The University of Leeds – School of Earth and Environment

Analysis and Prediction of the West African Monsoon Onset.

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Submitted in accordance with the requirements of the degree of Doctorate of Philosophy.

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The candidate confirms that the work submitted is his own, except where work which has formed part of jointly authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

It is the candidate's intension to continue in the field of academia after completion of their PhD. As such the decision to focus research and the thesis on publications was taken by the candidate and his supervisors. The results from the following work have direct impact on the West African research community; therefore the decision was made to relay the findings of this work to the community as soon as possible. The thesis has therefore been constructed as a thesis by publication. The layout of the thesis is as follow:

1. Introduction

2. Publication in the Journal of Climate. – The West African Monsoon Onset: A concise comparison of definitions

3. Publication accepted to Monthly Weather Review – On what scale can we predict the agronomic onset of the West African Monsoon

4. Publication prepared for submission to the Quarterly Journal of the Royal Meteorological Society – The influence of the MJO on local agronomic onset across West Africa

5. Conclusion

6. Appendix review of the use of onset definitions in current literature

5. Internal Met Office report prepared for submission – An assessment of the skill of the Met Office seasonal forecasting model in predicting the West African Monsoon onset.

Chapters 2 and 3 consist of jointly authored and published work. They are repeated here in their accepted and published versions. Full references for these works are:

Chapter 2 – Fitzpatrick, R. G. J., D. J. Parker, J. H. Marsham, P. Knippertz, and C. L. Bain (2015), The West African Monsoon Onset - A Concise Comparison of Definitions, *J. Clim.*, *28*, 8673-8694.

Chapter 3 – Fitzpatrick, R. G. J., D. J. Parker, J. H. Marsham, P. Knippertz, and C. L. Bain (2016), On what scale can we predict the agronomic onset of the West African Monsoon?, *Mon. Weather Rev.*

For Chapter 2, the initial motivation was provided by the candidate through research presented in Appendix A. Peter Knippertz suggested that the difference between definitions was explored in more detail. The candidate selected seven definitions to compare in various observational and re-analysis datasets which were then presented as a report and subsequently an article (Chapter 2). The candidate is the main author of this article; he received editorial support from his supervisors. The motivation for Chapter 3 came from the candidate who suggested to his supervisors that local onsets should be the focus of the remainder of the thesis. However the applicability of local onsets was unclear due to a presumed high level of noisiness. From analysis of current literature, the candidate realised that a bespoke method to analysis local onset homogeneity was required. With the assistance of Doug Parker, the germination of Chapter 3 was written as a short report to be presented initially as a poster. Through feedback it was decided to extend the short work into a full article to provide a definitive and complete analysis. As for Chapter 2, the algorithms, methods and text written was done by the candidate. Extensive editorial advice, particularly in understanding the logistics of how the results in Chapter 3 could be best presented was provided by all four supervisors. As a result, the work presented is written by the candidate, with initial motivation and continued development of the method provided by the candidate with support from his supervisors.

For Chapter 4, the motivation and text was again provided by the candidate with support from his co-authors. In conjunction with the candidate's supervisors, a list of potential triggers for local onset was formed. The candidate investigated each trigger and determined the most impactful and relevant trigger to extensively explore during the time of this work. The text was written by the candidate with editorial assistance and advice provided by his supervisors who also assisted with interpreting the results particularly John Marsham's assistance with the vertical velocity plots. All work presented in this thesis has been written by the candidate with the assistance of his supervisors. The direction of the thesis has been driven by the candidate with the underlying vison presented by him. Support has been given by the candidate's supervisors, particularly advice on how best to write academically allowing for substantial progress in the candidate's report writing skills. Whilst the help of the candidate's supervisors cannot be understated, the candidate has worked for considerable periods of time independently on this work and believes that his contribution to this thesis is extensive enough to meet the set criteria.

Acknowledgements

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Abstract

The West African Monsoon onset marks a vital point in the seasonal monsoon cycle over the region with direct implications for local farmers and other stakeholders. In this work, valuable insight into the exact definition of the monsoon onset, its level of spatial consistency and cause of inter-annual variability of onsets has been presented.

Criteria are presented to determine the value of monsoon onset definitions. There exist over seventeen unique onset definitions in publication. In this work, a representative sub-set of definitions have been compared to assess the relative value and suitability of onset definitions. It is found that the length scale over which a definition is defined determines the relevance to certain users. Local farmers require knowledge on local onset definitions which often have no similarity to regional onset definitions.

Local onset dates are shown to have a pragmatic level of spatial homogeneity. Local Onset Regions (LORs) are presented over which local onset variability can be studied using a representative time series of onset dates.

Using LORs, it is found that the seasonal progression of the Inter-Tropical Front and the phase of the Madden-Julian Oscillation drive the inter-annual variability of local onsets. The late passage of the Inter-Tropical Front past a LOR is linked to later onset in that region. Furthermore, when the Madden-Julian Oscillation inhibits convection across the Guinea Coast, local onset dates tend to be earlier than climatology. Further research into predicting drivers of local onset variability are suggested.

Finally, seasonal forecast models tend to under-predict the variability of onset dates across West Africa. There is little significant correlation between observed onset dates (regional or local) and forecasts. It is concluded that seasonal onset forecasts are currently of little value to forecast users in West Africa. Suggestions as to the cause of this limitation are discussed.

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List of Figures

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Common abbreviations

As each Chapter of this work is presented in the form of a stand-alone article, abbreviations are presented at the start of each Chapter. For general reference, a list of common abbreviations is also provided below. The abbreviations MART and AODM are inter-changeable due to editor suggestions in the publications of Chapters 2 and 3.

Abbreviation	**Meaning**
AEJ	African Easterly Jet
AEW(s)	African Easterly Wave(s)
AODM*	Agronomic Onset Definition of Marteau et al. (2009)
BN	Benin/Nigeria border (a local onset region defined in Chapter 3)
CH	Cameroon Highlands (a local onset region defined in Chapter 3)
CT	Coastal (a local onset region defined in Chapter 3)
ERA-I	The ERA-Interim dataset
FONT	Regional onset definition presented by Fontaine et al. (2008)
GoG	The Gulf of Guinea
GPCP	The Global Precipitation Climatology Project
IM	Indian Monsoon
ITCZ	The Inter-Tropical Convergence Zone
ITF	The Inter-Tropical Front
LeB_Loc	Local onset definition derived from Le Barbé et al. (1999)
LeB_Reg	Regional onset definition derived from Le Barbé et al. (1999)
LOR(s)	Local Onset Region(s)
MART*	Local onset definition of Marteau et al. (2009)
MBF	Mali/Burkina Faso (a local onset region defined in Chapter 3)
MCS(s)	Meso-scale Convective System(s)
MJO	Madden-Julien Oscillation

NN	Niger/Nigeria border (a local onset region defined in Chapter 3)
OLR	Outgoing Longwave Radiation
OMO	Local onset definition from Omotosho et al. (2000)
SHL	Saharan Heat Low
SJ	Subjective onset definition from Sultan and Janicot (2003)
SJ_10/SJ10	Objective recreation of the regional onset definition of Sultan and Janicot (2003)
SST(s)	Sea Surface Temperature(s)
TCW	Total Column Water
TRMM (v6/v7)	The Tropical Rainfall Measurement Mission dataset (version 6/version 7)
WAM	The West African Monsoon
YAM	Local onset definition presented by Yamada et al. (2013)

Chapter 1

Introduction

1. Introduction

One of the greatest present humanitarian challenges facing our society is the growing stress on water resources in developing countries. The needs of an increasing population coupled with the added water usage of rapidly industrialised economies leads to particular demands on the availability of clean water. Furthermore, given the financial limitations of local farmers (particularly subsidence farmers as identified by Douxchamps et al. 2016) within developing countries, there is a dependence on accurate knowledge of precipitation either through forecast predictions or individual's experience due to the lack of irrigation and crop insurance. This issue is particularly compounded within monsoon regions given the large disparity in seasonal precipitation totals between wet and dry seasons (Janicot et al. 2011). The Sudanian and Sahelian regions of West Africa (taken here as 20°W–20°E, 8–16°N) are particularly vulnerable to incorrect forecasting of the seasonality of monsoon rainfall and are the focus of this study.

Several countries within West Africa are amongst the least developed in the world and are largely reliant on small-scale farming to meet internal food demands without imports. For example, currently Nigeria imports approximately NGN365 billion (about £1.2 billion) worth of rice per year to make up the shortfall in rice produced in the country (presentation by Dr Olumeko at Revitalizing Irrigation in Sub-Saharan Africa workshop, 2013). Approximately 90% of farmland within West Africa is rain-fed giving increased emphasis to the accurate forecasting of the timing of monsoon rains. Despite recent developments by the Comprehensive Africa Agriculture Development Programme (CAADP) in conjunction with the United States Agency for International Development (USAID), including improving water supply for farmers from the White Volta River basin in Burkina Faso and Ghana, the region has a very fragile dependence on the seasonal variability of monsoon rains. From 2009-2010 over 10 million people were affected by drought across the Sahel due to the poor rainy season (World Health Organization annual report 2010). In general, roughly one in four crop sowings fails due to inaccurate monsoon onset predictions (Marteau et al. 2011).

In 2012, the United Nations (UN) estimated the cost of humanitarian aid for the Sahelian region of West Africa at US$1.6 billion. Sub-Saharan Africa regularly receives the highest proportion of available financial aid given globally (Fig. 1.1). The UN Office for the Coordination of Humanitarian Affairs (OCHA) stated that food security in the Sahel had "deteriorated dramatically through 2012 owing to drought and sporadic rains, poor harvest, rising food prices, displacement and insecurity". With accurate prediction of the seasonality of monsoon rains and key characteristics (such as onset date, risk of false onset and seasonal rainfall amount), it is possible to improve crop selection and sowing date choice leading to improved harvest yields within the region. In isolation, successful monsoon forecasts will not cure all agricultural issues over West Africa, but will provide substantial benefit.

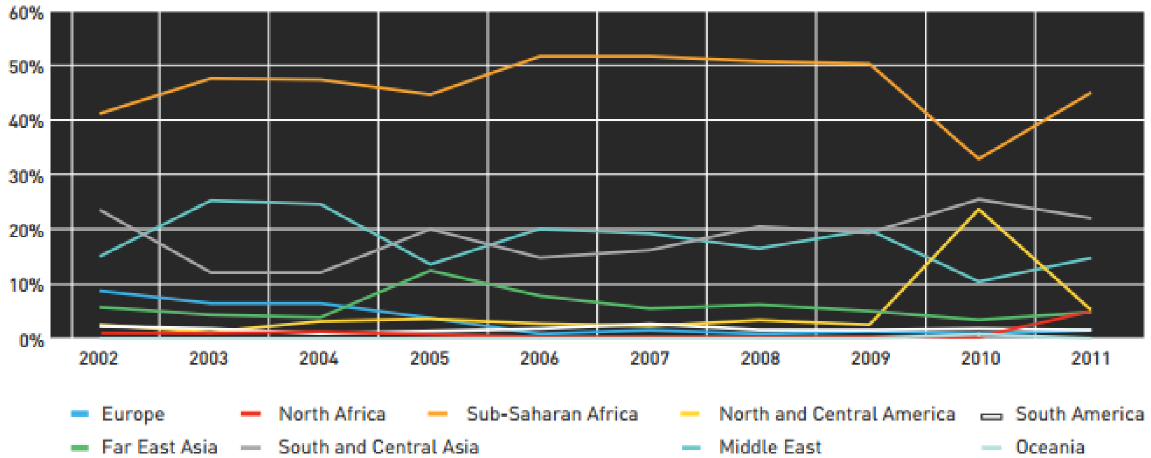

Figure 1.1 - International humanitarian response proportions by region for period 2002 – 2011. Source Global Humanitarian Assistance report 2013

(http://www.globalhumanitarianassistance.org/wp-content/uploads/2013/07/GHA-Report-2013.pdf).

Ingram et al. (2002) note that the onset date of Sahelian monsoon rainfall is the most important information that can be provided to local farmers. Sultan et al. (2005a) study the dependence of millet seed growth with respect to accurate prediction of monsoon onset date. The study finds that modelled yield of millet seed is over 70% of maximum attainable yield for planting dates between 8 days before to 11 days after monsoon onset. The study suggests that millet seed production is quite invariant to errors in monsoon onset prediction, however the authors admit that millet is naturally a more stable crop then other locally grown crops. Other commonly grown crops may have higher dependence on accurate onset prediction (Ewansiha and Singh 2006).

In addition to agricultural benefits, accurate seasonal prediction of monsoon onset date and total rainfall would allow humanitarian organizations to predict and prevent the spread of water borne diseases such as cholera, insect transmitted diseases such as dengue fever (break-bone fever) and malaria or bacterial infections such as meningitis (Molesworth et al. 2003; Sultan et al. 2005b; Mera et al. 2014). The threat of an infectious outbreak is increased sufficiently with malnutrition, overcrowding and heavy rainfall; West Africa is therefore a region of very high risk for pandemic outbreaks.

The WAM onset can be considered on various scales such as the local (grid-point) and regional (supra-national) scale. Understanding the similarities and differences between different onset metrics over different scales is important as different forecast users require bespoke onset information. Furthermore, in order to fully understand the dynamical causes of monsoon onset, a comprehensive awareness of the range of onset dates that can be used or assessed is required. This work considers multiple onset definitions applicable over different scales. The findings of this work therefore provide insight into multiple stages of the WAM season, particularly the different onset phases that can occur (including but not limited to the difference between large scale shifts in the system and the localised onset of societally-useful rainfall).

The work presented here aims to improve understanding and forecasting capabilities of the WAM onset. In order to achieve this goal, focus has been given to improving the value of WAM onset forecasts for forecast users. Within this Chapter, Section 2 outlines the aims of the work, with Section 3 providing a critical evaluation of the current WAM literature with focus on the regional (supra-national) scale. Section 4 expands on Section 3 to highlight current understanding of local onset variability and introduce the motivation for the remaining Chapters of this work. Section 5 highlights the limitations of the study with Section 6 outlining the structure of the remainder of the thesis.

2. Strategy and aims of the thesis

2.1. Target audience for the work

When analysing the cause of variability in the WAM onset, it is important to first understand the audience that the work is presented for. Analysis of the WAM can be performed on multiple length or time scales and different forecast users will prioritise information at scales relevant to their goals. Each forecast user with a vested interest in the quality and outcomes of forecasts or meteorological analysis over West Africa can be considered a stakeholder. However, not all information is relevant to decision making strategies for all forecast users. For example, understanding of the conditions that may lead to a meso-scale convective system (MCS) developing into a hurricane over the eastern Atlantic Ocean is not relevant to the needs of a local self-sustenance farmer.

Much like the term “onset”, which is explored in more detail in Chapter 2, the term “stakeholder” is sometimes used without definition suggested that the meaning of the word should be implicit (an example is the work of Bhave et al. 2016). Identifying relevant stakeholders for this work requires further interrogation.

In this work, the primary interest is in the local, agronomic monsoon onset which is described in more detail later. The decision behind this focus was led by the work of Marteau et al. (2009) and also by the literature review performed in Appendix A. As such, the work presented here is primarily aimed towards forecast users with a direct interest in local agriculture across West Africa. Douxchamps et al. (2016) present four agricultural household types found in three West African countries. These household types are denoted as: subsistence, diversified, extensive, and intensified. The four household types in Douxchamps et al. (2016) vary in size, food security, capacity for adaption, and their likely use of climate information. However, all four household types can be considered to have an interest in accurate forecasting of the agronomic onset. In this work, no discrimination between the household types is provided as all can be considered interested stakeholders.

Whilst ultimately improved forecasting of the agronomic monsoon onset should enhance decision making for farmers, the work presented here cannot be directly applied by farmers unlike for example the work of Lodoun et al. (2013). Rather, the work presented here is aimed at improving forecasts and understanding of forecast limitations. The ultimate target audience of this work should therefore be considered to be forecast centres and African meteorological institutions. As an example, the identification of local onset regions in Chapter 3 provides information that could be used by Regional Climate Outlook Forums such as the annual Forum on Climate Variability and its Application in Early Warning Systems for Food Security (PRESAO) who in turn can provide relevant information for local farmers.

In this work, with the exception of Chapters 2 and 3 (which are reprinted in their published form), the term stakeholder is replaced with the most relevant group of interested parties in the work presented. It is hoped that this allows for greater understanding of the scope of the presented work.

2.2. Evaluation of forecasts

The work presented within this thesis aims to improve forecast value across West Africa. This includes both improving general understanding of the WAM onset and providing areas where forecast quality can be improved. Before considering the current level of WAM understanding, a full appreciation of forecast skill is required.

The fundamental aim of any meteorological work is to better understand weather-related events, interactions or processes in order to improve forecasts and decision making strategies by forecast users. How well a forecast accurately predicts a given climatological phenomenon (or phenomena) is often referred to as the forecast skill.

