. Sci.*, **56**, 147–172, https://doi.org/10.1007/s13143-019-00130-z.

American Meteorological Society, A., 2019: Glossary of Meteorology: Flash Drought. 1. https://glossary.ametsoc.org/wiki/Flash_drought (Accessed August 25, 2021).

Anderson, M. C., J. M. Norman, J. R. Mecikalski, J. A. Otkin, and W. P. Kustas, 2007a: A climatological study of evapotranspiration and moisture stress across the continental United States based on thermal remote sensing: 2. Surface moisture climatology. *J. Geophys. Res. Atmos.*, **112**, 1–13, https://doi.org/10.1029/2006JD007507.

——, ——, ——, ——, and ——, 2007b: A climatological study of evapotranspiration and moisture stress across the continental United States based on thermal remote sensing: 1. Model formulation. *J. Geophys. Res. Atmos.*, **112**, 1–17, https://doi.org/10.1029/2006JD007506.

——, C. Hain, J. Otkin, X. Zhan, K. Mo, M. Svoboda, B. Wardlow, and A. Pimstein, 2013: An Intercomparison of Drought Indicators Based on Thermal Remote Sensing and NLDAS-2 Simulations with U.S. Drought Monitor Classifications. *J. Hydrometeorol.*, **14**, 1035–1056, https://doi.org/10.1175/JHM-D-12-0140.1.

Balston, J., and B. English, 2009: Defining and predicting the “break of the season” for north-east Queensland grazing areas. *Rangel. J.*, **31**, 151, https://doi.org/10.1071/RJ08054.

Beesley, C. A., A. J. Frost, and J. Zajaczkowski, 2009: A comparison of the BAWAP and SILO spatially interpolated daily rainfall datasets. *18th World IMACS Congr. MODSIM 2009 - Int. Congr. Model. Simul. Interfacing Model. Simul. with Math. Comput. Sci. Proc.*, 3886–3892.

Berry, G. J., and M. J. Reeder, 2016: The dynamics of Australian monsoon bursts. *J. Atmos. Sci.*, **73**, 55–69, https://doi.org/10.1175/JAS-D-15-0071.1.

Bliefernicht, J., M. Waongo, S. Salack, J. Seidel, P. Laux, and H. Kunstmann, 2019: Quality and value of seasonal precipitation forecasts issued by the West African regional climate outlook forum. *J. Appl. Meteorol. Climatol.*, **58**, 621–642, https://doi.org/10.1175/JAMC-D-18-0066.1.

Borges, P. de A., C. Bernhofer, and R. Rodrigues, 2018: Extreme rainfall indices in Distrito Federal, Brazil: Trends and links with El Niño southern oscillation and Madden–Julian oscillation. *Int. J. Climatol.*, **38**, 4550–4567, https://doi.org/10.1002/joc.5686.

Christian, J. I., J. B. Basara, J. A. Otkin, and E. D. Hunt, 2019a: Regional characteristics of flash droughts across the United States. *Environ. Res. Commun.*, **1**, 125004, https://doi.org/10.1088/2515-7620/ab50ca.

Christian, J. I., J. B. Basara, J. A. Otkin, E. D. Hunt, R. A. Wakefield, P. X. Flanagan, and X. Xiao, 2019b: A Methodology for Flash Drought Identification: Application of Flash Drought Frequency across the United States. *J. Hydrometeorol.*, **20**, 833–846, https://doi.org/10.1175/JHM-D-18-0198.1.

Cook, G. D., and R. G. Heerdegen, 2001: Spatial Variation In The Duration Of The Rainy Season In Monsoonal Australia. *Int. J. Climatol.*, **1732**, 1723–1732, https://doi.org/10.1002/joc.704.

Cowan, T., M. Wheeler, and R. Stone, 2020: Prediction of Northern Australian Rainfall Onset Using the ACCESS-Seasonal Model. *Proceedings*, **36**, 189, https://doi.org/10.3390/proceedings2019036189.

CSIRO and Bureau of Meteorology, 2015: *Climate Change in Australia Information for Australia's Natural Resource Management Regions: Technical Report*. https://www.climatechangeinaustralia.gov.au/.

Drosdowsky, W., 1996: Variability of the Australian summer monsoon at Darwin: 1957-1992. *J. Clim.*, **9**, 85–96, https://doi.org/10.1175/1520-0442(1996)009<0085:VOTASM>2.0.CO;2.

——, and M. C. Wheeler, 2014: Predicting the Onset of the North Australian Wet Season with the POAMA Dynamical Prediction System. *Weather Forecast.*, **29**, 150–161, https://doi.org/10.1175/WAF-D-13-00091.1.

Duncan, J. M. A., J. Dash, and P. M. Atkinson, 2013: Analysing temporal trends in the Indian Summer Monsoon and its variability at a fine spatial resolution. *Clim. Change*, **117**, 119–131, https://doi.org/10.1007/s10584-012-0537-y.