Forecast skill encompasses many different concepts and can be measured in multiple ways (a list of examples can be found at http://www.nws.noaa.gov/oh/rfcdev/docs/Glossary_Verification_Metrics.pdf). Additionally, the papers of Murphy and Winkler (1987) and Murphy (1993) provide different methods whereby forecast skill can be evaluated. The authors separate forecast skill into three distinct categories: the forecast’s consistency, the forecast’s quality and the forecast’s value. This is in contrast to many common forecast verification techniques which focus purely on skill scores and associated measures of skill (which can be considered measures of forecast quality).

a. <u>Forecast consistency</u>

Forecast consistency can be paraphrased as “does a forecast do what it should do given our knowledge of the climate system”. As an example, if a forecast correctly captures observed teleconnections between sea surface temperatures (SSTs) and seasonal precipitation totals, this forecast is more consistent than a forecast that does not capture this teleconnection. It is possible that a forecast can be judged as consistent when tested for one event, and not consistent when tested on other events; as such forecast consistency is summarised on a case study basis (e.g., does the model successfully capture the location and intensity of the maximum rain belt).

Forecast consistency can only be addressed on events which are “well known” to some extent. Without knowledge of causes, evaluating a forecast’s consistency with regard to monsoon onset would be naturally limited. Whilst regional monsoon dynamics are relatively well understood and covered in scientific literature (see references in Appendix A), local onset consistency is not currently measurable as there is insufficient information on the reasons for local onset variability. An assessment of forecast consistency is not produced in this project given the focus on local onset variability.

b. <u>Forecast quality</u>

Forecast quality is the most common form of forecast verification used in literature and can be assessed using a variety of skill scores (Roca et al. 2010; Vellinga et al. 2012). Although it is possible to use “simple” skill scores, such as correlation statistics or the Brier Skill Score, it is suggested by Murphy and Winkler (1987) that joint-distribution skill scores provide a fuller assessment of forecast quality. One of the primary reasons for this is that most simple skill scores (such as the Brier Skill Score) only provide a ratio of forecast “hits” to forecast “misses” without necessarily containing information on the type or magnitude of forecast “misses”. When considering a forecast of WAM onset dates, it is possible to suggest that an erroneously early onset forecast presents greater risk to local farmers (particularly smaller scale sustenance farmers) than an erroneously late onset forecast (as a late forecast could be adapted to more easily by farmers). Joint-distribution quality assessments, such as the calibration-refinement factorization assessment allow for distillation of this information and are explained in full in Appendix B which is presented in the form of a Met Office internal report.

A forecast can be shown to have quality even if it has little to no consistency. For example, a forecast can be perfectly anti-calibrated (or anti-correlated) with observations. A perfectly anti-calibrated model has some semblance of quality (as whatever outcome the forecast predicts, the opposite outcome is the most likely). However, this result could be due to a compensation of model errors meaning there would be very low forecast consistency. In our assessment, forecast quality is measured using joint-distribution methods with results presented in Appendix B.

c. Forecast value

The value of a forecast encompasses many factors of forecast skill. Whereas measures of the consistency and quality of a forecast are assessments of model skill, forecast value is a measure both of the model and of the methodologies used. Forecast value therefore is not only a measure of forecast skill, but of forecaster skill. The value of a forecast (here taken as the WAM onset forecast) can be assessed along five branches:

- Forecast availability – *Is the forecast accessible at a lead time that is useful?* Availability captures the means of providing information to intended forecast users and the timeliness of data. When considering a planting date for rain fed crops, it is important that relevant data is provided with enough time to be accessed by decision makers (both institutional and individual) and acted upon accordingly. A high quality forecast that is only available one day prior to predicted onset date will be less valuable than a forecast of similar quality available two to three weeks earlier. It is important to note here that whilst most WAM onset definitions are only available *a posteriori* (e.g. Sultan and Janicot 2003; Gazeaux et al. 2011), here onset forecasts and reliable onset precursors are considered which are expected to be available *a priori*.
- Forecast metric usability – *Is the metric predictable?* All aspects of meteorological forecasts have a limit of predictability. This can differ between metrics and is partially dependant on precision (spatial resolution, threshold values etc.). Therefore, a valuable onset forecast study answers both the question “can we predict the onset?” and “to what extent can onset be predicted?” Measuring the usability of the forecasted metric allows for a holistic analysis of the problems encountered in forecasting. For certain events (such as accurate prediction of the absolute timing of local onsets), the

issue may not be that current forecasts cannot accurately predict the event, rather that the event is unpredictable.

- Forecast relevance – *Does the forecast provide the right information?* A good forecast must be user-centric and cover the widest range of potential user needs. Whilst accurate forecasts of cyclogenesis off the West African coast stimulated by African Easterly Waves (AEWs, see Berry and Thorncroft 2005), will be of interest to some forecast users, it is of little interest to farmers across the continent. Therefore for a forecast to be valuable for a specific subset of decision makers, it must contain information relevant to their needs. Forecast relevance is therefore an evaluation of forecast value given specific groups of forecast users.
- Forecast necessity – *Is the forecast required?* Certain aspects of weather are more variable than others. For events with little inter-annual variability (e.g. the timing of regional onset; see Chapter 2 or Sultan and Janicot 2003), a climatological mean date may act as a suitable predictor for most interested users in most years. By contrast, highly variable metrics (such as agronomic onset dates) require accurate forecasts every time the event occurs. Forecast necessity can be assessed using a cost/loss study into the relative uplift a forecast user would expect by using a given forecast over other decision making tools (such as a climatological or persistent forecast). Uplift could be in the form of financial benefit related to increased crop yield through forecast selection but can take other forms. An example of this is given in Sultan and Janicot (2005b) where millet yield is measured against the timing of crop planting relative to onset date.

- Forecast quality – *Is the forecast high quality?* Forecast quality is a determining factor in forecast value. A forecast of higher quality will intuitively have higher value. As previously mentioned, forecast consistency is not naturally coupled with forecast quality and thus forecast consistency is not a determining factor in forecast value. A forecast can be inconsistent with state of the art knowledge of the forecasted system, yet still have value.

As the value of a forecast encompasses many different metrics with specific focus towards the forecast users, increasing the value of a forecast provides the most immediate benefit for interested parties. The underlying motivation of this project is therefore to increase the value of information on the WAM onset and thus improve predictive capabilities.

d. Relevance of study

Many current works regarding the WAM provide sensitivity studies based on a particular model using specifically created metrics without understanding the implications for forecast users and decision makers. As an example, Nguyen et al. (2014) create a unique monsoon onset definition (termed the Nguyen-McGregor-Renwick method), analogous to the date when zonal winds change signs at a given latitude. The authors find that their selected forecast model can accurately forecast their created onset date thus concluding that the model used accurately represents the WAM onset and the onset definition used is fit for task. However, there is no appreciation of spatial variability in the onset definition or how pragmatic the onset date would be to use (is it usable, relevant, necessary etc.). Therefore whilst the onset definition is predictable, it is questionable how much value it has.

Unlike the Nguyen-McGregor-Renwick method, the onset definition presented by Marteau et al. (2009) was made in conjunction with decision makers in Senegal, Mali and Burkina Faso; the definition therefore relates directly to agronomic needs. Compared to the onset definition presented by Nguyen et al. (2014), it is arguable that the definition presented in Marteau et al. (2009) is more relevant and has greater value albeit only objectively assessed *a posteriori*; thus the agronomic definition should be of heightened interest for future study. However, as previously mentioned, forecast value is multifaceted, thus the agronomic definition can only be said to be more valuable if it is potentially usable. Deeming the predictability of local onset dates ties the narrative of chapters 3 and 4 of this work presenting the common theme.

The underlying goal of this work is therefore to improve the value of future forecasts and analyses of the WAM onset through the five branches of forecast value listed above. By using freely available observational and re-analysis datasets with focus on seasonal forecasting timescales, we ensure that our results meet the availability criterion listed. The other four branches of forecast value are explored within the rest of the work.

3. Critical evaluation of current onset literature, onset predictability and limitations

There has been substantial prior work performed on the WAM onset. In order to improve forecast value of the onset, a critical perspective of current onset studies is required. Successes and criticisms of current work as well as opportunities for extension of scientific knowledge are provided with primary focus in this Section on the large-scale WAM dynamics.

a. What is the West African Monsoon onset?

Before interrogating the drivers of onset variability over West Africa, it is important first to establish what is meant by the WAM onset. The definition of the WAM onset is very fluid with many definitions present in the literature. In addition, onset definitions are often presented using different data across different time periods and analysed over different regions of West Africa (compare Sultan and Janicot 2003; Gazeaux et al. 2011 and Yamada et al. 2013).

A concise and comprehensive list of onset definitions has not been presented previously. In this work, a reference point for researchers to understand the variability of onset definitions present for the WAM is given. Chapter 2 of this work provides the most comprehensive comparison of multiple onset definitions analysed using the same observational and re-analysis data currently available.

Chapter 2 provides necessary information for researchers of the WAM that has been absent previously. Whilst studying the existing literature on the WAM onset and its variability, the authors of this work noticed that there is an apparent acceptance as to the singular definition of the WAM onset despite the wide variety of onset definitions present. Appendix A lists a selection of recent papers that study the monsoon onset and compares the definition of monsoon onset used. Several conclusions can be drawn from Appendix A. Firstly, it is apparent that there is no consensus as to the exact definition (or definitions) of the WAM onset. The majority of onset studies focus on regional onset, primarily the onset definition from Sultan and Janicot (2003), however this definition is not universally applied and indeed may not serve the needs of local users. In addition, several studies present new onset definitions which are subsequently not compared to previously presented definitions.

Strikingly, several studies listed in Appendix A do not directly reference an onset definition, instead allowing inference of onset definition which highlights a larger issue. It appears that some researchers consider the WAM onset as a clear and axiomatic statement that needs no further expansion. Given the wide variety of definitions available, this assumption can lead to confusion for the reader. For practical advancement of monsoon understanding, either a consensus on what the WAM onset is, or greater appreciation of the range of onset definitions is required. The onset of the WAM is a man-made construction relating to the needs of local, regional or remote forecast users. Therefore, it is to be expected that different onset definitions will be required depending on the specific needs of forecast users. Chapter 2 helps establish the importance in distinguishing different onset definitions and applying multiple definitions for different user needs.

The work of Chapter 2 highlights the difference between different onset dates as a function of the scale on which they are applied. In the subsequent work, onset definitions applied on a sub-national or grid-point scale are termed “local” onsets with “regional” onsets established on the supra-national scale. Chapter 2 finds an apparent disparity between the timing of, and inter-annual variability of, local and regional onsets; these two forms of onset are considered separate throughout the rest of the work.

b. The cause of regional onset variability

Over the past 70 years, there has been a concerted effort to understand the cause of the rapid northwards advancement of the zone of maximum precipitation from the Guinea Coast towards the Sahel. The band of maximum precipitation and convergence is sometimes referred to as the Inter-Tropical Convergence Zone, however over West Africa this definition is contentious (see Nicholson 2013); the terms zonal rain belt, maximum rain belt, the maximum zone of convergence or similar terms are predominantly employed here.

The seasonal structure of the WAM has been well established. The most concise description of the WAM is provided by Thorncroft et al. (2011; Fig. 1.2), who segment the annual monsoon progression into four distinct periods which track the location of the zonal maximum rain belt. Between November and April, the maximum rain belt is located just north of the equator; this period is denoted the oceanic phase. From mid-April until the end of June the maximum precipitation belt is located around 4°N, off the Guinea Coast (termed the coastal phase). After the coastal phase, there is a two-week transitional phase as the maximum rain belt rapidly progresses from its quasi-stationary coastal phase location towards the Sahel. Finally, from mid-July until September, the maximum rain belt is located around 10°N during what is termed the Sahelian phase. The large scale monsoon structure presented by Thorncroft et al. (2011) is in agreement with other studies, however the timing of phases differs between studies (see for example Walker 1957; Hasthenrath 1991; Sultan and Janicot 2003). From a large-scale or regional perspective, the monsoon onset is often considered as the start of the Sahelian monsoon phase.

One of the most striking things about previous onset studies is the lack of agreement in findings (such as the role of the Atlantic Cold Tongue on regional onset timing). Included in this section are several areas where a lack of agreement in findings is present. It is important to be aware of areas of disagreement within the WAM literature in order to fully appreciate the complicated nature of the monsoon system and not over-stress the importance of certain climatological features.

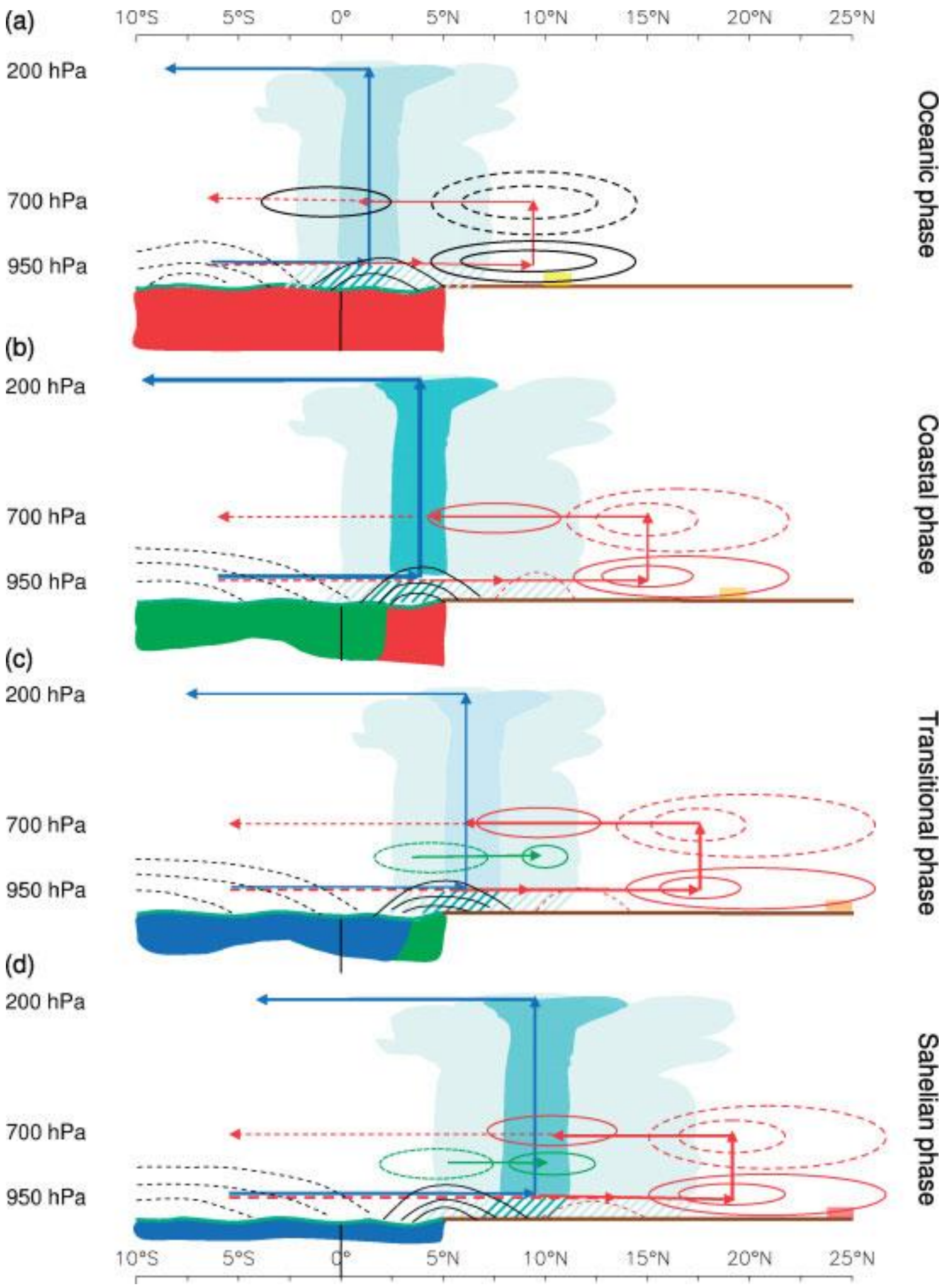

Figure 1.2 - Thorncroft et al. (2011), Fig. 12. Schematic showing the four key phases of the annual cycle of the West African monsoon. Included for each phase are the following: the location of the main rain band (indicated by clouds and rainfall with peak values highlighted by darker shaded clouds and rainfall), the location of the Saharan heat-low (indicated by yellow, orange and red shading at the surface poleward of the rain band, with increased redness indicating increased intensity). Atlantic Ocean temperature and associated mixed-layer depth (with decreased temperatures indicated by the red-to-green-to-blue transition). Moisture flux convergence maxima and minima (solid

contours indicate moisture flux convergence and dashed contours indicate moisture flux divergence), and the deep and shallow meridional circulations (blue and red lines with arrows); dashed lines suggest some uncertainty about the extent to which shallow meridional circulation return flow penetrates the latitude of the main rain band or not. The moisture flux convergence quadrupole structure is highlighted by red contours and the dipole at 850 hPa structure is highlighted by green contours.

c. First-principle overview of the West African Monsoon

From first principles, the northwards advancement of the maximum rain belt can be thought of as a response to an increased pressure gradient between the Gulf of Guinea (GoG) and the Saharan Heat Low (SHL).

During late April and early May, an upwelling of cooler SSTs occurs over the GoG forming the Atlantic Cold Tongue (Okumura and Xie 2004; Caniaux et al. 2011). When the Atlantic Cold Tongue is established, there is an increase in surface pressure over the GoG which is believed to be partially responsible for suppression of deep convection over the Guinea Coast. This reduction in deep convection marks the beginning of the transitional phase of the monsoon.

Throughout May-June, there is a deepening of a large-scale low pressure region across the Sahara (termed the SHL, Lavaysse et al. 2009). This low pressure region, in conjunction with the higher pressure system across the Guinea Coast leads to a latitudinal gradient that favours increased northwards advection of cool moist monsoon air into the Sahel and ultimately a northwards shift of the maximum rain belt. The northwards shift of the maximum rain belt from the Guinea Coast to the Sahel is very rapid and often referred to as the monsoon “jump” (Sultan and Janicot 2003; Fig. 1.3). However, when considering other metrics (such as meridional moisture flux) the “jump” perceived in precipitation Hovmöllers is not present (Fig. 1.4).

Sultan and Janicot (2003) suggest that orography plays a key part in the regional monsoon onset and the subsequent positioning of the maximum rain belt. Subsidence over the Atlas-Ahaggar Mountains contributes to high geopotential values north of the mountains and leads to the development of a leeward trough that reinforces the SHL. A positive feedback between the enhanced subsidence, a deepening of the SHL, enhanced moisture advection from the GoG and an intensification of the Hadley circulation over West Africa ensues, maintaining the maximum ran belt's position through boreal summer. A similar process is found in a numerical study by Hagos and Cook (2007).

The orientation of the mountains can lead to the monsoon rain belt shifting northwards over the western half of the monsoon region before the northwards shift over the eastern half of the monsoon region. This is further reinforced by the orientation of the Inter-Tropical Front (ITF) which is located closer to the SHL over its western portion. Regional averaging of metrics may therefore mask local variability, a topic covered in more detail in the remainder of this work.

Finally, Peyrillé et al. (2016) also show that to first order, the WAM onset is a response to the pressure difference between the GoG and the SHL with the shallow meridional circulation (a return flow which occurs higher in the troposphere than the low level monsoon flow and travels from the SHL towards the GoG) helping to limit the northwards extent of the maximum rain belt. It is therefore possible to deduce that, from a regional perspective, the pressure gradient present across West Africa must have some level of dominant control over the WAM system.

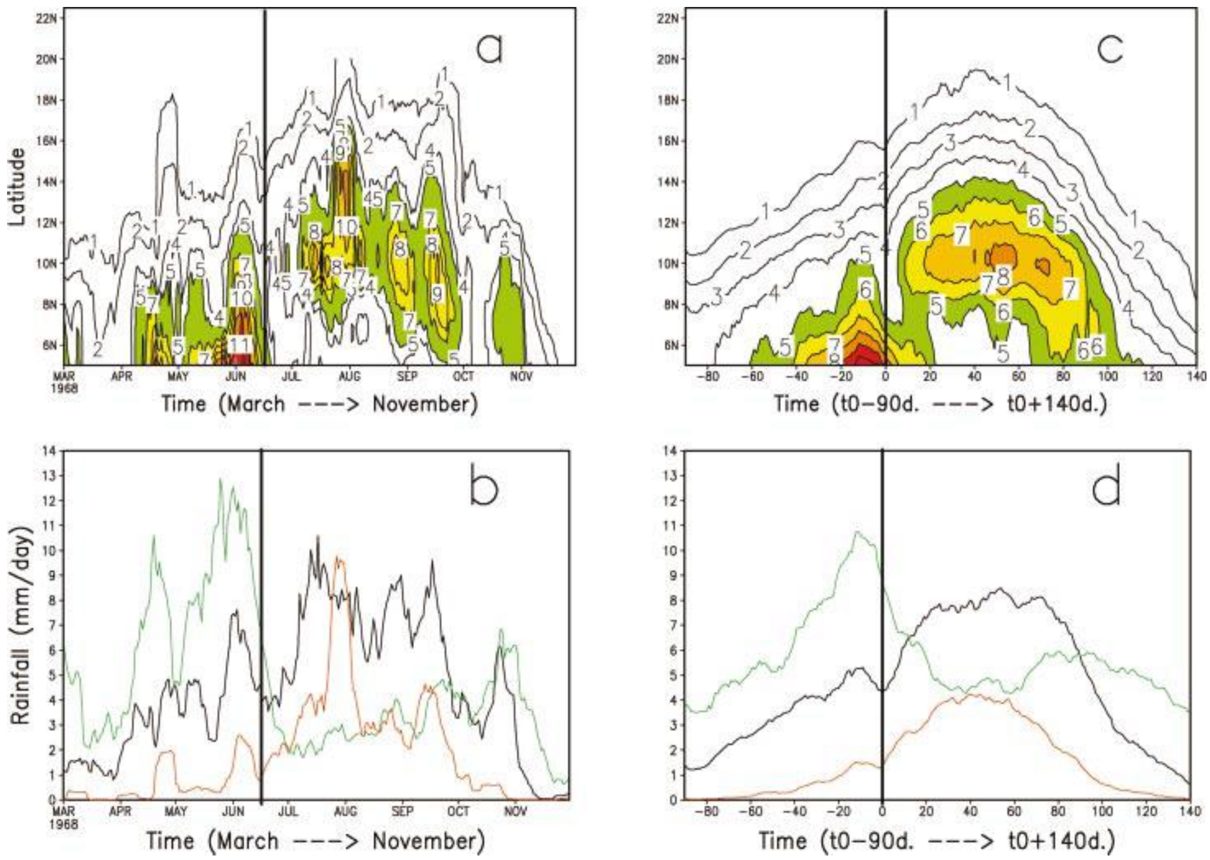

Figure 1.3 – Sultan and Janicot (2003), Fig. 4. (a) Time-latitude diagram from 1 March to 30 November 1978 of daily rainfall (mm day^{-1}), averaged over 10°W–10°E and filtered to remove variability lower than 10 days. Values greater than 5 mm day^{-1} are coloured [sic]. (b) Time sections of diagram (a) at 5° (green curve), 10° (black curve), and 15°N (red curve). In (a) and (b), the vertical line localizes the date selected for the ITCZ shift (17 June). (c) Composite time-latitude diagram of daily rainfall (mm day^{-1}) averaged over 10°W–10°E, filtered to remove rainfall variability lower than 10 days, and averaged over the period 1968–90 by using as the reference date the shift date of the ITCZ for each year. Values are presented from t_0 (the shift date) – 90 days to t_0 + 140 days. Values greater than 5 mm day^{-1} are coloured [sic]. (d) Time sections of diagram (c) at 5° (green curve), 10° (black curve), and 15°N (red curve). In (c) and (d), the vertical line localizes the date of the ITCZ shift at t_0 (the mean date over the period 1968–90 is 24 June).

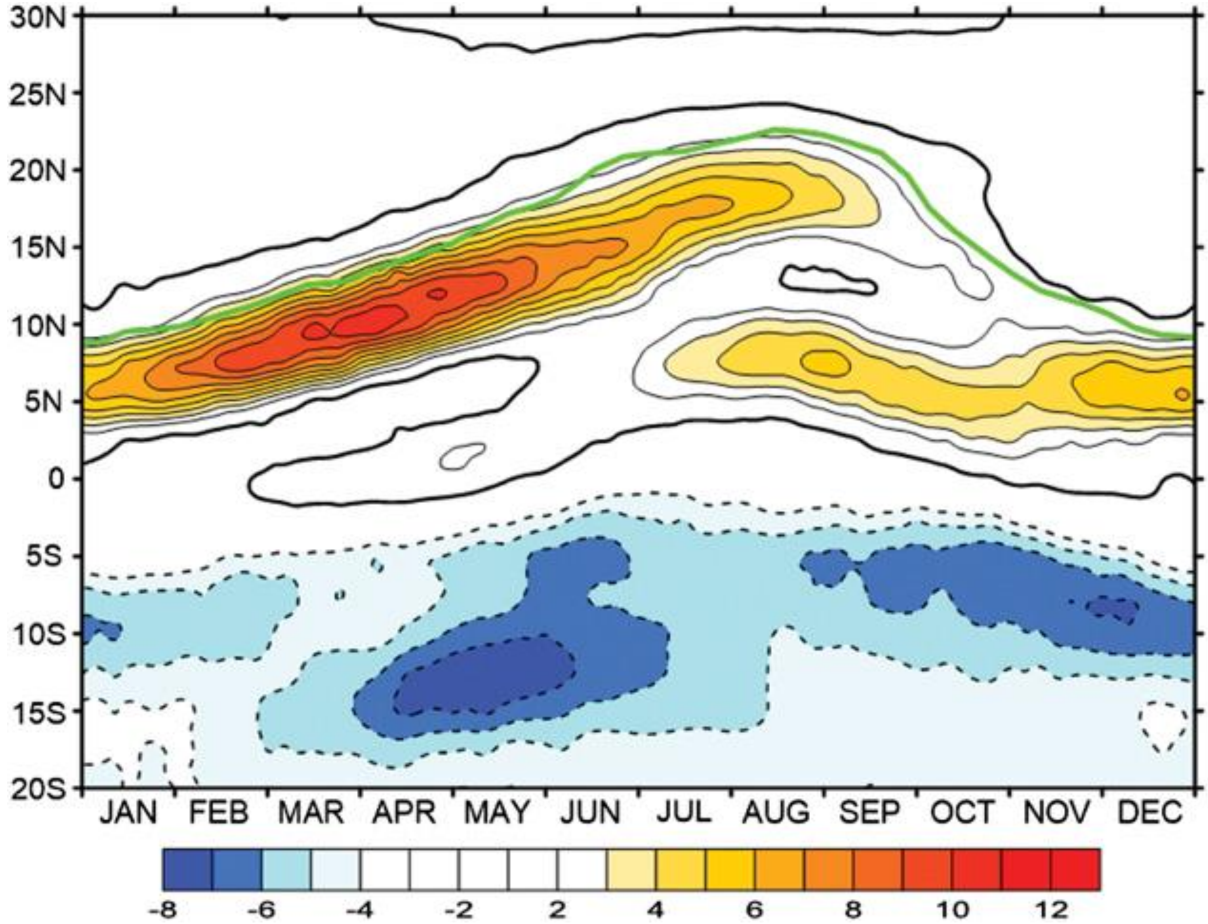

Figure 1.4 - Lélé et al. (2015) Fig. 5. Hovmöller diagrams of pentad mean annual cycles of total moisture flux convergence averaged over 10°W–10°E in millimetres per day. The latitude position of the ITF from the 15°C dew-point temperature (green line) is superimposed. The contour/shading interval is 1 mm day^{-1}.

d. <u>The nature of tropical convection</u>

The self-sustaining nature of the maximum rain belt at both quasi-stationary locations (Figs. 1.2b,d and 1.3c) follows the principles of gregarious tropical convection outlined in Mapes (1993). In the presence of a large, mature MCS, internal gravity wave dynamics provide conditions conducive to the production of further MCS activity near to the placement of the original MCS. Similarly, a region of subsidence is located at a further distance from the MCS, near the limit of the MCS outflow. This area of subsidence acts to inhibit the genesis of large scale convective

systems and thus the original MCS can be said to “feed” convection near itself and “starve” convection further away. This creates a self-sustaining convective system or a gregarious system. Furthermore, recent work has stressed the importance of the feedback between convection and convergence across West Africa both on a regional and more localised scale (Marsham et al. 2013; Birch et al. 2014a). Moisture flux convergence feeds convection which in turn potentially intensifies the surrounding pressure gradient favouring increased moisture flux convergence furthering the concept of gregarious convection. However, the cause and effect of this interaction is not fully understood and the forecasting potential of such an interaction is currently limited. For example, forecasting cold pools is currently difficult in coarse forecasting models with parameterized convection.
Gregarious behaviour has been shown to occur naturally when convective cells can create a proximate area that is more favourable for new convective cells than the more distant environment (Randall and Huffman 1980; Mapes 1993). Over West Africa, prior to the regional monsoon shift, the conditions for convection are much more favourable over the GoG than over the Sahel. Given the change in conditions around late June/early July listed in Sultan and Janicot (2003), and Flaounas et al. (2012a,b), this situation is reversed with superior conditions for convection over the Sahel.

Prior to the regional monsoon onset, there is little available moisture within the Sahel. In addition, the general large-scale atmospheric conditions are relatively stable and not conducive to deep large scale convection as opposed to the impact of the Madden-Julian Oscillation (MJO, Madden and Julian 1994) in destabilizing the environment presented in Matthews (2004). From a zonal perspective, the Sahel prior to regional onset can be said to have overall low convectively available potential energy and high convective inhibition (CIN). Overcoming this high CIN environment is critical for genesis and maintenance of high-intensity rainfall (Birch et al. 2014a,b).

CIN is a measure of the amount of energy required by a parcel of air to reach its level of free convection. As such, high CIN environments are not favourable for frequent deep convection as few air parcels will have enough energy to reach their free convection levels (although convective events in high CIN environments are often very intense). In order for deep convection to occur, the level of CIN in the proximate environment must be reduced. CIN can be reduced through (from Birch et al. 2014a):

- Daytime surface heating (as this destabilizes the vertical temperature profile)
- Synoptic upward forcing (which could be due to cold pool outflows, gravity wave currents or other dynamics)
- Low-level convergence (particularly present around the ITF)
- Low-level warm air advection (especially if coupled with high dew-point temperature)

In addition, latent heat flux can help to reduce CIN. It is also shown that localised convection has a much greater likelihood of eroding high CIN environments than large-scale convergence (Birch et al. 2014a). Therefore, prior to the shift of the maximum rain belt from the GoG into the Sahel, localised convergence and upscaling of smaller convective cells is the most likely genesis of MCSs over the Sahel. One potential trigger for localised or isolated convection over the Sahel prior to the regional onset is the uplift of moist air through cold-pool outflows (Provod et al. 2015).

Having established the variability of the WAM onset definition and an overview of the nature of tropical precipitation, climatic drivers of monsoon rainfall and regional onset are considered in the rest of this Section.

e. The impact of sea surface temperatures on the monsoon system

SST anomalies have been linked to many facets of the WAM, particularly the onset date and seasonal precipitation totals. A summary of current knowledge of SST teleconnections is provided in Rowell (2013), which is an extension of the work of Rowell et al. (1995). It is found that seasonal Sahelian precipitation anomalies are inversely correlated with higher SSTs over the GoG, the Indian Ocean and the eastern Atlantic Ocean. Sahelian precipitation is also positively correlated with SST anomalies over the Mediterranean Sea. These teleconnections also appear when considering the regional onset (see Caniaux et al. 2011; Liu et al. 2012 and Flaounas et al. 2012a).

There are contrasting results as to exactly how SSTs affect onset dates. By running a hindcast model with and without the seasonal upwelling in GoG SSTs, Druyan and Fulakeza (2015), find that the regional WAM onset date is not affected by the Atlantic Cold Tongue for the years 1999–2004. This result brings into question the role of GoG SSTs on the regional shift of monsoon rains suggested by Caniaux et al. (2011; Fig. 1.5).

Whilst it is widely accepted that SST anomalies impact seasonal precipitation totals over West Africa, their impact on monsoon onset (both local and regional) is not fully understood or agreed upon. Highlighting to what degree proximate and remote SST features impact the WAM onset is an area that needs future consideration.