Fitzpatrick, R. G. J., C. L. Bain, P. Knippertz, J. H. Marsham, and D. J. Parker, 2015: The West African monsoon onset: A concise comparison of definitions. *J. Clim.*, **28**, 8673–8694, https://doi.org/10.1175/JCLI-D-15-0265.1.

Ford, T. W., and C. F. Labosier, 2017: Meteorological conditions associated with the onset of flash drought in the Eastern United States. *Agric. For. Meteorol.*, **247**, 414–423, https://doi.org/10.1016/j.agrformet.2017.08.031.

Frost, A. J. ., A. . Ramchurn, and A. . Smith, 2018: The Australian Landscape Water Balance model (AWRA-L v6). Technical Description of the Australian Water Resources Assessment Landscape model version 6. *Bur. Meteorol. Tech. Rep.*, 58.

Ghelani, R. P. S., E. C. J. Oliver, N. J. Holbrook, M. C. Wheeler, and P. J. Klotzbach, 2017: Joint Modulation of Intraseasonal Rainfall in Tropical Australia by the Madden-Julian Oscillation and El Niño-Southern Oscillation. *Geophys. Res. Lett.*, **44**, 10,754-10,761, https://doi.org/10.1002/2017GL075452.

Giangrande, S. E., M. J. Bartholomew, M. Pope, S. Collis, and M. P. Jensen, 2014: A summary of precipitation characteristics from the 2006-11 Northern Australian wet seasons as revealed by ARM disdrometer research facilities (Darwin, Australia). *J. Appl. Meteorol. Climatol.*, **53**, 1213–1231, https://doi.org/10.1175/JAMC-D-13-0222.1.

Hendon, H. H., and B. Liebmann, 1990: The Intraseasonal (30–50 day) Oscillation of the Australian Summer Monsoon. *J. Atmos. Sci.*, **47**, 2909–2924, https://doi.org/10.1175/1520-0469(1990)047<2909:TIDOOT>2.0.CO;2.

Holland, G. J., 1986: Interannual Variability of the Australian Summer Monsoon at Darwin: 1952–82. *Mon. Weather Rev.*, **114**, 594–604, https://doi.org/10.1175/1520-0493(1986)114<0594:IVOTAS>2.0.CO;2.

Hung, C.-W., and M. Yanai, 2004: Factors contributing to the onset of the Australian summer monsoon. *Q. J. R. Meteorol. Soc.*, **130**, 739–758, https://doi.org/10.1256/qj.02.191.

Jackson, R. C., S. M. Collis, V. Louf, A. Protat, and L. Majewski, 2018: A 17 year climatology of the macrophysical properties of convection in Darwin. *Atmos. Chem. Phys.*, **18**, 17687–17704, https://doi.org/10.5194/acp-18-17687-2018.

Jeffrey, S. J., J. O. Carter, K. B. Moodie, and A. R. Beswick, 2001: Using spatial interpolation to construct a comprehensive archive of Australian climate data. *Environ. Model. Softw.*, **16**, 309–330, https://doi.org/10.1016/S1364-8152(01)00008-1.

Jones, D. A., W. Wang, and R. Fawcett, 2009: High-quality spatial climate data-sets for Australia.

*Aust. Meteorol. Oceanogr. J. 58*, **58**, 233–248.

Keenan, T. D., and R. E. Carbone, 1992: A Preliminary Morphology of Precipitation Systems In Tropical Northern Australia. *Q. J. R. Meteorol. Soc.*, **118**, 283–326, https://doi.org/10.1002/qj.49711850406.

Kim, K.-Y., K. Kullgren, G.-H. Lim, K.-O. Boo, and B.-M. Kim, 2006: Physical mechanisms of the Australian summer monsoon: 2. Variability of strength and onset and termination times. *J. Geophys. Res.*, **111**, 1–17, https://doi.org/10.1029/2005JD006808.

Kullgren, K., and K. Y. Kim, 2006: Physical mechanisms of the Australian summer monsoon: 1. Seasonal cycle. *J. Geophys. Res. Atmos.*, **111**, 1–13, https://doi.org/10.1029/2005JD006807.

Lisonbee, J., and J. Ribbe, 2021: Seasonal climate influences on the timing of the Australian monsoon onset. *Weather Clim. Dyn.*, **2**, 489–506, https://doi.org/10.5194/wcd-2-489-2021.

——, ——, and M. Wheeler, 2020: Defining the north Australian monsoon onset: A systematic review. *Prog. Phys. Geogr. Earth Environ.*, **44**, 398–418, https://doi.org/10.1177/0309133319881107.

——, M. Woloszyn, and M. Skumanich, 2021: Making sense of flash drought: definitions, indicators, and where we go from here. *J. Appl. Serv. Climatol.*, **2021**, 1–19, https://doi.org/10.46275/joasc.2021.02.001.

Liu, Y., Y. Zhu, L. Zhang, L. Ren, F. Yuan, X. Yang, and S. Jiang, 2020: Flash droughts characterization over China: From a perspective of the rapid intensification rate. *Sci. Total Environ.*, **704**, 135373, https://doi.org/10.1016/j.scitotenv.2019.135373.