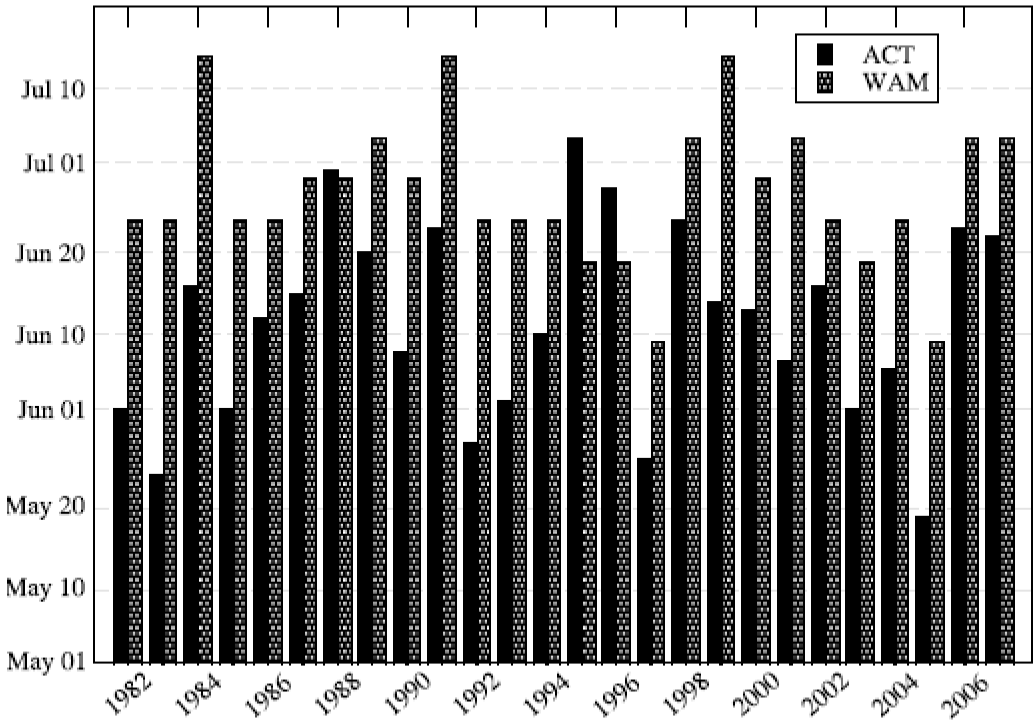

Figure 1.5 - Caniaux et al. (2011), Fig. 11. Onset dates for the Atlantic cold tongue (black bars) and West African Monsoon (grey [sic] bars) during the period 1982–2007. For the Atlantic cold tongue, the dates were computed with index T_1 (see article for more details); West African monsoon onset dates are from Fontaine and Louvet (2006) obtained with the Global Precipitation Climatology Project (GPCP; Xie et al. 2003) precipitation data set.

f. The impact of the Saharan Heat Low on the monsoon system

During boreal spring, there is an established westwards migration and deepening of the West African Heat Low (WAHL) towards its summer location over the Sahara forming the SHL (Lavaysse et al. 2009). The SHL establishes its summer location roughly two days prior to the regional monsoon onset shift. This increases the pressure gradient between the regional high over the GoG and the regional low over the SHL and provides conditions suitable for the jump of the maximum rain belt towards the Sahel.

Flaounas et al. (2012a) find that surface albedo changes across West Africa, in particular correspondent with the SHL, do not affect the timing of monsoon onset. Furthermore, from a seasonal forecasting perspective, the proximity of the SHL deepening to the regional monsoon onset limits its usefulness as a predictor of monsoon onset.

Whilst it is understood that the seasonality of the monsoon rain belt migration is linked to the migration and intensification of the SHL, the exact controls that the SHL exhibits on the monsoon onset are not entirely understood. The works of Sultan and Janicot (2003), Lavaysse et al. (2009) and Flaounas et al. (2012a) offer insight but also contain potentially contrasting information. To what extent the SHL impacts the timing of onset compared to how much it controls the maintenance and positioning of the maximum rain belt is a topic that deserves further consideration. Further work also should consider the variability of the SHL and how this can impact the monsoon onset on both the inter-annual and longer time scales (Roehrig et al. 2011).

g. The impact of the Madden-Julian Oscillation on the monsoon system

The MJO and its associated impact on the monsoon onset has also been extensively explored. The MJO is one the dominant planetary features affecting large-scale convection and precipitation within the tropics (Madden and Julian 1971; Madden and Julian 1994; Hendon and Salby 1994). Cyclical oscillations between enhanced and suppressed convection over the Pacific warm pool impact tropical convection through large scale wave dynamic responses. With a standard period of 40–90 days the MJO can provide predictive information into sub-seasonal variability of convection across the tropics on a pragmatic timescale (Janicot et al. 2009).

With respect to West Africa, much research has been done on the MJO-based connection between the Indian Monsoon (IM) and the WAM, particularly with respect to the regional onset date and active or break phases in monsoon rainfall. The onset of the IM is linked to a 15-20 day period of decreased rainfall over West Africa

(Matthews 2004; Janicot et al. 2009; Camberlin et al. 2010; Flaounas et al. 2012b). As a result of deep convective activity over the IM region, two planetary wave structures are produced travelling in opposite directions around the tropics (Wang and Rui 1990). A dry, easterly equatorial Kelvin wave is stimulated which travels across the Pacific Ocean, is temporarily blocked over the mountainous regions over South America and reaches continental West Africa about 20 days after production (Matthews 2004). In the opposite direction, a dry Rossby wave structure travels westwards at a slower rate than the Kelvin wave towards West Africa, again reaching the Sahelian region roughly 20 days after being stimulated (Matthews 2004; Janicot et al. 2009; Flaounas et al. 2012b). The interaction of these two wave structures over the West African continent acts to destabilise the troposphere and help remove high CIN environments allowing for deep convective systems to form (Lavender and Matthews 2009).

There is seasonal variation in the response of the WAM system to the MJO. It has been argued, using the results of a modelling study, that the westward moving Rossby wave is the principal component of MJO forcing on WAM rainfall during boreal summer (Janicot et al. 2009; Mohino et al. 2012). Mohino et al. (2012) accurately capture observed West African convective responses to the MJO without a Kelvin wave reaching continental West Africa. It is therefore suggested that the Kelvin wave does not have a substantial effect on West African rainfall during and after the regional monsoon onset period.

Conversely, recent work has suggested that during boreal spring, the response of the WAM system to MJO-induced Kelvin wave forcing is different and indeed the Kelvin wave has an effect on early season rainfall across West Africa (Berhane et al. 2015). The reason for this difference in findings is unclear currently, but deserves more intensive investigation. For the purpose of studying early season rainfall (which coincides with the timing of many local onset dates), the MJO influence on the WAM must be considered as an interaction between Rossby and Kelvin waves.

The dynamical response to the Rossby wave emitted from the Indian warm pool region over West Africa is primarily centred on warm air intrusion and subsidence over the Sahel. The Rossby wave signal induces subsidence of dry, high tropospheric air over the Mediterranean towards West Africa. This dry air is deflected by the vortices over the SHL and Saudi Arabia causing regions of high CIN over the Sahel and potentially the Guinea Coast (Flaounas et al. 2012a,b). The cause of the regional jump in precipitation is then the reversal of the zonal gradient of atmospheric pressure anomalies over the eastern Mediterranean, leading to the lack of conditions favourable for dry air intrusions over West Africa (Flaounas et al. 2012b). The IM/MJO influence on West African convection can therefore be thought of as a “gatekeeper” with regards to the monsoon jump, whereby pressure anomalies and wave dynamics cause a temporary blocking of the northwards rain belt migration only to rapidly allow the shift. This would explain the somewhat abrupt nature of the rain belt transition (or monsoon jump from Sultan and Janicot 2003). Furthermore, the suppression of coastal rainfall caused by the MJO may promote increased rainfall further towards the Sahel. This idea is investigated in Chapter 4.

Recent work has suggested that increased focus on the impact of the MJO on monsoon onset is required. If the MJO has a dominant effect on the timing of local onset dates, its representation in seasonal forecasting models will come under increased scrutiny.

h. The impact of latent and non-latent heating on convection over West Africa

Hagos and Zhang (2010) separate the seasonal wind fields over West Africa from four re-analysis datasets into their divergent and non-divergent components. The authors find that the non-divergent wind fields have little impact on the seasonal monsoon flow. By distinguishing the divergent winds driven by latent and non-latent heating sources, the authors further find two separate regions of convergence across West Africa throughout the entire monsoon system (Fig. 1.6). There is a deep convective zone driven by latent-heat sources that appears to be related to the maximum convergence zone. Further north, a more shallow, convergence zone is found driven by non-latent heating sources in the approximate location of the ITF. Hagos and Zhang (2010) provide a schematic of the moisture flux driven by non-latent and latent heating winds (Fig. 1.7). The pressure gradient between the GoG and the SHL drives the low-level non-latent heat wind fields and drives moisture past the maximum convergence zone towards the Sahel. The non-latent heating wind fields are therefore seen to modulate the northernmost limit of convergence and precipitation over West Africa. By contrast, latent heat winds drive the zone of maximum convergence and the intensity of latent heat wind fields controls the location of the maximum rain belt.

The maximum zone of vertically integrated moisture flux is located north of the maximum precipitation band throughout the season (also seen in Thorncroft et al. 2011 and Lélé et al. 2015), potentially a result of the deepened SHL and the associated shallow meridional circulation. It appears from the findings of Hagos and Zhang (2010) that the ITF and the maximum convergence zone should be treated as two separate subsystems of the wider monsoon system.

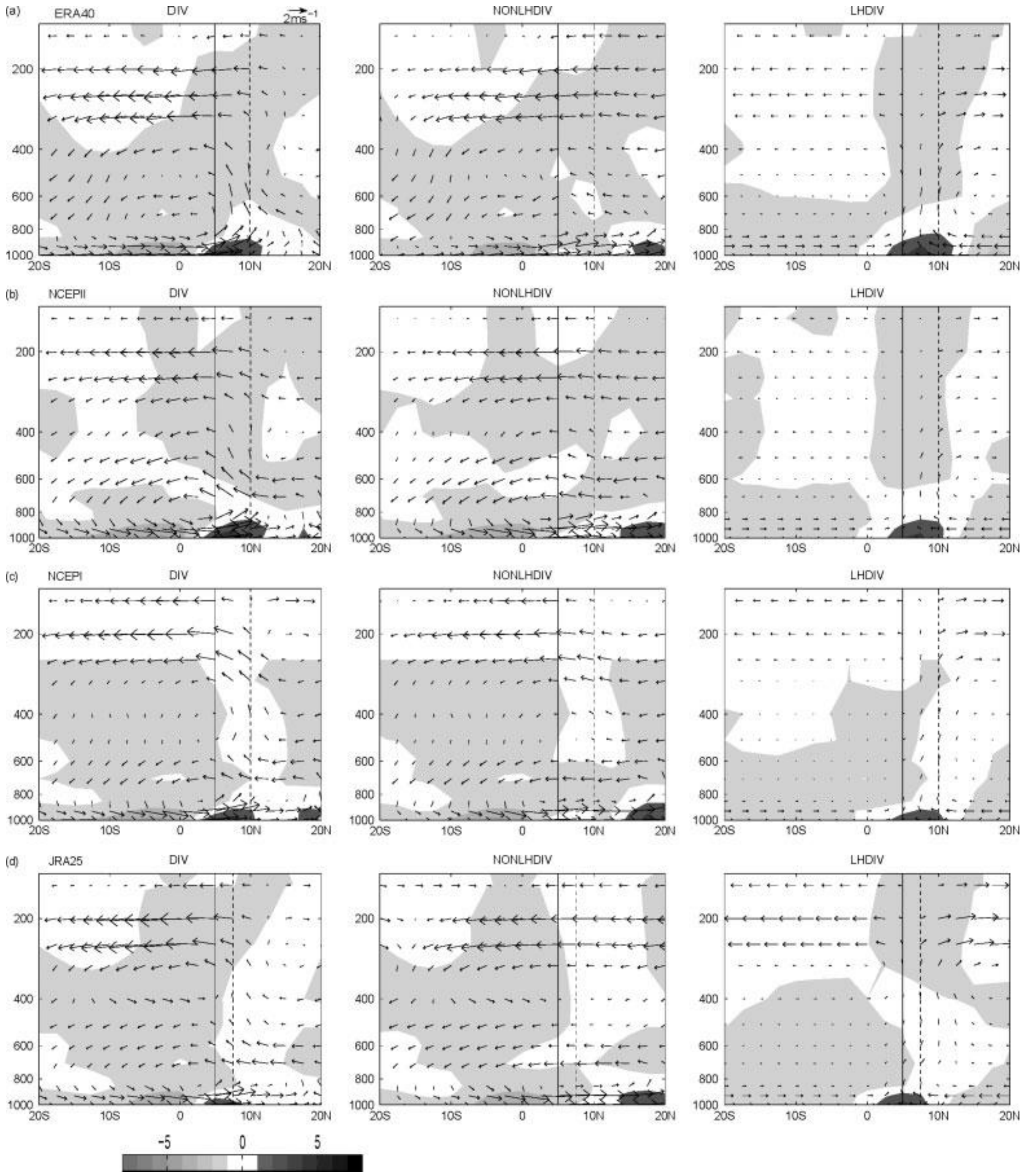

Figure 1.6 - Hagos and Zhang, Fig. 6. Total divergent meridional-vertical circulation, its components related to latent heating and non-latent heating, and their moisture convergence (shading g kg^{-1} day^{-1}) in summer (JAS), averaged over 15°W–10°E. The solid and dashed straight lines mark the coastline and latitude of the precipitation maximum, respectively. In the figure, DIV stands for the total divergent wind fields, NONLHDIV is the divergent wind field driven by non-latent heating sources and LHDIV is the divergent wind field driven by latent heating sources.

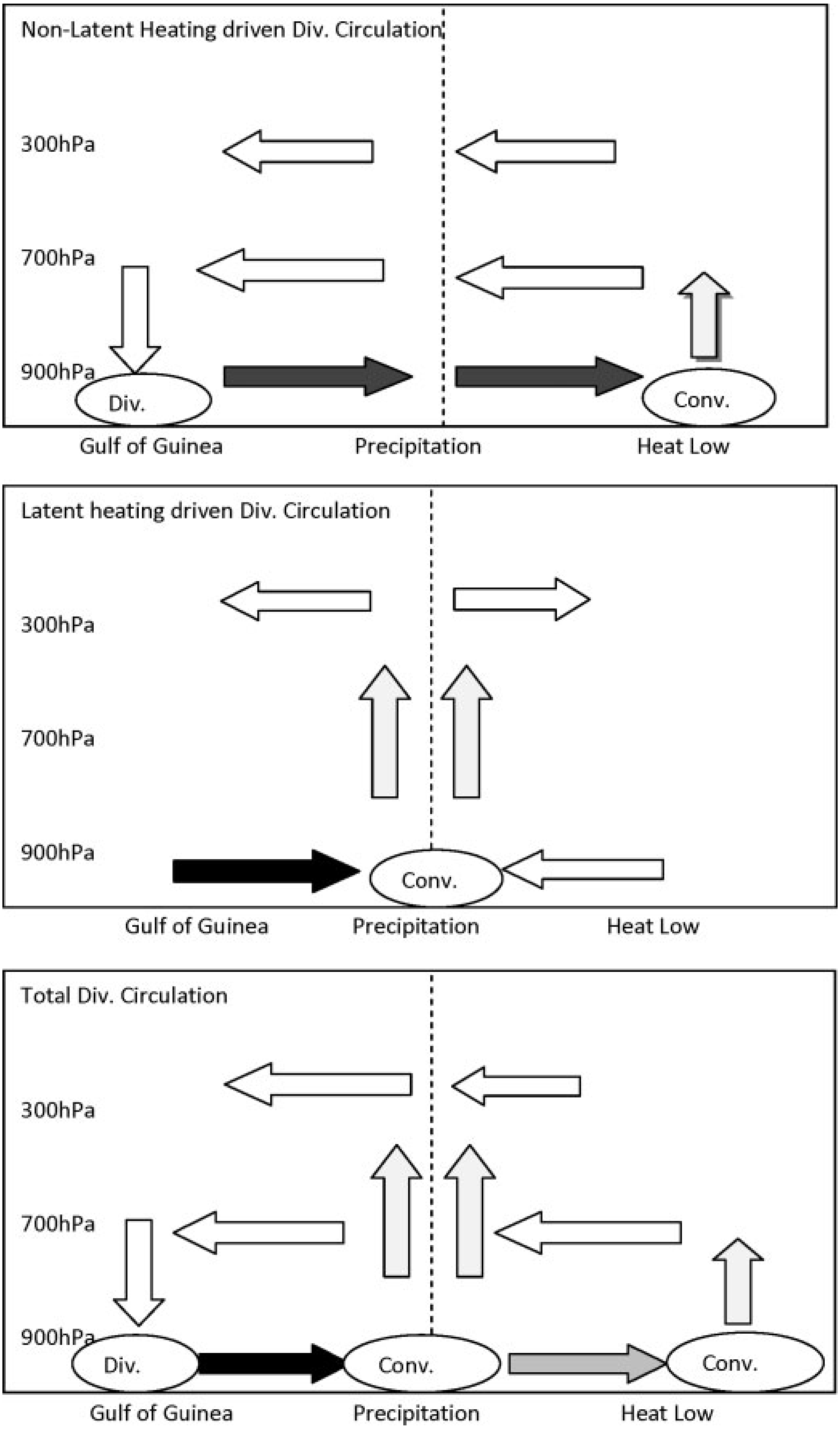
Non-Latent Heating driven Div. Circulation
300hPa
700hPa
900hPa
Div.
Conv.
Gulf of Guinea
Precipitation
Heat Low
Latent heating driven Div. Circulation
300hPa
700hPa
900hPa
Conv.
Gulf of Guinea
Precipitation
Heat Low
Total Div. Circulation
300hPa
700hPa
900hPa
Div.
Conv.
Conv.
Gulf of Guinea
Precipitation
Heat Low

Figure 1.7 - Hagos and Zhang, Fig. 11. Schematic diagrams summarizing the divergent circulations (arrows), their moisture transport (shading of the arrows) and convergence (ovals) associated with non-latent and latent heating in the West African monsoon system. Amount of moisture transport increases from white to dark shading.

i. <u>The role of the African Easterly Jet and African Easterly Waves</u>

A large proportion of precipitation over West Africa comes from MCSs. One of the common features across West Africa that can produce and modulate MCSs are AEWs, which are potentially excited and maintained by the African Easterly Jet (AEJ).