Lo, F., M. C. Wheeler, H. Meinke, and A. Donald, 2007: Probabilistic Forecasts of the Onset of the North Australian Wet Season. *Mon. Weather Rev.*, **135**, 3506–3520, https://doi.org/10.1175/MWR3473.1.

MacLeod, D., 2018: Seasonal predictability of onset and cessation of the east African rains. *Weather Clim. Extrem.*, **21**, 27–35, https://doi.org/10.1016/j.wace.2018.05.003.

Madden, R. A., and P. R. Julian, 1971: Detection of a 40–50 Day Oscillation in the Zonal Wind in the Tropical Pacific. *J. Atmos. Sci.*, **28**, 702–708, https://doi.org/10.1175/1520-0469(1971)028<0702:DOADOI>2.0.CO;2.

——, and ——, 1972: Description of Global-Scale Circulation Cells in the Tropics with a 40–50 Day Period. *J. Atmos. Sci.*, **29**, 1109–1123, https://doi.org/10.1175/1520-0469(1972)029<1109:DOGSCC>2.0.CO;2.

Mahto, S. S., and V. Mishra, 2020: Dominance of summer monsoon flash droughts in India. *Environ. Res. Lett.*, **15**, 104061, https://doi.org/10.1088/1748-9326/abaf1d.

Mcbride, J. L., 1983: Satellite observations of the southern hemisphere monsoon during Winter MONEX. *Tellus A*, **35 A**, 189–197, https://doi.org/10.1111/j.1600-0870.1983.tb00196.x.

McBride, J. L., and N. Nicholls, 1983: Seasonal Relationships between Australian Rainfall and the Southern Oscillation. *Mon. Weather Rev.*, **111**, 1998–2004, https://doi.org/10.1175/1520-0493(1983)111<1998:SRBARA>2.0.CO;2.

McCown, R. L., 1981: The climatic potential for beef cattle production in tropical Australia: Part III—Variation in the commencement, cessation and duration of the green season. *Agric. Syst.*, **7**, 163–178, https://doi.org/10.1016/0308-521X(81)90044-5.

McKeon, G. M., K. A. Day, S. M. Howden, J. J. Mott, D. M. Orr, W. J. Scattini, and E. J. Weston, 1990:

Northern Australian Savannas: Management for Pastoral Production. *J. Biogeogr.*, **17**, 355, https://doi.org/10.2307/2845365.

Mo, K. C., and D. P. Lettenmaier, 2016: Precipitation deficit flash droughts over the United States. *J. Hydrometeorol.*, **17**, 1169–1184, https://doi.org/10.1175/JHM-D-15-0158.1.

Moron, V., R. Barbero, J. P. Evans, S. Westra, and H. J. Fowler, 2019: Weather types and hourly to multiday rainfall characteristics in tropical Australia. *J. Clim.*, **32**, 3983–4011, https://doi.org/10.1175/JCLI-D-18-0384.1.

Murphy, M. J., S. T. Siems, and M. J. Manton, 2016: Regional variation in the wet season of northern Australia. *Mon. Weather Rev.*, **144**, 4941–4962, https://doi.org/10.1175/MWR-D-16-0133.1.

Narsey, S., M. J. Reeder, D. Ackerley, and C. Jakob, 2017: A midlatitude influence on Australian monsoon bursts. *J. Clim.*, **30**, 5377–5393, https://doi.org/10.1175/JCLI-D-16-0686.1.

Nguyen, H., M. C. Wheeler, J. A. Otkin, T. Cowan, A. Frost, and R. Stone, 2019: Using the evaporative stress index to monitor flash drought in Australia. *Environ. Res. Lett.*, **14**, 064016, https://doi.org/10.1088/1748-9326/ab2103.

——, ——, H. H. Hendon, E. P. Lim, and J. A. Otkin, 2021: The 2019 flash droughts in subtropical eastern Australia and their association with large-scale climate drivers. *Weather Clim. Extrem.*, **32**, 100321, https://doi.org/10.1016/j.wace.2021.100321.

Nicholls, N., 1984: A system for predicting the onset of the north Australian wet-season. *J. Climatol.*, **4**, 425–435, https://doi.org/10.1002/joc.3370040407.

Nicholls, N., J. L. McBride, and R. J. Ormerod, 1982: On Predicting the Onset of Australian Wet Season at Darwin. *Mon. Weather Rev.*, **110**, 14–17, https://doi.org/10.1175/1520-0493(1982)110<0014:OPTOOT>2.0.CO;2.

Otkin, J. A., M. C. Anderson, C. Hain, I. E. Mladenova, J. B. Basara, and M. Svoboda, 2013: Examining rapid onset drought development using the thermal infrared-based evaporative stress index. *J. Hydrometeorol.*, **14**, 1057–1074, https://doi.org/10.1175/JHM-D-12-0144.1.