The AEJ, is a large scale band of easterly winds within the troposphere that can favour the development of MCSs and is linked to the seasonal migration of the zonal rain belt (Burpee 1972; Thorncroft and Blackburn 1999). Necessary conditions for AEW development include a strong AEJ with strong vertical shear or a strong and extended potential vorticity reversal (Leroux and Hall 2009). AEWs are maintained along the AEJ through barotropic and baroclinic instability. A typical AEW can travel over 2,000 km and has an average life span of about 7-10 days (Thorncroft and Blackburn, 1999; Fink and Reiner 2003). AEWs affect convection in a dipole or potentially tripole structure with enhanced convection at the leading edge of the wave, a region of suppression trailing the front of the wave within the wave trough and potentially another region of enhanced convection leading subsequent ridges of the wave (Bain et al. 2011, their Fig. 10b).

Thorncroft and Blackburn (1999) highlight the importance of the meridional circulations associated with the maximum convergence zone (ITCZ in their work) and the SHL in maintaining the AEJ. The meridional circulations which maintain the

AEJ have also been found to have a clear diurnal cycle, particularly around the time of regional monsoon onset (Parker et al. 2005). Therefore accurate prediction of the strength, location and seasonality of the AEJ and associated features that can affect precipitation is likely to be dependent on an accurate diurnal cycle within models. Recent high resolution model studies with explicit convection schemes have been shown to have an improved diurnal cycle compared to more traditional parameterised convection schemes (Birch et al. 2014b, their Fig. 3).

Importantly, the majority of AEW activity occurs after the regional monsoon onset and thus AEWs cannot be seen as an indicator of regional onset date or variability (note this is not necessarily true for local onsets as discussed in Section 4f). Whilst their connection to precipitation both on the regional and local scale is an important factor in sub-seasonal precipitation variability, from the perspective of the regional monsoon onset they are of little direct interest.

By contrast, the northwards progression of the AEJ may have impact on the WAM jump (Cook 2015). Prior to the beginning of the transitional monsoon phase, the AEJ acts to preserve inertial stability and therefore convergence (Tomas and Webster, 1997) over the coast through negative meridional zonal wind gradients. As the AEJ migrates northwards, the gradients weaken effectively reducing the inertial stability over the coast. In the presence of low-level inertial instability, low-level convergence cannot be maintained (Cook 2015; Plumb and Hou 1992). The increased inertial instability over the coast as a result of the transition of the AEJ therefore acts to decrease coastal rainfall thus marking the beginning of the transitional monsoon phase (Cook 2015). It is however noted by Cook (2015) that although the monsoon jump is present, Sahelian rainfall increases steadily throughout the season.

Therefore the AEJ does not simply shift the total rainfall from the coast towards the Sahel, rather impacting the sudden decrease in rainfall over the Guinea Coast.

j. Summary

This Section has presented a general overview of the current level of WAM onset understanding as well as introducing several of the main established drivers of regional monsoon onset. In the next Section, similar work is presented for the local onset. The following Section includes findings that will be presented in the rest of the thesis, as before this work the amount of information on local onset variability was very limited.

4. Local onset inter-annual variability

The cause of local onset variability is currently unknown with few theories presented in the literature. In this work we aim to begin to understand what climatic factors occurring on the seasonal timescale could have a significant impact on local onsets. There is naturally some overlapping to be expected between regional and local onset drivers, however there is also enough disparity between local and regional onsets that they should be considered different events occurring within the same overlying system.

Within this Section, there is a mix of current literature and strategy provided for the remainder of the thesis. First we consider potential reasons why local onset variability has not been extensively considered previous. Motivation for future work is also presented here as are topics beyond the scope of this thesis worthy of detailed future exploration.

a. Why is local onset variability under-studied?

The main reason for the lack of local onset variability studies appears to be the fact that local precipitation, and by proxy local onsets, are considered too spatially noisy to warrant consideration (Maloney and Shaman 2008; Marteau et al. 2009). The genesis and transect of large-scale rainfall systems across West Africa can be controlled by many factors. Orographic triggering, inertial stability (which promotes convergence) or soil moisture gradients (such as those discussed by Taylor 2008) can cause the genesis of deep convective systems, which have the potential to precipitate over large regions. The path that these systems take can be modulated by various large-scale or more localised features (such as AEWs or orography). In addition, the passage of an MCS over a given location is not a guarantee of intense rainfall over that location. Taylor et al. (2011) provide a synopsis of key land-atmosphere feedback processes occurring on a multitude of scales (from hourly to inter-annual; their Table 1). In summary, whilst on a macro scale the genesis and path of MCSs can be described with a degree of accuracy, a more localised analysis is very complex.

Over bare soil regions (such as significant parts of West Africa, particularly at the end of the dry season), wet soil can induce moisture driven low-level convergence allowing for the genesis of secondary mesoscale convective circulations as soil moisture gradients can create a convergence zone akin to a sea breeze (Taylor et al. 2007). MCSs also have the ability to trigger subsequent MCS activity proximate to their location through internal gravity wave dynamics and cold pools (as mentioned in Section 3d). The ability of seasonal forecasting models at relatively coarse resolution to accurately capture these dynamics is poor. Whilst Birch et al. (2013)

show that high resolution, convection permitting models can capture this process, the exact location and timing of subsequent storm triggering may not be completely accurate and therefore threshold based forecasts may be skewed. In order to accurately model secondary storm genesis, detailed knowledge of the large-scale climatology and local soil moisture gradients are required. Even in high-resolution models the quality of these forecastable metrics may not be sufficient to give valuable results.

Compounding the issues listed above is the sparsity of reliable *in situ* data with a sufficiently long time-scale for analysis (Fitzpatrick 2015). Figure 1.8 shows the global density of *in situ* data assimilated as part of the re-analysis verification performed by the European Centre for Medium-Range Weather Forecasts (ECMWF). Compared to other major monsoon regions such as the Indian Subcontinent and south-east Asia, Africa has very poor coverage of *in situ* data and there are almost no reliable daily observations over the Sahara, the location of the SHL and main source of aerosol over the region. A recent study of local rainfall over Nigeria made use of 23 synoptic weather stations across the entire country (Adeniyi 2014). By contrast there are almost 50 weather stations contributing to ECMWF and Met Office re-analysis in Scotland (http://www.metoffice.gov.uk/public/weather/climate-network). This lack of local observations leads to complications when attempting to study the causes of local onset variability. These complications are discussed further in Section 5.

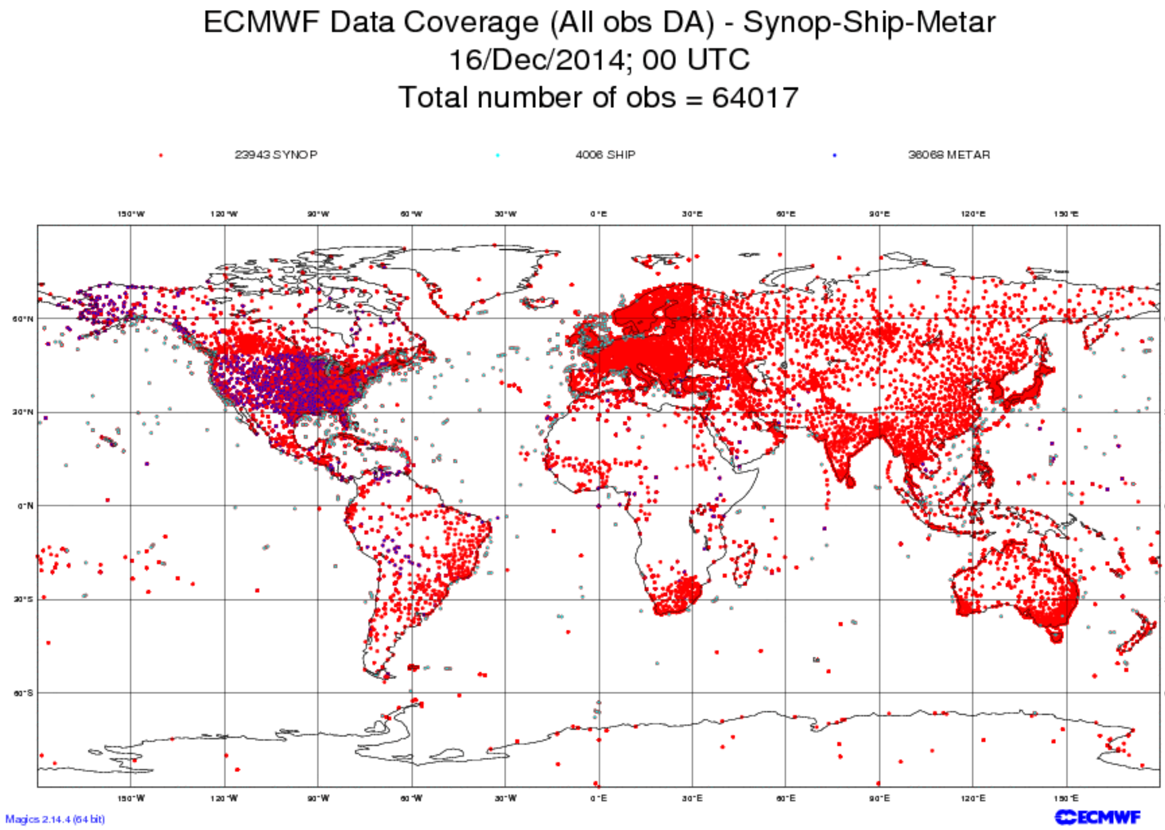

Figure 1.8 – Fitzpatrick (2015), Fig. 1. Location of all in situ weather data available for use by the European Centre of Medium-Range Weather Forecasts data assimilation system as of 16 December 2014. Here Synop denotes a fixed land observational station, Ship can either be moored or drifting data (no buoys are included in this plot) and Metar refers to data from air terminals.

b. <u>How can local onset variability be assessed?</u>

Given the needs of local farmers and the findings presented later in this work as part of Chapter 2, the difficulty of local onset prediction poses a serious problem. If meaningful information regarding the cause of local onset variability cannot be found, it is questionable how useful seasonal forecasts can be to local forecast users.

In this work, it was decided that greater focus needed to be placed on local onsets than previously performed. Specifically, it was deemed necessary for both forecast users and the science community to know whether local onsets held any pragmatic level of spatial consistency.

Chapter 3 contains an initial attempt to quantify the level of spatial homogeneity of local onsets across West Africa using information that would be useful for forecast users. This work differs from previous studies in its fundamental approach. Prior works on the spatial uniformity of local onsets have taken a “top-down” approach and calculated statistical measures of consistency within a pre-defined region typically along national borders or river basin catchments (e.g. Marteau et al. 2009). Measures applied have included storm tracking, degree of freedom analysis and empirical orthogonal functions. National borders are not drawn along lines of similar weather patterns and hence a top-down approach can limit the impact of results (as more impactful results may be found over other regions).

In Chapter 3, we apply a “bottom-up” approach to find the largest possible region of consistency. A pragmatic level of spatial uniformity in onset dates and inter-annual onset variability is found. The findings of Chapter 3 give the first usable regions over which local onsets can be considered sufficiently consistent for analytic and forecasting purposes.

Chapter 3 marks a potential turning point in WAM onset studies. Whereas previously investigations into the local onset were not deemed worthwhile due to the high levels of noise found in local precipitation data, we suggest that non-arbitrary and practical regions over which local onset variability can be assessed exist. From this foundation, we approach the question as to what causes inter-annual variability of local onsets with examples provided below.

c. The impact of the Inter-Tropical Front on local rainfall

The ITF marks the northernmost extent of cool moist monsoon winds into the West African subcontinent. Intuitively, the onset of substantial rainfall at a given location will not occur until after the ITF has passed the given location. Ilesanmi (1971) highlights the potential for a link between the passage of the ITF and local rainfall across Nigeria. Expanding on this work, Lélé and Lamb (2010) provide a statistical and visual link between the ITF and precipitation across the entire of West Africa (Figs. 1.9 and 1.10). Furthermore, Lélé et al. (2015) suggest that there is a 20-day lag between northwards moisture flux at a given location and precipitation anomalies (Fig. 1.11). These three works provide the basis on which we explore the link between the ITF and local onsets. Any link between the ITF and local onset dates could provide a measurable precursor to monsoon onset with a pragmatic lead time. The potential of such a link is explored within the work of Chapter 3.

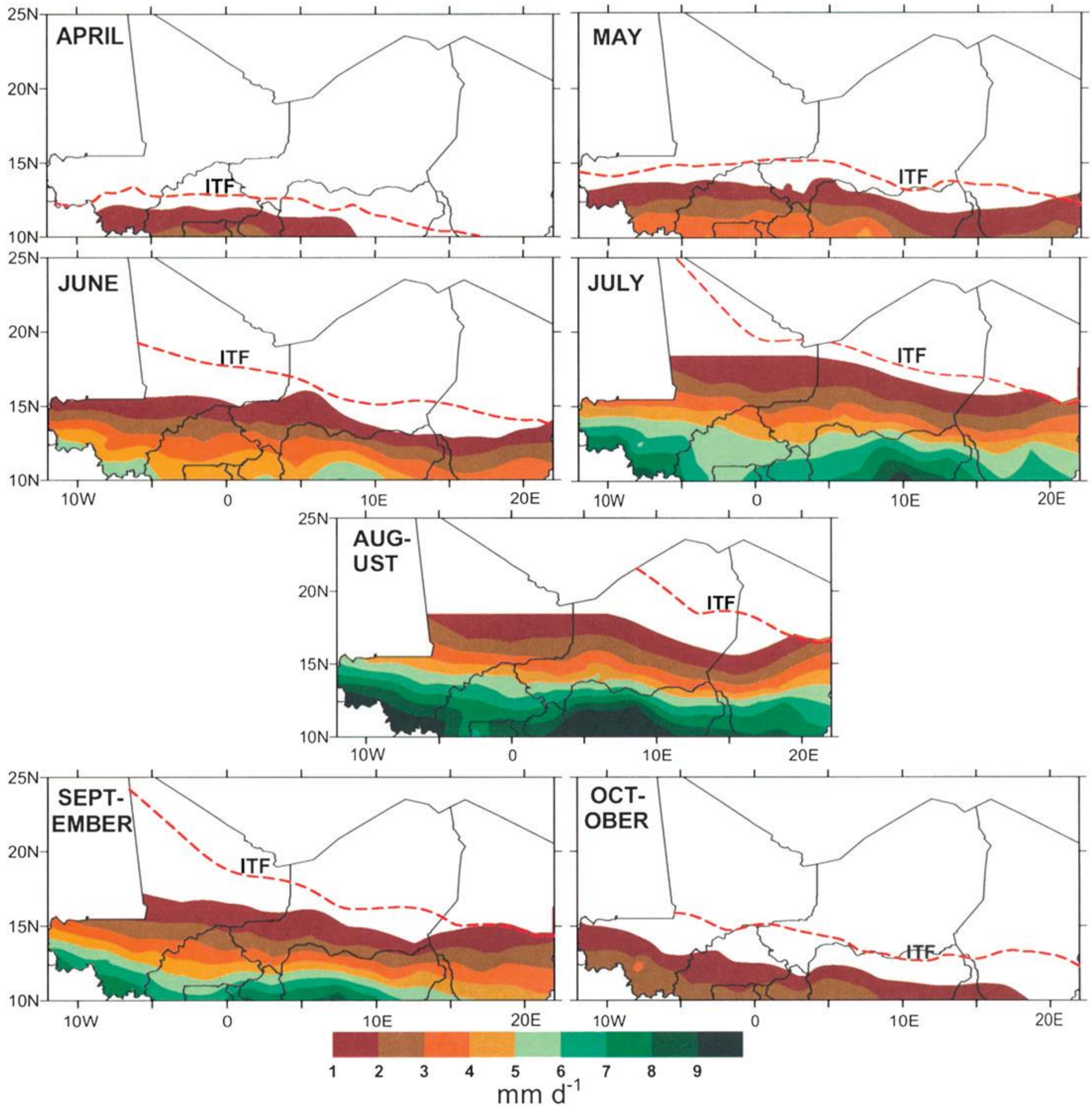

Figure 1.9 – Lélé and Lamb (2010), Fig. 4. Long-term (1974–2003) average calendar monthly rainfall rate isohyets (mm day^{-1}) in relation to the long-term average (1974–2003) monthly ITF position (red broken line) for April–October in the West African Sudan–Sahel zone.