——, ——, ——, and M. Svoboda, 2014: Examining the Relationship between Drought Development and Rapid Changes in the Evaporative Stress Index. *J. Hydrometeorol.*, **15**, 938–956, https://doi.org/10.1175/JHM-D-13-0110.1.

——, ——, ——, and ——, 2015: Using temporal changes in drought indices to generate probabilistic drought intensification forecasts. *J. Hydrometeorol.*, **16**, 88–105, https://doi.org/10.1175/JHM-D-14-0064.1.

Otkin, J. A., and Coauthors, 2016: Assessing the evolution of soil moisture and vegetation conditions during the 2012 United States flash drought. *Agric. For. Meteorol.*, **218**–**219**, 230–242, https://doi.org/10.1016/j.agrformet.2015.12.065.

Otkin, J. A., T. Haigh, A. Mucia, M. C. Anderson, and C. Hain, 2018a: Comparison of Agricultural Stakeholder Survey Results and Drought Monitoring Datasets during the 2016 U.S. Northern Plains Flash Drought. *Weather. Clim. Soc.*, **10**, 867–883, https://doi.org/10.1175/wcas-d-18-0051.1.

——, M. Svoboda, E. D. Hunt, T. W. Ford, M. C. Anderson, C. Hain, and J. B. Basara, 2018b: Flash Droughts: A Review and Assessment of the Challenges Imposed by Rapid-Onset Droughts in the United States. *Bull. Am. Meteorol. Soc.*, **99**, 911–919, https://doi.org/10.1175/BAMS-D-17-0149.1.

——, Y. Zhong, D. Lorenz, M. C. Anderson, and C. Hain, 2018c: Exploring seasonal and regional relationships between the Evaporative Stress Index and surface weather and soil moisture anomalies across the United States. *Hydrol. Earth Syst. Sci.*, **22**, 5373–5386, https://doi.org/10.5194/hess-22-5373-2018.

Parija, P., 2018: India's Monsoon. *Bloomberg*,. https://www.bloomberg.com/quicktake/indias-monsoon (Accessed August 25, 2021).

Parker, T., A. Gallant, M. Hobbins, and D. Hoffmann, 2021: Flash drought in Australia and its relationship to evaporative demand. *Environ. Res. Lett.*, **16**, 064033, https://doi.org/10.1088/1748-9326/abfe2c.

Pendergrass, A. G., and Coauthors, 2020: Flash droughts present a new challenge for subseasonal-to-seasonal prediction. *Nat. Clim. Chang.*, **10**, 191–199, https://doi.org/10.1038/s41558-020-0709-0.

Pirret, J. S. R., J. D. Daron, P. E. Bett, N. Fournier, and A. K. Foamouhoue, 2020: Assessing the Skill and Reliability of Seasonal Climate Forecasts in Sahelian West Africa. *Weather Forecast.*, **35**, 1035–1050, https://doi.org/10.1175/WAF-D-19-0168.1.

Pope, M., C. Jakob, and M. J. Reeder, 2009: Regimes of the North Australian Wet Season. *J. Clim.*, **22**, 6699–6715, https://doi.org/10.1175/2009JCLI3057.1.

Pradhan, M., A. S. Rao, A. Srivastava, A. Dakate, K. Salunke, and K. S. Shameera, 2017: Prediction of Indian Summer-Monsoon Onset Variability: A Season in Advance. *Sci. Rep.*, **7**, 1–14, https://doi.org/10.1038/s41598-017-12594-y.

Qiao, Y., W. Huang, and M. Jian, 2012: Impacts of El Niño-Southern Oscillation and local sea surface temperature on moisture source in Asian-Australian monsoon region in boreal summer. *Aquat. Ecosyst. Health Manag.*, **15**, 31–38, https://doi.org/10.1080/14634988.2012.649667.

Rajan, D., T. Koike, and J. Matsumoto, 2005: The Abnormal Indian Summer Monsoon of 2002 : JRA25 Reanalysis. *Earth*, 1–6.

Ramage, C. S., 1971: *Monsoon Meteorology*. Academic Press, 296 pp.

Risbey, J. S., M. J. Pook, P. C. McIntosh, M. C. Wheeler, and H. H. Hendon, 2009: On the remote drivers of rainfall variability in Australia. *Mon. Weather Rev.*, **137**, 3233–3253, https://doi.org/10.1175/2009MWR2861.1.

Robertson, A. W., S. Kirshner, P. Smyth, S. P. Charles, and B. C. Bates, 2006: Subseasonal-to-interdecadal variability of the Australian monsoon over North Queensland. *Q. J. R. Meteorol. Soc.*, **132**, 519–542, https://doi.org/10.1256/qj.05.75.

Saji, N. H., and T. Yamagata, 2003: Possible impacts of Indian Ocean Dipole mode events on global climate. *Clim. Res.*, **25**, 151–169, https://doi.org/10.3354/cr025151.

——, B. N. Goswami, P. N. Vinayachandran, and T. Yamagata, 1999: A dipole mode in the tropical Indian Ocean. *Nature*, **401**, 360–363, https://doi.org/10.1038/43854.