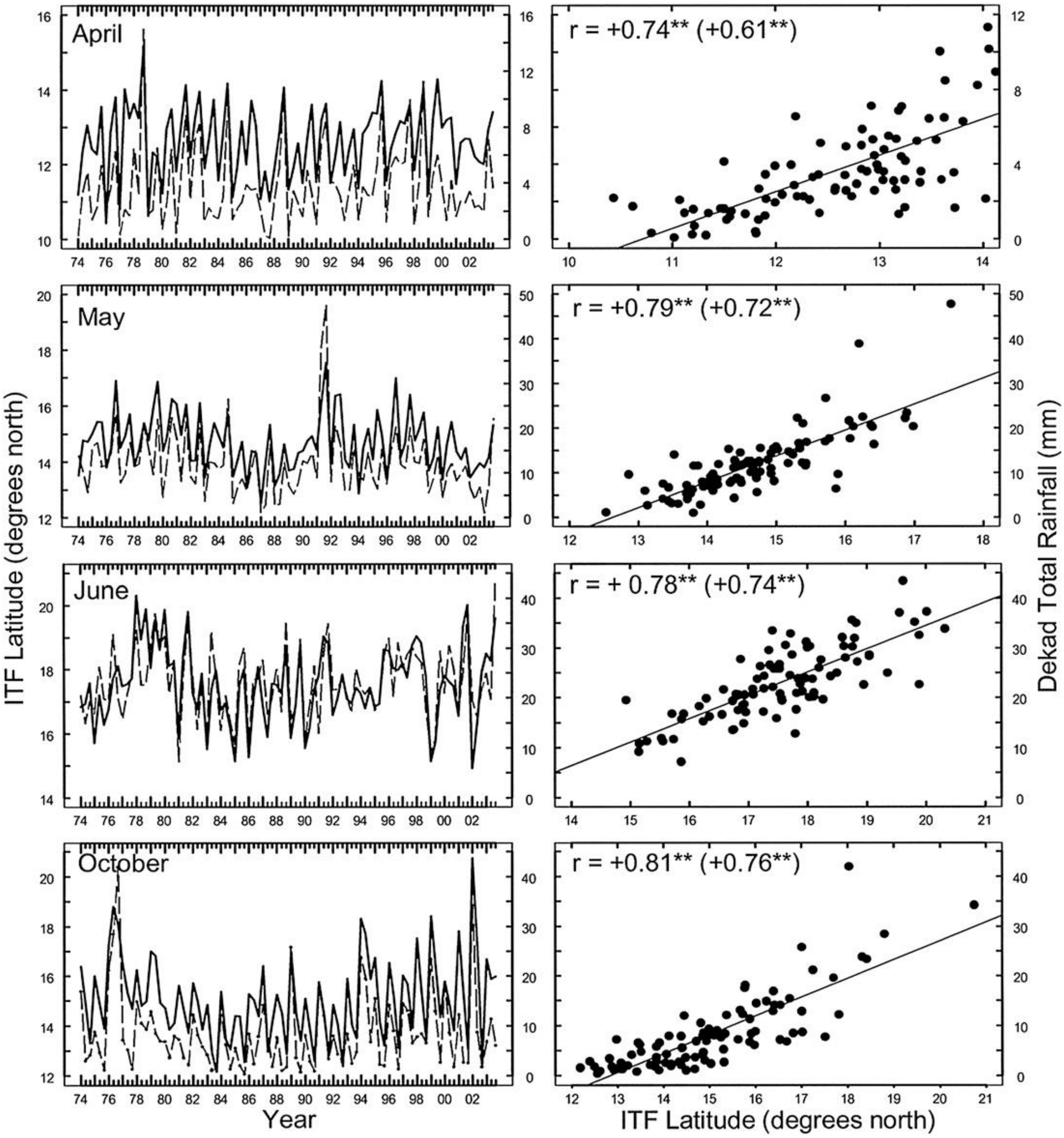

Figure 1.10 – Lélé and Lamb (2010), Fig. 5. Relationship between ITF latitude and total rainfall for early (April–June) and late (October) rainy season months in the West African Sudan–Sahel zone. (left) Time series (1974–2003) if 10-day (dekad) averaged ITF latitude (°N, solid line, left ordinate) and 10-day area-averaged total rainfall (mm, broken line, right ordinate) for domain between 10°–20°N and 12°W–24°E (Fig. 2). (right) The corresponding scatter diagrams and linear correlation coefficients, all of which are significant at the 1% level (indicated by two asterisks) according to a two-tailed Student's *t* test (Wilks 2006, pp. 131–135). Time series consists of three dekadal values per month for each year between 1974 and 2003, with the abscissa labelled in yr. Correlation coefficients in parentheses are for time series with seasonal cycles removed, where each dekadal value was the departure from the 1974–2003 dekadal mean.

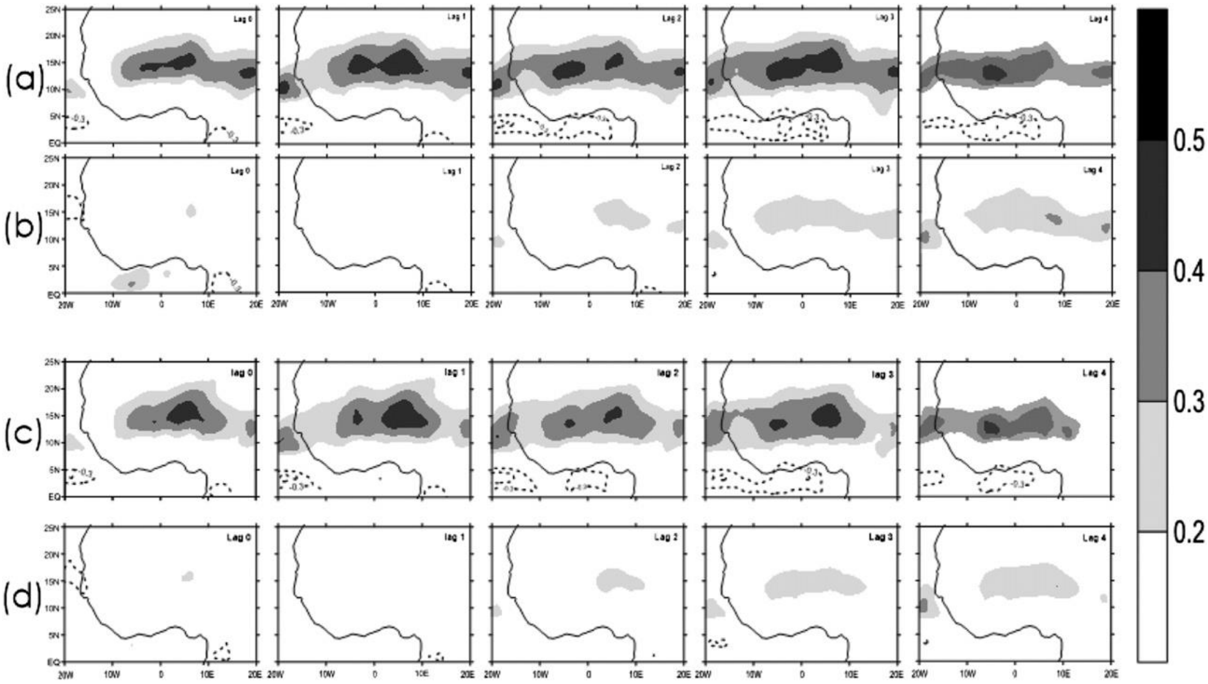

Figure 1.11 – Lélé et al. (2015), Fig. 9. Lag correlations in pentads between the (a) zonal and (b) meridional components of moisture flux and the GPCP precipitation for the 1979–2008 period. Shading denotes positive correlations and dashed contours denote negative correlations. Only positive correlation coefficients exceeding the 95% confidence levels are shown. (c), (d) As in (a), (b), but the correlations are with the Climate prediction centre Morphed Analysis of Precipitation (CMAP) data.

d. <u>The impact of sea surface temperatures on local onsets</u>

There are many previous studies that explore the impact of SSTs on seasonal precipitation totals over West Africa and the regional transition of the maximum rain belt. Despite this prior research, an extension towards understanding the link between SSTs and local onsets has not been presented.

Appendix B compares the quality of three generations of the UK Met Office seasonal forecasting system in predicting the regional and local WAM onset. Across the three generations of forecasting model studied, there is an improvement in the resolution and accuracy of SST hindcast predictions on the seasonal timescale (MacLachlan et al. 2015). Through the three generations, the ocean model resolution has been improved from 1° to 0.25°. Thus a link between local onsets and SST anomalies should result in an improved seasonal forecast of local onsets across the three generations of model. In this work, Appendix B suggests that there is little to no improvement in local onset timings or quality of forecast. It is therefore possible to suggest that improved recreation of realistic SST values will not improve prediction of local onset.

In addition, local onset regions (LORs, defined in full in Chapter 3) have been lag correlated with SST anomalies using observation data in a fashion similar to Rowell (2013). It was found that there exists little significant correlation (at the 95% confidence interval) between onset dates and SST anomalies (not shown). This result is in line with the findings of Druyan and Fulakeza (2015) and Flaounas et al. (2012a), who find that SSTs do not affect the exact timing of regional monsoon onsets.

Given the two results listed above, it was decided that SSTs would not be studied further as part of this work. Whilst there may exist a dynamical link between SSTs and the local agronomic monsoon onset, the exact dynamics of this link are left to future studies.

e. The impact of the Madden-Julian Oscillation on local onsets

The MJO has already been extensively studied with regards to the regional monsoon. In particular, the works of Flaounas et al. (2012a,b) provide dynamical interpretation of the MJO’s impact on the West African climate during early June (which is referred to as the transitional monsoon stage in their work). This period marks an important phase for local onsets as well. Given the results found in

Chapter 3, as well as the findings of Lélé et al. (2015), there appears to be a 20-day lag between the ITF advancement past LORs and the median local onset date within an LOR. In addition, the median local onset date for two of the major LOR areas occurs approximately 20 days after the transitional monsoon phase, around the time of the IM onset. Juxtaposing these two findings implies that a dynamical link between the MJO and local onsets may be present.

Chapter 4 explores the potential response of early season precipitation and other dynamical metrics to different MJO conditions over West Africa in late May and early June. This work provides the first evaluation of how a planetary scale process impacts local onset across West Africa utilizing the LORs presented in Chapter 3.

f. <u>The impact of African Easterly Waves on local onset</u>

The impact of AEW activity on the genesis and migration of MCSs has been studied with key references provided in Section 4i. The ability of seasonal forecasts to track AEW activity is limited. Whilst seasonal forecasting models can accurately capture sufficient AEWs across a season, they often fail to correctly forecast the exact timing and track of AEWs across an entire season at the seasonal timescale (see for example the difference between explicit and parameterised convection models in Birch et al. 2014b). A simple and repeatable method to track AEWs has been provided in Bain et al. (2014). In the same paper, the authors find that within the Met Office Unified Model (Met_UM), precipitation is less coupled to AEW activity than observed in observation and re-analysis data (Fig. 1.12).

Understanding how AEW activity impacts local onsets across West Africa is an important problem that deserves further consideration. In this work, it was decided to focus on the MJO rather than AEWs due to the relative skill levels of the Met Office model and more established links to the onset in literature.

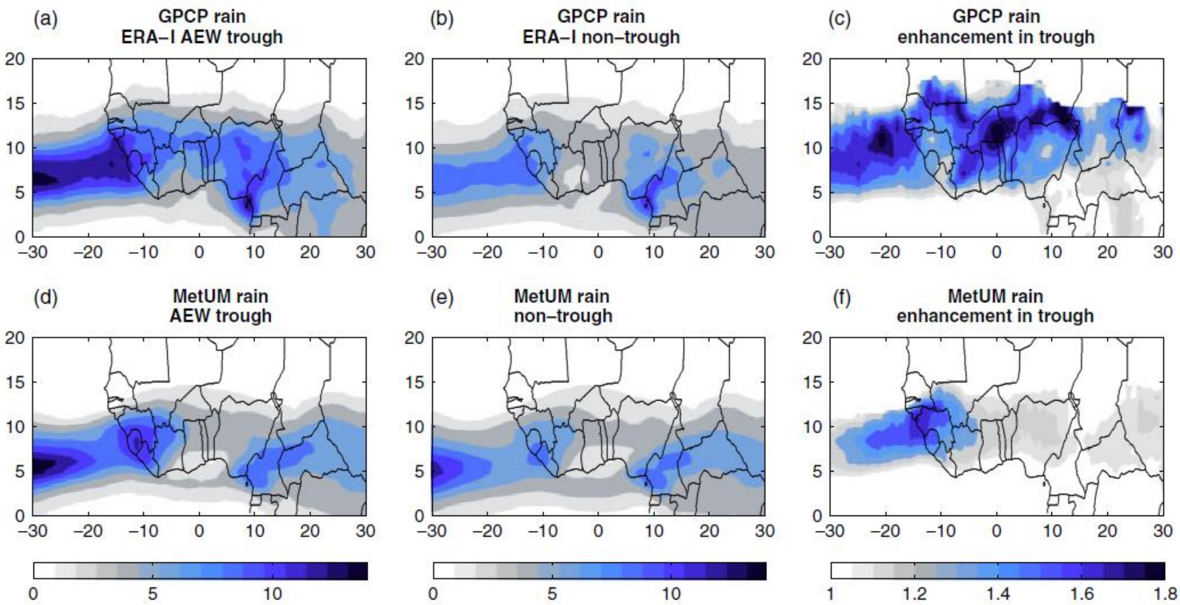

Figure 1.12 - Bain et al. (2014), Fig. 4. Impact of AEW trough passage on rainfall. Composite of reanalysed AEWs from (a, b, c) ERA-Interim and GPCP rainfall for 1997–2008 and (d, e, f) Met_UM global atmosphere 3rd generation model (ga3) AEWs and rainfall 1990–2008. (a, d) show the average rainfall rate when a trough is passing, (b, e) the average rainfall rate when a trough is not passing, and (c, f) is the relative rainfall enhancement when a trough is passing. Low rainfall regions (<1 mm day^{-1}) have been masked out on (d, e, f) so that arid data regions are not exaggerated.

5. The role of observational limitations on the findings of this study

As mentioned in Section 4a, the lack of *in situ* measurements is a key issue across West Africa. A spatially dense and reliable rain gauge network would be of practical use and valuable both for forecasters and local or institutional forecast users. Increased coverage of observations would also have potential to increase capacity building across West Africa and allow for more involvement of local farmers and representatives in the West African scientific community.

Recent large scale observation projects such as the African Monsoon Multidisciplinary Analysis (AMMA, Redelsperger et al. 2006; Lebel et al. 2009, 2011), have greatly improved scientific understanding of the WAM. The special observation period of AMMA was 15 May–15 September 2006 (http://www.amma-international.org; Redelsperger et al. 2006) and thus covers a large period of agronomic onset dates and the timing of the regional onset. However, multi-decadal analysis of observations captured as part of the legacy of such projects (if such observations are available) will not be possible for quite some time.

The lack of *in situ* data leads to a reliance towards satellite based observations over West Africa. Satellite observations can give a more complete picture of the West African climate without spatial or temporal gaps than interpolation of *in situ* observations. Satellite observations also offer opportunities to measure metrics that cannot be observed from the surface (such as cloud top temperature). However, satellite observations of surface data such as precipitation are inferred instead of explicitly observed and therefore cannot be considered completely reliable (Roca et al. 2010; Seto et al. 2011). Most satellite datasets employ bias correction to their findings in order to remove erroneous values, but they are still not guaranteed to capture the nature of conditions at the surface.

The relatively recent advent of high-resolution precipitation satellite observation products such as the Tropical Rainfall Measurement Mission (TRMM, Huffman et al. 2007) and the Climate Prediction Centre MORPHing technique (CMORPH, Joyce et al. 2004) have allowed for analysis of local onset dates across West Africa despite the lack of comprehensive rain gauge coverage. However, there are a couple of issues with modern satellite data. High resolution daily precipitation data has a climatologically short history. The TRMM dataset is available from 1998-2015.

CMORPH data is available from 2002 to the present day. These short time periods make it difficult to reliably establish climatology of onset dates (such as those present in Le Barbé et al. 2002; Sultan and Janicot 2003 and Lélé and Lamb 2010).

Local onset definitions often include threshold precipitation values in their construction (Omotosho et al. 2000; Marteau et al. 2009; Yamada et al. 2013). These threshold values can be erroneously met or missed given dataset biases. By comparison a regional precipitation based onset compares relative rainfall totals zonally-averaged at different latitudes. Therefore regional onsets are more resistant to localised precipitation biases, although they can still be affected by large scale biases (such as a land-sea precipitation bias).

A fundamental aim of this work was to understand how choice of observational dataset could skew forecast quality assessment. Seto et al. (2011) compare the representation of heavy rainfall events in two generations of TRMM data. The authors conclude that there is a better representation of heavy precipitation events in the latter TRMM product studied. For threshold based onset definitions, these biases can cause disparity in onset dates observed which can skew analysis. Chapter 2 provides further insight into the level of observational uncertainty found in onset dates.