Smith, I. N., L. Wilson, and R. Suppiah, 2008: Characteristics of the Northern Australian Rainy Season. *J. Clim.*, **21**, 4298–4311, https://doi.org/10.1175/2008JCLI2109.1.

State of Queensland Government, 2021: SILO - Australian climate data from 1889 to yesterday. https://longpaddock.qld.gov.au/silo/ (Accessed June 30, 2021).

Stojanovic, M., and Coauthors, 2020: Trends and Extremes of Drought Episodes in Vietnam Sub-Regions during 1980–2017 at Different Timescales. *Water*, **12**, 813, https://doi.org/10.3390/w12030813.

Taschetto, A. S., A. Sen Gupta, H. H. Hendon, C. C. Ummenhofer, and M. H. England, 2011: The contribution of Indian Ocean sea surface temperature anomalies on Australian summer rainfall during EL Niño events. *J. Clim.*, **24**, 3734–3747, https://doi.org/10.1175/2011JCLI3885.1.

Troup, A. J., 1965: The "southern oscillation." *Q. J. R. Meteorol. Soc.*, **91**, 490–506, https://doi.org/10.1002/qj.49709139009.

Verdon, D. C., and S. W. Franks, 2005: Indian Ocean sea surface temperature variability and winter rainfall: Eastern Australia. *Water Resour. Res.*, **41**, 1–10, https://doi.org/10.1029/2004WR003845.

Wang, B., and Q. Ding, 2008: Global monsoon: Dominant mode of annual variation in the tropics. *Dyn. Atmos. Ocean.*, **44**, 165–183, https://doi.org/10.1016/j.dynatmoce.2007.05.002.

Webster, P. J., 1981: Monsoons. *Sci. Am.*, **245**, 108–118.

Wheeler, M. C., and H. H. Hendon, 2004: An All-Season Real-Time Multivariate MJO Index: Development of an Index for Monitoring and Prediction. *Mon. Weather Rev.*, **132**, 1917–1932, https://doi.org/10.1175/1520-0493(2004)132<1917:AARMMI>2.0.CO;2.

——, ——, S. Cleland, H. Meinke, and A. Donald, 2009: Impacts of the Madden-Julian oscillation on australian rainfall and circulation. *J. Clim.*, **22**, 1482–1498, https://doi.org/10.1175/2008JCLI2595.1.

Yancheva, G., and Coauthors, 2007: Influence of the intertropical convergence zone on the East Asian monsoon. *Nature*, **445**, 74–77, https://doi.org/10.1038/nature05431.

Yang, X., and Coauthors, 2020: Spatial and Temporal Characterization of Drought Events in China Using the Severity-Area-Duration Method. *Water*, **12**, 230, https://doi.org/10.3390/w12010230.

Yuan, X., L. Wang, and E. Wood, 2018: Anthropogenic Intensification of Southern African Flash Droughts As Exemplified By The 2015/16 Season [in "Explaining Extreme Events of 2016 from a Climate Perspective"]. *Bull. Am. Meteorol. Soc.*, **99**, S54–S59, https://doi.org/https://doi.org/10.1175/ BAMS-D-17-0077.1.

Zajaczkowski, J., and S. Jeffrey, 2020: Potential evaporation and evapotranspiration data provided by SILO. *Queensl. Gov. Dep. Environ. Sci.*, 1–45.

Zhang, H., 2010: Diagnosing Australia-Asian monsoon onset / retreat using large-scale wind and moisture indices. *Clim. Dyn.*, **35**, 601–618, https://doi.org/10.1007/s00382-009-0620-x.

Zhang, H., C. Wu, and B. X. Hu, 2019a: Recent intensification of short-term concurrent hot and dry extremes over the Pearl River basin, China. *Int. J. Climatol.*, **39**, 4924–4937, https://doi.org/10.1002/joc.6116.

Zhang, Q., and Coauthors, 2020: Causes and Changes of Drought in China: Research Progress and Prospects. *J. Meteorol. Res.*, **34**, 460–481, https://doi.org/10.1007/s13351-020-9829-8.

Zhang, Y., Q. You, C. Chen, and X. Li, 2017: Flash droughts in a typical humid and subtropical basin: A case study in the Gan River Basin, China. *J. Hydrol.*, **551**, 162–176, https://doi.org/10.1016/j.jhydrol.2017.05.044.

——, ——, G. Mao, C. Chen, and Z. Ye, 2019b: Short-term concurrent drought and heatwave frequency with 1.5 and 2.0 °C global warming in humid subtropical basins: a case study in the Gan River Basin, China. *Clim. Dyn.*, **52**, 4621–4641, https://doi.org/10.1007/s00382-018-4398-6.

# **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.

# REFERENCES


American Meteorological Society, A., 2012a: Glossary of Meteorology: Climate Change. https://glossary.ametsoc.org/wiki/Climate_change (Accessed October 12, 2021).

——, 2012b: GLossary of Meteorology: Climate Variability. https://glossary.ametsoc.org/wiki/Climate_variability (Accessed October 12, 2021).

Berry, G. J., and M. J. Reeder, 2016: The dynamics of Australian monsoon bursts. *J. Atmos. Sci.*, **73**, 55–69, https://doi.org/10.1175/JAS-D-15-0071.1.

Christian, J. I., J. B. Basara, J. A. Otkin, E. D. Hunt, R. A. Wakefield, P. X. Flanagan, and X. Xiao, 2019: A Methodology for Flash Drought Identification: Application of Flash Drought Frequency across the United States. *J. Hydrometeorol.*, **20**, 833–846, https://doi.org/10.1175/JHM-D-18-0198.1.

CLIVAR, 2015: CLIVAR special monsoons issue: Persistence of Systematic errors in the Asian-Australian monsoon Precipitation in climate models: a way forward H. *CLIVAR Exch. (no. 66)*, **19**, 10–15.

CSIRO, 2009: *Water in northern Australia Summary of reports to the Australian Government from the CSIRO Northern Australia Sustainable Yields Project*. 12 pp.

Davidson, N. E., K. J. Tory, M. J. Reeder, and W. L. Drosdowsky, 2007: Extratropical–Tropical Interaction during Onset of the Australian Monsoon: Reanalysis Diagnostics and Idealized Dry Simulations. *J. Atmos. Sci.*, **64**, 3475–3498, https://doi.org/10.1175/JAS4034.1.

Drosdowsky, W., 1996: Variability of the Australian summer monsoon at Darwin: 1957-1992. *J. Clim.*, **9**, 85–96, https://doi.org/10.1175/1520-0442(1996)009<0085:VOTASM>2.0.CO;2.

——, and M. C. Wheeler, 2014: Predicting the Onset of the North Australian Wet Season with the POAMA Dynamical Prediction System. *Weather Forecast.*, **29**, 150–161, https://doi.org/10.1175/WAF-D-13-00091.1.

Evans, S., R. Marchand, and T. Ackerman, 2014: Variability of the Australian Monsoon and precipitation trends at Darwin. *J. Clim.*, **27**, 8487–8500, https://doi.org/10.1175/JCLI-D-13-00422.1.

Fitzpatrick, R. G. J., C. L. Bain, P. Knippertz, J. H. Marsham, and D. J. Parker, 2015: The West African monsoon onset: A concise comparison of definitions. *J. Clim.*, **28**, 8673–8694, https://doi.org/10.1175/JCLI-D-15-0265.1.

Ford, T. W., and C. F. Labosier, 2017: Meteorological conditions associated with the onset of flash drought in the Eastern United States. *Agric. For. Meteorol.*, **247**, 414–423, https://doi.org/10.1016/j.agrformet.2017.08.031.

Green, D., S. Jackson, and J. Morrison, 2009: *Risks from Climate Change to Indigenous Communities in the Tropical North of Australia*. i–194 pp.

Haylock, M. R., and J. L. McBride, 2001: Spatial Coherence and Predictability of Indonesian Wet Season Rainfall. *J. Clim.*, **14**, 3882–3887.

Hendon, H. H., and B. Liebmann, 1990: A Composite Study of Onset of the Australian Summer Monsoon. *J. Atmos. Sci.*, **47**, 2227–2240, https://doi.org/10.1175/1520-0469(1990)047<2227:ACSOOO>2.0.CO;2.

——, E. P. Lim, and G. Liu, 2012: The role of air-sea interaction for prediction of Australian summer monsoon rainfall. *J. Clim.*, **25**, 1278–1290, https://doi.org/10.1175/JCLI-D-11-00125.1.

Holland, G. J., 1986: Interannual Variability of the Australian Summer Monsoon at Darwin: 1952–82. *Mon. Weather Rev.*, **114**, 594–604, https://doi.org/10.1175/1520-0493(1986)114<0594:IVOTAS>2.0.CO;2.

Hung, C.-W., and M. Yanai, 2004: Factors contributing to the onset of the Australian summer monsoon. *Q. J. R. Meteorol. Soc.*, **130**, 739–758, https://doi.org/10.1256/qj.02.191.

IPCC, 2021a: Annex VII: Glossary [Matthews, J. B. R., J. S. Fuglestvedt, V. Masson-Delmotte, V. Möller, C. 36 Méndez, R. van Diemen, A. Reisinger, S. Semenov (ed.)]. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, V. Masson-Delmotte et al., Eds., Cambridge University Press, p. 73.

——, 2021b: Annex V: Monsoons [Cherchi, A., A. Turner (eds.)]. *Climate Change 2021: The Physical 19 Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental 20 Panel on Climate Change*, V. Masson-Delmotte et al., Eds., Cambridge University Press.

Jiang, N., W. Qian, and J. C. H. Leung, 2016: The global monsoon division combining the k-means clustering method and low-level cross-equatorial flow. *Clim. Dyn.*, **47**, 2345–2359, https://doi.org/10.1007/s00382-015-2967-5.