6. Structure of the Thesis

Given the urgent need for improved seasonal forecasting in West Africa, this work has been constructed so that key findings can be quickly and easily shared with decision makers and researchers. The thesis consists of four self-contained articles (Chapters 2, 3, 4 and Appendix B). Chapters 2 and 3 have been published and are presented here in their accepted proof form. Chapter 4 is in preparation for submission to the Quarterly Journal of the Royal Meteorological Society. The findings of Appendix B are written in article format for the internal use of the UK Met Office. The results of these chapters provide important information for decision makers and forecasters and are expected to lead to further research into the WAM.

A more specified literature review pertinent for each of the major aims of the thesis are found within the subsequent chapters as well as information on the data used within this work. Conclusions for each of the major aims are presented in their respective chapters as well as Appendix B. A summary of the work presented within this thesis is provided in Chapter 5 as well as suggestions for future improvement in understanding and predicting the WAM onset.

Throughout the work presented, a conscious decision whether to prioritize pragmatic solutions or interesting scientific problems has been required. This decision has at all times been based on assessing a result’s value to decision makers and forecasters. A seasonal forecast that cannot be used is by definition useless. For example, an onset definition with a high likelihood of false onset immediately succeeding onset date will lead to unnecessary risk for local farmers who plant rain-fed crops on the onset date. Likewise, a forecast that cannot distinguish between the probability of relative early, average or late onset date occurring at a given location (a forecast with little sharpness), offers little to no added information for forecast users and as such is unlikely to have much value. Understanding the potential increase in value of findings has therefore helped shape the work presented. All three Chapters presented provide new and relevant information for forecasters and forecast users and therefore achieve the overarching goal of the work.

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Chapter 2

The West African Monsoon Onset: A Concise Comparison of Definitions

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Abstract

The onset of the West African Monsoon (WAM) marks a vital time for local and regional stakeholders. Whilst the seasonal progression of monsoon winds and the related migration of precipitation from the Guinea Coast towards the Soudan/Sahel is

apparent, there exist contrasting man-made definitions of what the WAM onset means. Broadly speaking, onset can be analyzed regionally, locally or over a designated intermediate scale. There are at least eighteen distinct definitions of the WAM onset in publication with little work done on comparing observed onset from different definitions or comparing onset realizations across different datasets and resolutions. Here, nine definitions have been calculated using multiple datasets of different metrics at different resolution. It is found that mean regional onset dates are consistent across multiple datasets and different definitions. There is low inter-annual variability in regional onset suggesting that regional seasonal forecasting of the onset provides few benefits over climatology. In contrast, local onsets show high spatial, inter-annual and inter-definition variability. Furthermore it is found that there is little correlation between local onset dates and regional onset dates across West Africa implying a disharmony between regional measures of onset and the experience on a local scale. The results of this study show that evaluation of seasonal monsoon onset forecasts is far from straightforward. Given a seasonal forecasting model, it is possible to simultaneously have a good and bad prediction of monsoon onset simply through selection of onset definition and observational dataset used for comparison.

1. Introduction

The annual advance of the West African Monsoon (WAM) is a pivotal period for the inhabitants of the region. Due to a lack of irrigation, most farmers in West Africa are dependent on monsoon rains for sustainable crop farming (Ingram *et al.* 2002; Sultan *et al.* 2005). Furthermore, the onset of rains affects health organization operations, particularly for preparation and prevention of dengue fever and malaria epidemics and mapping the seasonal reduction in meningitis over West Africa (Molesworth *et al*. 2003; Sultan *et al*. 2005; Mera *et al*. 2014). For meteorologists the progression of the monsoon system into the Sahel marks a shift in regional climate dynamics signifying the beginning of an active period for the formation of westward propagating meso-scale convective systems and African easterly waves (Fink and Reiner 2003), which can transform into tropical storms in the Atlantic Ocean (Berry and Thorncroft 2005).

During boreal spring and early summer, warm sea surface temperatures over the Gulf of Guinea (GoG) and eastern equatorial Atlantic (10°W - 10°E, 5°S - 5°N) lead to an increase in atmospheric water content. The rapid cooling of the sea surface around 5°S during April and May leads to the increase in coastal rainfall around 5 - 7°N; this marks the beginning of the coastal onset of the WAM (Okumura and Xie, 2004; Hagos and Cook 2009; Thorncroft *et al*. 2011; Nguyen *et al*. 2011; Brandt *et al*. 2011; Caniaux *et al*. 2011; Liu *et al*. 2012). Precipitation is maximised at this time near 5°N. Due to the strengthening of the north–south pressure gradient during this time (with high pressure near the coast and low pressure towards the Sahara), moist, cool, south-westerly winds protrude from the Gulf of Guinea and the Eastern Atlantic inland towards the Sudanian region. At the Inter-Tropical Front (ITF) these winds meet the drier, warmer, north-easterly winds emanating from farther inland.

The location of the ITF establishes the northern-most location of seasonal rains and its passage marks the beginning of the local rainy season (Dettwiller 1965; Sultan and Janicot 2003; Lélé and Lamb 2010). The location of maximum deep convection and heavy precipitation, sometimes referred to as the Inter-Tropical Convergence Zone (ITCZ) or the tropical rain belt, is located approximately 400 km to the south of the ITF (Lafore *et al*. 2010; Lélé and Lamb 2010). As the heating of the Sahara intensifies, increasing the magnitude of the Saharan heat low (SHL) the pressure gradient between the coastal region and the Sahara maximises (Roca *et al*. 2005; Lavaysse *et al*. 2009; Messager *et al*. 2010; Janicot *et al*. 2011). For reasons not yet fully understood, convection is supressed at 5°N, followed swiftly by a rapid shift of the ITCZ towards a new quasi-stationary location in the Sudanian region around 10°N across the *monsoon region* (typically defined as the longitude range 10°W-10°E). The northward shift of the ITCZ marks the regional onset of the WAM (Sultan and Janicot 2003; Fontaine and Louvet 2006; Fontaine *et al*. 2008; Gazeaux *et al.* 2011). The timing of this shift appears to be reasonably consistent with a standard deviation of eight days (Sultan and Janicot 2003). One important result from previous work is that the timing of the start of the local rainy season and the ITCZ shift are very weakly correlated (0.01) (Sultan and Janicot 2003).

Whilst there is a clear overarching structure to the monsoon progression over West Africa, the concept of monsoon onset is more fluid and open to interpretation and modification for end-user needs. Onset definitions can be broadly classified as local or regional based on the scale on which they are applied. The majority of regional onsets identify a sudden northwards shift (or jump) of the ITCZ (or closely linked variant) from near the Guinea Coast into the Sahel (e.g. Sultan and Janicot 2003). It is important to note that the abrupt jump of the monsoon system may not be a reliable feature for forecasting every year. Gazeaux *et al.* (2011) looks for a statistical switch point in monsoon dynamics representative of the jump, but found no such feature present in 25% of studied years. Currently it is not fully understood why in some years regional onset is more gradual than in other years.

Local onset definitions by contrast predominantly focus on precipitation totals at single locations and provide a more specific onset measure for local stakeholders (see Table 2). Due to the inherently noisy nature of local precipitation (alluded to in Maloney and Shaman 2008 for example), these onset definitions often have low spatial and inter-annual homogeneity and their patterns have not been explored extensively. Nevertheless, the onset dates provided by these definitions could be far more suitable for individuals and local agencies operating in West Africa.

Onset can be diagnosed either from satellite or local *in-situ* observations such as rain gauges. Satellite data are generally more complete but may show substantial biases (e.g., Tompkins and Adebiyi 2012). Rain gauges are usually a more accurate representation of localised rainfall, but due to the inhomogeneity of rainfall may not be representative over scales of more than 50-100 km. Furthermore the coverage of *in-situ* observations across West Africa is not spatially consistent, and there exist many regions in which observations are very sparse (Ali *et al.* 2005; Roca *et al.* 2010).

There are few inter-comparisons of the multiple onset definitions that have been proposed (exceptions include: Ati *et al.* 2002; Fontaine *et al.* 2008; Gazeaux *et al.* 2011, Nguyen *et al*. 2011). In addition, to the best of our knowledge, there is no study which systematically and objectively compares WAM onset definitions realised over different scales using multiple datasets. Without a systematic overview of onset definitions and evaluation of dataset variability on onset, a complete and reliable study of onset forecasting skill is not possible. We offer here an evaluation of onset calculation methods and recommend pragmatic local and regional onset definitions for forecasters.

The purpose of this article is to provide an overview of existing definitions of the WAM onset and examine the variability of onset date found using different definitions and datasets. It is not the aim of this paper to evaluate the triggers for local and regional onset, nor to evaluate the predictability of onsets. This is left for future studies.

Section 2 provides an outline of published onset definitions with section 3 providing a brief overview of datasets chosen for analysis. Section 4 and 5 analyse specific regional and local onset definitions with section 6 offering recommendation for future work.

2. Onset Definitions

2.1. Overview of published onset definitions

There exist at least eighteen definitions of the WAM onset explicitly defined or inferable from literature (this excludes local definitions used by non-academic stakeholders such as local farmers with traditional methods). The definitions can be grouped by the scale of onset considered. Regional definitions are classed as definitions of monsoon onset on a supranational scale. Local onset definitions work with data from a single rain gauge or grid cell with no additional spatial information. Any onset definition that exists between these scales is termed as semi-local.

Table 1 shows a list of published regional onset definitions; all onset definitions have been taken as written in their initial publication including any wording that can be open to interpretation. The regional definitions employ a variety of data: precipitation, outgoing longwave radiation (OLR), moist static energy (MSE), zonal winds and daily rainfall event frequency amongst others. Certain regional definitions include a level of subjectivity (e.g. Sultan and Janicot 2003; Fontaine *et al.* 2008). These definitions require relative changes in observable features across the monsoon region as opposed to specific metric thresholds being met (a common feature of local onsets).

Whereas regional onset definitions focus on the large-scale migration and modulation of dynamics over the West African region, local onset definitions almost exclusively define monsoon onset as a given threshold of local precipitation (Table 2). Local onset definitions based on precipitation data at one grid cell have an inherent "ignorance" of rainfall from any neighbouring locations. The separation of local and regional onsets in literature betrays a disconnection between local stakeholders and global climate model work; it is important to appreciate the difference between local and regional WAM onset to understand the effects of prediction on end users.

Onset dates with explicit thresholds (Kowal and Knabe 1972; Sivakumar 1988; Omotosho *et al.* 2000; Marteau *et al.* 2009; Yamada *et al.* 2013) carry the risk of dataset and resolution bias and may not be applicable across the whole of West Africa. For agronomic definitions it is difficult to ascertain the risk/reward of flexible threshold values without further investigation as chosen thresholds relate directly to crop yield information. Further northwards into the Sahel, the likelihood of precipitation reaching a certain level is lower than for more southern locations. Local stakeholders within these regions have therefore adapted and constructed local onset indicators for their specific purposes which may not reflect the thresholds often found in literature. This is not a failing of onset definitions in publication, as most local definitions are created for a specific study region (Ati *et al.* 2002; Marteau *et al.* 2009).

Over-reliance on one particular definition for monsoon onset can lead to unintended bias in forecasting (Vellinga *et al.* 2012). Recent works suggest that using a combination of several different local and regional onset definitions with different observed metrics is preferable (Fontaine *et al.* 2008; Gazeaux *et al.* 2011; Vellinga *et al.* 2012).

Table 2.1 - List of regional definitions in publication sorted by publication date

Reference	**Input data**	**Original dataset and time period**	**Onset definition**
Le Barbé *et al.* (2002) – *LeB_Reg*	daily precipitation data	Rain gauge data taken from AGRHYMET dataset 1950-1990.	Onset date inferred from an appreciable jump in the maximum of zonally-averaged (10°W-10°E) 10-day smoothed daily rain event occurrence from 5°N to 10°N.
Sultan and Janicot (2003) - *SJ*	precipitation data (daily or pentad)	Rain gauge data taken from Institut de Recherche pour le Developpement, Agence pour la Securite de la	Date at which 10-day time smoothed, zonal averaged (10°W-10°E) precipitation time series at 5°N decreases simultaneous with precipitation increase at 10°N and 15°N

		Navigation Aerienne en Afrique et a Madagascar and Comite Interafricain d'Etudes Hydrauliques interpolated to a 2.5° x 2.5° grid for period 1968-1990. Re-analysis data from NCEP-NCAR and ERA-15.	
Fontaine and Louvet (2006)	precipitation data (daily or pentad)	Satellite data from CPC Merged Analysis Product and GPCP at 2.5° x 2.5° resolution for period 1979-2004.	Using zonally averaged (10°W - 10°E), 15-day filtered precipitation data, onset occurs in the first pentad of the 20 day period for which northern standardised rainfall (7.5°N-20N) is greater than southern standardised rainfall (0N-7.5°N)

Fontaine *et al.* (2008) - *Font*	daily OLR data (smoothed to 5-day)	NOAA interpolated OLR for period 1979-2005 at 2.5° x 2.5° resolution.	Date at which these three criteria occur successively: 1) convective maxima is located at, or north of 5°N, 2) part of convective maxima shifts to 10°N where OLR %<180°Wm^{-2} is less than 25% 3) convective maxima remains here or shifts northwards
Fontaine *et al.* (2008)	MSE data (pentad)	NCEP/DOE AMIP-II re-analysis at 2.5° x 2.5° resolution for the period 1979-2005.	For a period of at least 20 days, the gradient in Moist Static Energy (MSE) between the Sudan-Sahel and Guinea regions is oriented northwards while the WAMI index is >0.1.
Gazeaux *et al.* (2011)	Daily Outgoing Longwave Radiation data	NOAA interpolated OLR data for period 1979-2008 at 2.5° x 2.5° resolution.	Onset can be seen as a clear shift point in the season time series of OLR data using statistical inference
Vellinga *et al.* (2012)	MSE data (daily)	Re-analysis data from ERA-	Onset occurs at time when jointly, (1) monsoon circulation over W Africa (5-

		Interim and MERRA (Rienecker *et al.* 2011) for the period 1979-2010.	15°N) has become sufficiently established and (2) the difference in boundary layer moist-static energy over the Sahel minus that over the Gulf of Guinea coast has become positive
Nguyen *et al,* (2014)	Mean sea level pressure and zonal winds at 850 hPa (daily data)	Japanese re-analysis data at 2.5° x 2.5° resolution for the period 1979-2010.	Using the Nguyen, Renwick and McGregor index defined as: $NRM = sign(U850) \times \vert MSLP \times U850\vert$ Onset occurs as sign of NRM changes from negative values to positive (i.e. a change in the signage of the zonal winds value).
Diallo *et al.* (2014)	Daily or pentad rainfall data	GPCP daily rainfall at 1° x 1° resolution for period 1998-2009. TRMM v7 daily precipitation data at 0.25° x 0.25° resolution for period 1998-2007.	Motivated by Sijikumar *et al.* (2006), onset occurs during the first pentad rainfall in a pre-defined Sahelian Index is greater than for a Guinean Index for at least 5 consecutive pentads.

Table 2.2 - List of local onset definitions in publication ordered by date published. All onset definitions use daily rainfall data as input.

Reference	Original dataset and resolution used	Onset definition
Walter (1967) *As analysed in Ati et al. (2002)*	Rain gauge data taken from eight stations in Nigeria for varying time periods (maximum range 1961-1991)	OD = D(50.8 – F)/R D - number of days in first month with P>50.8mm (MER) R – rainfall in MER F – total rainfall in previous months
Kowal and Knabe (1972) *As analysed in Ati et al. (2002)*	Same data as Walter (1967)	The first 10-day period in which rainfall exceeds 25 mm and the subsequent 10-day rainfall total is greater than 0.5 of the potential evapotranspiration
Benoit	Same data	Date when accumulated daily rainfall exceeds 0.5 of the

(1977) *As analysed in Ati et al. (2002)*	as Walter (1967)	accumulated potential evapotranspiration for the remainder of the season, provided this date is not immediately followed by a five day dry spell
Olaniran (1983) *As analysed in Ati et al. (2002)*	Same data as Walter (1967)	Assuming for Walter (1967, onset listed above) month following MER has rainfall < 50.8mm: Onset date = $D(50.8 – F_x)/R_x$ D – number of days in first month with precipitation>50.8mm (MER) F_x – rainfall of month following MER R_x – rainfall of 2^{nd} month following MER
Sivakumar (1988) *As analysed in Ati et al. (2002)*	Same data as Walter (1967)	First date after 1 May when 3-day accumulated rainfall exceeds 20 mm with no seven-day dry spell in subsequent thirty days.
Omotosho *et al.* (2000) – *Omo* See also	Rain gauge station data. Data used for years between	The first three or four rainy days (>10 mm) to occur with not more than seven days between them.