Kajikawa, Y., B. Wang, and J. Yang, 2010: A multi-time scale Australian monsoon index. *Int. J. Climatol.*, **30**, 1114–1120, https://doi.org/10.1002/joc.1955.

Kim, K.-Y., K. Kullgren, G.-H. Lim, K.-O. Boo, and B.-M. Kim, 2006: Physical mechanisms of the Australian summer monsoon: 2. Variability of strength and onset and termination times. *J. Geophys. Res.*, **111**, 1–17, https://doi.org/10.1029/2005JD006808.

Li, J., and Q. Zeng, 2002: A unified monsoon index. *Geophys. Res. Lett.*, **29**, 115-1-115–4, https://doi.org/10.1029/2001GL013874.

Lim, Y., S. W. Son, and D. Kim, 2018: MJO prediction skill of the subseasonal-to-seasonal prediction models. *J. Clim.*, **31**, 4075–4094, https://doi.org/10.1175/JCLI-D-17-0545.1.

Lisonbee, J., and J. Ribbe, 2021: Seasonal climate influences on the timing of the Australian monsoon onset. *Weather Clim. Dyn.*, **2**, 489–506, https://doi.org/10.5194/wcd-2-489-2021.

——, ——, and M. Wheeler, 2020: Defining the north Australian monsoon onset: A systematic review. *Prog. Phys. Geogr. Earth Environ.*, **44**, 398–418, https://doi.org/10.1177/0309133319881107.

——, M. Woloszyn, and M. Skumanich, 2021: Making sense of flash drought: definitions, indicators, and where we go from here. *J. Appl. Serv. Climatol.*, **2021**, 1–19, https://doi.org/10.46275/joasc.2021.02.001.

Lo, F., M. C. Wheeler, H. Meinke, and A. Donald, 2007: Probabilistic Forecasts of the Onset of the North Australian Wet Season. *Mon. Weather Rev.*, **135**, 3506–3520, https://doi.org/10.1175/MWR3473.1.

Mahto, S. S., and V. Mishra, 2020: Dominance of summer monsoon flash droughts in India. *Environ. Res. Lett.*, **15**, 104061, https://doi.org/10.1088/1748-9326/abaf1d.

McBride, J. L., and N. Nicholls, 1983: Seasonal Relationships between Australian Rainfall and the Southern Oscillation. *Mon. Weather Rev.*, **111**, 1998–2004, https://doi.org/10.1175/1520-0493(1983)111<1998:SRBARA>2.0.CO;2.

McBride, J. L., M. R. Haylock, and N. Nicholls, 2003: Relationships between the maritime continent heat source and the El Niño-Southern oscillation phenomenon. *J. Clim.*, **16**, 2905–2914, https://doi.org/10.1175/1520-0442(2003)016<2905:RBTMCH>2.0.CO;2.

Moron, V., A. W. Robertson, and R. Boer, 2009: Spatial coherence and seasonal predictability of monsoon onset over Indonesia. *J. Clim.*, **22**, 840–850, https://doi.org/10.1175/2008JCLI2435.1.

——, ——, and D. S. Pai, 2017: On the spatial coherence of sub-seasonal to seasonal Indian rainfall anomalies. *Clim. Dyn.*, **49**, 3403–3423, https://doi.org/10.1007/s00382-017-3520-5.

Murakami, T., and J. Matsumoto, 1994: Summer Monsoon over the Asian Continent and Western North Pacific. *J. Meteorol. Soc. Japan*, **72**, 719–745, https://doi.org/https://doi.org/10.2151/jmsj1965.72.5_719.

Nguyen, H., M. C. Wheeler, J. A. Otkin, T. Cowan, A. Frost, and R. Stone, 2019: Using the evaporative stress index to monitor flash drought in Australia. *Environ. Res. Lett.*, **14**, 064016, https://doi.org/10.1088/1748-9326/ab2103.

Nicholls, N., 1984: A system for predicting the onset of the north Australian wet-season. *J. Climatol.*, **4**, 425–435, https://doi.org/10.1002/joc.3370040407.

Nicholls, N., J. L. McBride, and R. J. Ormerod, 1982: On Predicting the Onset of Australian Wet Season at Darwin. *Mon. Weather Rev.*, **110**, 14–17, https://doi.org/10.1175/1520-0493(1982)110<0014:OPTOOT>2.0.CO;2.

Noska, R., and V. Misra, 2016: Characterizing the onset and demise of the Indian summer monsoon. *Geophys. Res. Lett.*, **43**, 4547–4554, https://doi.org/10.1002/2016GL068409.

Otkin, J. A., Y. Zhong, D. Lorenz, M. C. Anderson, and C. Hain, 2018: Exploring seasonal and regional relationships between the Evaporative Stress Index and surface weather and soil moisture anomalies across the United States. *Hydrol. Earth Syst. Sci.*, **22**, 5373–5386, https://doi.org/10.5194/hess-22-5373-2018.

Pickering, C., and J. Byrne, 2014: The benefits of publishing systematic quantitative literature reviews for PhD candidates and other early-career researchers. *High. Educ. Res. Dev.*, 534–548, https://doi.org/10.1080/07294360.2013.841651.

Pope, M., C. Jakob, and M. J. Reeder, 2009: Regimes of the North Australian Wet Season. *J. Clim.*, **22**, 6699–6715, https://doi.org/10.1175/2009JCLI3057.1.

Qian, W., Y. Deng, Y. Zhu, and W. Dong, 2002: Demarcating the Wolrdwide Monsoon. *Theor. Appl. Climatol.*, **71**, 1–16, https://doi.org/10.1007/s704-002-8204-0.

Ramage, C. S., 1971: *Monsoon Meteorology*. Academic Press, 296 pp.

Saji, N. H., B. N. Goswami, P. N. Vinayachandran, and T. Yamagata, 1999: A dipole mode in the tropical Indian Ocean. *Nature*, **401**, 360–363, https://doi.org/10.1038/43854.

Smith, I. N., L. Wilson, and R. Suppiah, 2008: Characteristics of the Northern Australian Rainy Season. *J. Clim.*, **21**, 4298–4311, https://doi.org/10.1175/2008JCLI2109.1.

Tanaka, M., 1994: The Onset and Retreat Dates of the Austral Summer Monsoon over Indonesia, Australia and New Guinea. *J. Meteorol. Soc. Japan. Ser. II*, **72**, 255–267, https://doi.org/10.2151/jmsj1965.72.2_255.

Taschetto, A. S., A. Sen Gupta, H. H. Hendon, C. C. Ummenhofer, and M. H. England, 2011: The contribution of Indian Ocean sea surface temperature anomalies on Australian summer rainfall during EL Niño events. *J. Clim.*, **24**, 3734–3747, https://doi.org/10.1175/2011JCLI3885.1.

Troup, A. J., 1961: Variation in Upper Tropospheric Flow associated with the onset of the Australian Summer Monsoon. *Indian J. Meteorol. Geophys.*, **12**, 217–230.

UCAR, 2021: Monsoons. https://scied.ucar.edu/learning-zone/storms/monsoons (Accessed September 25, 2021).

Verdon, D. C., and S. W. Franks, 2005: Indian Ocean sea surface temperature variability and winter rainfall: Eastern Australia. *Water Resour. Res.*, **41**, 1–10, https://doi.org/10.1029/2004WR003845.

Wang, B., and Q. Ding, 2008: Global monsoon: Dominant mode of annual variation in the tropics. *Dyn. Atmos. Ocean.*, **44**, 165–183, https://doi.org/10.1016/j.dynatmoce.2007.05.002.

——, L. Ho, Y. Zhang, and M.-M. Lu, 2004: Definition of South China Sea Monsoon Onset and Commencement of the East Asia Summer Monsoon. *J. Clim.*, **17**, 699–710.

Wang, P. X., B. Wang, H. Cheng, J. Fasullo, Z. T. Guo, T. Kiefer, and Z. Y. Liu, 2014: The global monsoon across timescales: Coherent variability of regional monsoons. *Clim. Past*, **10**, 2007–2052, https://doi.org/10.5194/cp-10-2007-2014.

Webster, P. J., 1981: Monsoons. *Sci. Am.*, **245**, 108–118.

Webster, P. J., V. O. Magaña, T. N. Palmer, J. Shukla, R. A. Tomas, M. Yanai, and T. Yasunari, 1998: Monsoons: Processes, predictability, and the prospects for prediction. *J. Geophys. Res. Ocean.*, **103**, 14451–14510, https://doi.org/10.1029/97JC02719.

Wheeler, M. C., and H. H. Hendon, 2004: An All-Season Real-Time Multivariate MJO Index: Development of an Index for Monitoring and Prediction. *Mon. Weather Rev.*, **132**, 1917–1932, https://doi.org/10.1175/1520-0493(2004)132<1917:AARMMI>2.0.CO;2.

Wheeler, M. C., and J. L. McBride, 2012: Australasian monsoon. *Intraseasonal Variability in the Atmosphere-Ocean Climate System*, Springer Berlin Heidelberg, 147–197.

Xie, P., and P. A. Arkin, 1997: Global Precipitation: A 17-Year Monthly Analysis Based on Gauge Observations, Satellite Estimates, and Numerical Model Outputs. *Bull. Am. Meteorol. Soc.*, **78**, 2539–2558, https://doi.org/10.1175/1520-0477(1997)078<2539:GPAYMA>2.0.CO;2.

Yang, X., and Coauthors, 2020: Spatial and Temporal Characterization of Drought Events in China Using the Severity-Area-Duration Method. *Water*, **12**, 230, https://doi.org/10.3390/w12010230.

Zhang, H., 2010: Diagnosing Australia-Asian monsoon onset / retreat using large-scale wind and moisture indices. *Clim. Dyn.*, **35**, 601–618, https://doi.org/10.1007/s00382-009-0620-x.

# **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.

# **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** |