Omotosho 1990	1971 and 1997 but not continuous.	
Le Barbé *et al.* (2002) – *LeB_Loc* (semi-local)	Rain gauge data taken from AGRHYMET dataset 1950-1990.	Onset date inferred from an appreciable jump in the maximum of zonally-averaged (10°W-10°E) 10-day smoothed daily rain event occurrence from 5°N to 10°N. Here we adapt the method found in the original work to prescribe a specific onset date. This method can be modified to be studied either regionally or semi-locally.
Zeng and Lu (2003) (semi-local)	Global daily precipitable water data 1988-1997	Taking a grid-cell within the West African region, and its eight direct neighbouring grid-cells. Onset occurs at the first date when the Normalised Precipitable Water Index (a measure of current Precipitable Water values against historical values for the last 10 years) exceeds the golden ration (0.618) in seven of the nine locations examined.
Marteau *et al.* (2009) - *Mart*	Rain gauge data from the Flow Regimes from International Experimental and Network	First rainy day (>1 mm) of two consecutive rainy days with total rainfall > 20 mm with no seven day period of total rainfall less than 5 mm in the succeeding twenty days

	Data-Afrique de l'Ouest et Centrale and Senegalese Direction de la Météorologie Nationale from 1950-2000	
Vellinga *et al.* (2012)	GPCP daily data at 1° x 1° resolution for period 1979-2010 and TRMM v6 3-hourly data at 0.25° x 0.25° resolution for period 1998-2010.	The date before which a given percentage of climatological annual rainfall has fallen (20% given as example)
Yamada *et al.*	Atmosphere general	Date when six day average rainfall exceeds 2 mm/day

(2013) - *Yam*	circulation model study.	

2.2. Comparison of definitions

Five regional definitions, three local definitions and one semi-local definition have been chosen. The regional definitions were taken from: Le Barbé *et al.* (2002) [*LeB_Reg*], three realizations of Sultan and Janicot (2003) [*SJ, SJ_10* and *SJ_15*], and the OLR definition from Fontaine *et al.* (2008) [*Font*]. The three local definitions chosen were from: Omotosho *et al.* (2000) [*Omo*], Marteau *et al.* (2009) [*Mart*] and Yamada *et al.* (2013) [*Yam*], with the semi-local application of Le Barbé *et al.* (2002) [*LeB_Loc*] also studied. Here we expand on the construction of the selected onset definitions where the descriptions found in Tables 1 and 2 are not sufficient and provide comments on each definition used. Where definitions are self-evident discussion is left for sections 4 and 5.

The most prevalent onset definition in literature comes from Sultan and Janicot (2003). There exists a level of subjectivity within specific calculation of onset date using this definition (this is also true for *Font* and *LeB_Reg*). In order to determine the level of influence this subjectivity has on onset observation three realizations of the original definition have been produced. We compare the verbatim definition from Sultan and Janicot (2003) (called *SJ* here) to two objective modifications, denoted *SJ_10* and *SJ_15*. Full description of these and comparison can be found in section 4.1.

Le Barbé *et al.* (2002) infer daily rainfall event frequency data from daily rainfall totals. Their work highlights an appreciable “jump” (or abrupt northwards surge) of the time smoothed maximum daily rain event frequency in composites from 1950-1990 from 5°N to 10°N during late June/early July. This result allowed for formation of a regional onset definition, *LeB_Reg*, influenced by the original work. In our definition, a rain event is any precipitation event of at least 1 mm that lasts for at least 3 hours. It is possible for there to be more than one rain event on a given day, or for a rain event to continue overnight. For the latter of these situations, the rain event has been credited to the day on which the initial rainfall occurred. A semi-localised equivalent of *LeB_Reg*, *LeB_Loc*, has also been produced. *LeB_Loc* has been constructed in the same way as *LeB_Reg* for 1 degree longitude ranges as opposed to zonal-averaging across 10°W-10°E. This allows for examination of longitudinal variability across the monsoon region within a given onset definition and a direct comparison of one definition across two scales of observations.

The inclusion of the regional definition *Font* in our analysis allows for a contrast between calculating onset using different satellite data. Whilst precipitation is the most key factor for local stakeholders in the region, there is always an inherent risk with precipitation data that totals calculated are not guaranteed to be representative of true rainfall on the ground (though most satellite data products are very good; see Roca *et al.* 2010). Instead by measuring onset using cold cloud top coverage, onset is not subject to potential observational bias (however cold cloud top temperature is not necessarily directly indicative of precipitation rate). Both *Font* and *SJ* focus on the seasonal northwards movement of the ITCZ but use different observational metrics. *SJ* highlights the northwards migration of the maximum rain belt whereas *Font* considers the northwards shift of the maximum zone of convergence. It is to be expected for a well-established ITCZ that these two definitions would be largely similar.

Mart was produced and analysed originally in Senegal, Mali and Burkina Faso for agronomic purposes. The use of a twenty day *dry-test* period following the initial rainfall event allows for capture of potential false onsets or sporadic rain events. It is possible that in some regions a more restrictive dry-test is necessary (this is considered in Marteau *et al.* 2009). The relatively long observation window of *Mart* can limit its use for real-time analysis compared to *Omo* or *Yam*. A potential link between local and regional definitions, or a consistent seasonal trigger for *Mart* onset would reduce this restriction.

The definition *Yam* is in direct contrast to other local definitions, most notably that of *Mart*. *Yam* does not consider the onset with regards to specific needs of the end users nor does it relate onset to a key shift in local or regional dynamics. The comparison between this definition and that given by *Mart* provides an interesting contrast between a readily modifiable and agronomic definition WAM onset.

3. Datasets

Two daily, satellite-based datasets and one re-analysis dataset have been used to map precipitation based onset dates. The period 1998-2012 is used, giving 15 years of data.

Daily precipitation data from the NASA Tropical Rainfall Measurement Mission level 3 product 3B42 (TRMM) (Huffman *et al*. 2007) and the Global Precipitation Climatology Project (GPCP) (Adler *et al.* 2003; Xie *et al.* 2003), retrieved over 0.25°x0.25° and 1°x1° grids, respectively, have been used. In addition we have calculated onset using re-analysis data from the ECMWF ERA-Interim (ERA-I) on a 1.5°x1.5° grid (Dee *et al.* 2011). ERA-I is often used as a benchmark analysis product for West African dynamical studies. Therefore it is of interest to compare the onset statistics found using re-analysis data to observational datasets; however it must be stressed that ERA-I results should not be considered true observed onset dates. In order to test onset sensitivity to spatial resolution, TRMM v6 and v7 data were coarse-grained to 0.5°x0.5°, 1°x1° and 2.5°x2.5°.

The recent development of TRMM version 7 (Huffman *et al.* 2007; see http://trmm.gsfc.nasa.gov/3b42.html for more details) offers a comparison of onset dates found in versions 6 and 7 (hereafter v6 and v7) for the period 1998-2010. Finally, TRMM v6, 3-hourly data have been used for comparison of *LeB_Reg* and *LeB_Loc* with other onset definitions for the period 1998-2010.

For all definitions, analysis of data was performed for the period 1 May – 30 August. This period encompasses the date of ITF advancement towards 15°N (Sultan and Janicot 2003; Lélé and Lamb 2010) until after the annual monsoon season in the Sahel. For local onset definitions, this allows for onset dates triggered by the pre-onset phase of the monsoon (as defined by Sultan and Janicot 2003) to be observed. It was expected that regional onset dates would not be altered by this early observation window and special care was taken to make sure that all regional onset dates reflect the large-scale shift studied in the original work.

The OLR-based definition *Font* was calculated using the National Oceanographic and Atmospheric Administration (NOAA) daily-averaged, OLR, satellite-based dataset interpolated on a 2.5°x2.5° grid (see http://www.cdc.noaa.gov/cdc/data.interpOLR.html for more details). During the analysed period, there are no relevant missing dates.

Given that this study aims to recreate published onset definitions, time-smoothing of data has been performed only on definitions where time-smoothing was originally performed. The regional definitions *SJ*, *SJ_10*, *SJ_15*, *Font* and *LeB_Reg* as well as the semi-local onset definition *LeB_Loc* use time-smoothed data to better relate the results shown here to the original papers.

4. Regional definition comparison

4.1. Regional onset definition by Sultan and Janicot (2003)

The onset definition *SJ* taken verbatim from Sultan and Janicot (2003) does not use set onset thresholds and contains a level of subjectivity in specific onset date selection. An example of unambiguous onset selection can be found using TRMM v7 data for 2009 (Fig. 2.1a). Here there is a decrease in precipitation at 5°N (red line), simultaneous with an increase in precipitation at 10°N (blue) and 15°N (green); regional onset is taken as 4 July (black line in Fig. 2.1a). By contrast, Fig. 2.1b shows the corresponding time series in 2010. Evidently, there is no clear time at which the three precipitation time series satisfy the criteria given by Sultan and Janicot (2003) simultaneously. Subjectively, for 2010 it is unclear whether onset should be defined as occurring around date 15 June or after 1 July; a significant difference. The plots suggest that the clear triggering of *SJ* and existence of a definitive onset date for each year is not guaranteed.

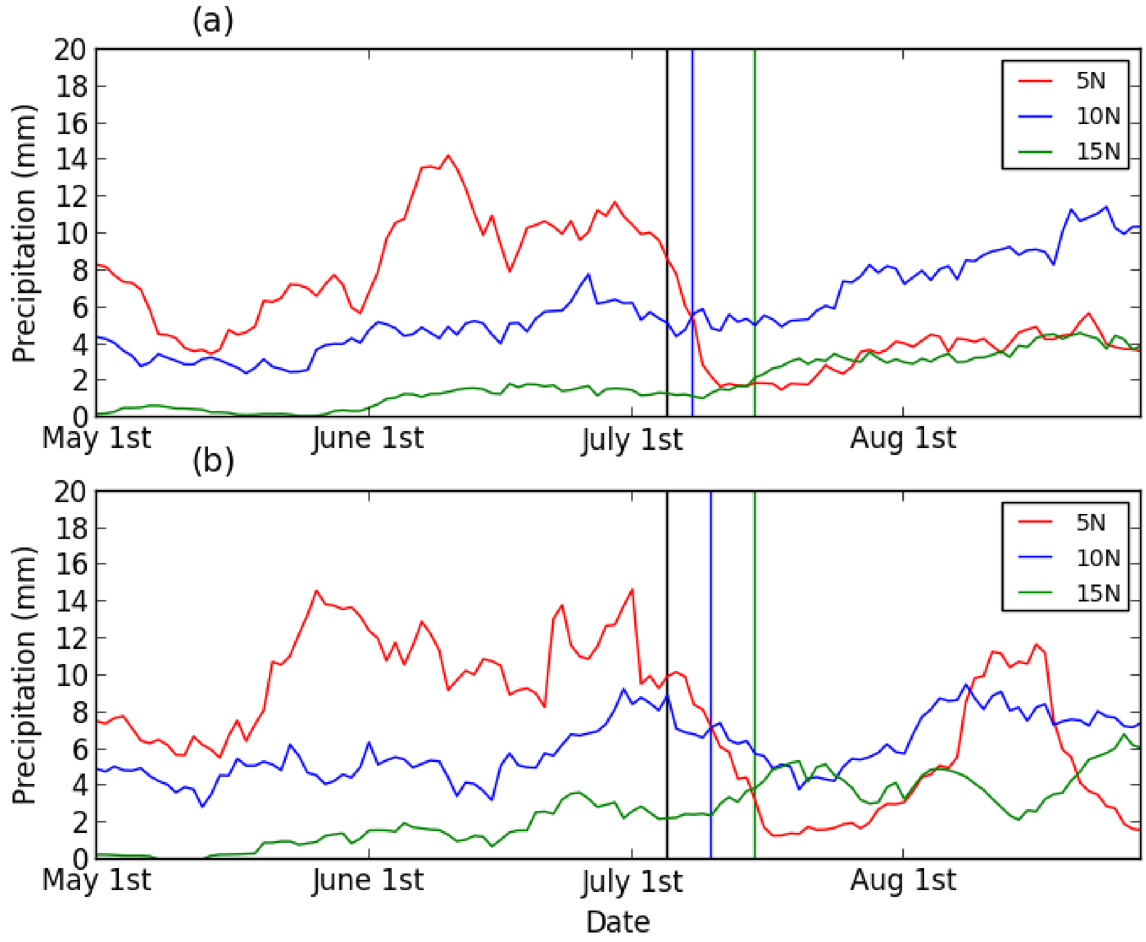

Figure 2.1 - 10-day time smoothed precipitation time series for (a) 2009 and (b) 2010 using the TRMM v7 dataset at 0.25 degree resolution. Black line denotes our subjective realization of *SJ*, blue line denotes *SJ_10* and green line denotes *SJ_15*. See table 1 for definition of SJ and section 4.1 for definition of *SJ_10* and *SJ_15*.

In order to provide consistency and repeatability of the results found here, two objective modifications of *SJ* have been made. The new definitions *SJ_10* and *SJ_15* are given as the first date when zonally-averaged, 10-day smoothed precipitation at 5°N is below precipitation levels at 10°N and 15°N respectively for at least 7 days. The two objective onset definitions have statistically significant (to the 5% level) rank correlation (0.52 for TRMM v7), but the objective onset definitions do not correlate well with *SJ* (0.22 for *SJ* and *SJ_10* using TRMM v7). This is disconcerting as it implies that the perceived onset given all three time series is not linked to the onset date identified using two of the three time series. For the rest of this section, we use the objective definition *SJ_10* given its clarity and repeatability.

For consistency with other regional onsets and to avoid the potential of erroneously early regional onset, *SJ_10* is calculated for the period 1 June – 30 August each year. This removes two early onsets found within the TRMM v6 1-degree and ERA-I datasets which occur in early May and skew results. Given a 1 May start date, regional onset in the 1-degree coarse grained version of TRMM v6 occurs on 20 May. With a 1 June start date onset is 11 July, which agrees much closer with other datasets and expected results (not shown).

4.1.1. Summary statistics

Table 2.3 gives the mean *SJ_10* onset date and standard deviation for each dataset studied here and those found in Sultan and Janicot (2003). The mean onset dates for *SJ_10* calculated in this study for different datasets closely agree with the result of the original paper, suggesting a consistency of the definition across differing time periods and datasets. In our study, there is greater variability of the onset dates which could potentially be due to the smaller sample size in our study; however this difference is only of the order of days.

Overall the largest spread of onset dates occurs in the ERA-I dataset with 42 days separating the earliest (2005) and latest (1998) onsets. TRMM v6 and v7 show a similar range of onset dates however the inter-quartile range of v6 is much larger than v7. The majority of onsets are observed within a narrow date range in the TRMM v7 dataset, implying that typical inter-annual variability within this dataset is very low. Whilst the inter-annual variability of regional onset is of scientific interest, in general a forecasted onset date within a week of true observed onset is sufficient for agronomical purposes (Sultan *et al.* 2005). Therefore, a climatological regional onset date taken from any of the datasets studied here would generally provide sufficient information on onset for practical purposes. This raises the question of the need for accurate prediction of regional onset on an inter-annual basis. A similar argument can be made for GPCP and the two coarse-grained TRMM v6 datasets. The standard deviation coupled with the spread of onset dates shows the low inter-annual variability given by this onset definition. Given the much higher inter-annual variability found in local onsets (highlighted in Section 5), this raises the question of whether a regional definition can provide sufficient information for practical use at the local scale. This does not nullify the use of regional onsets for other forecasting needs and scientific research. Instead it is important to highlight that onset date selection must relate to the needs of the forecast end users.

Table 2.3 - Mean onset dates for SJ_10 in all datasets studied as well as statistics from literature for comparison.

Dataset used	Mean onset date	Median onset date	Standard deviation (days)	Range (days)	Inter-quartile range (days)
Sultan and Janicot 2003	24 June	n/a	8	n/a	n/a
Janicot *et al.*	24-30 June	n/a	~8	n/a	n/a

(2011)					
ERA-Interim	26 June	4 July	13.9	42	19
GPCP	28 June	30 June	11.8	44	13.5
TRMM v6 quarter degree	28 June	29 June	9.9	26	19
TRMM v6 half degree	5 July	8 July	8.2	28	7
TRMM v6 one degree	6 July	8 July	9.6	39	7
TRMM v7 quarter degree	5 July	7 July	9.7	39	8.5
TRMM v7 half degree	4 July	6 July	9.5	38	10.5
TRMM v7 1 degree	5 July	6 July	9.6	38	12
TRMM v7 2.5 degree	4 July	5 July	11.0	37	11.5

4.1.2. Sensitivity of *SJ* to dataset and resolution for individual years

The mean onset results mask inter-annual disagreements between datasets. Figure 2.2 gives the precipitation time series at 5°N, 10°N and 15°N for GPCP and TRMM v7 in 2008 as well as the *SJ_10* onset date for both datasets. GPCP gives earlier than dataset mean onset (13 June compared to average of 29 June) whereas TRMM v7 observes 2008 as a slightly later than average onset (8 July compared to 4 July average).

The reason for this difference in onset date is the relative levels of precipitation found at 5°N and 10°N prior to and around 13 June. For GPCP (Fig. 2.2a), precipitation at 5°N gradually decreases from a peak value at the end of May, and is less than precipitation at 10°N from the date of *SJ_10* onset until the end of our observed period. By contrast, in TRMM v7 (Fig. 2.2b), there is a secondary peak in rainfall at 5°N in early June and, whilst the precipitation at 5°N does temporarily dip below that found at 10°N, this does not trigger our *SJ_10* onset.

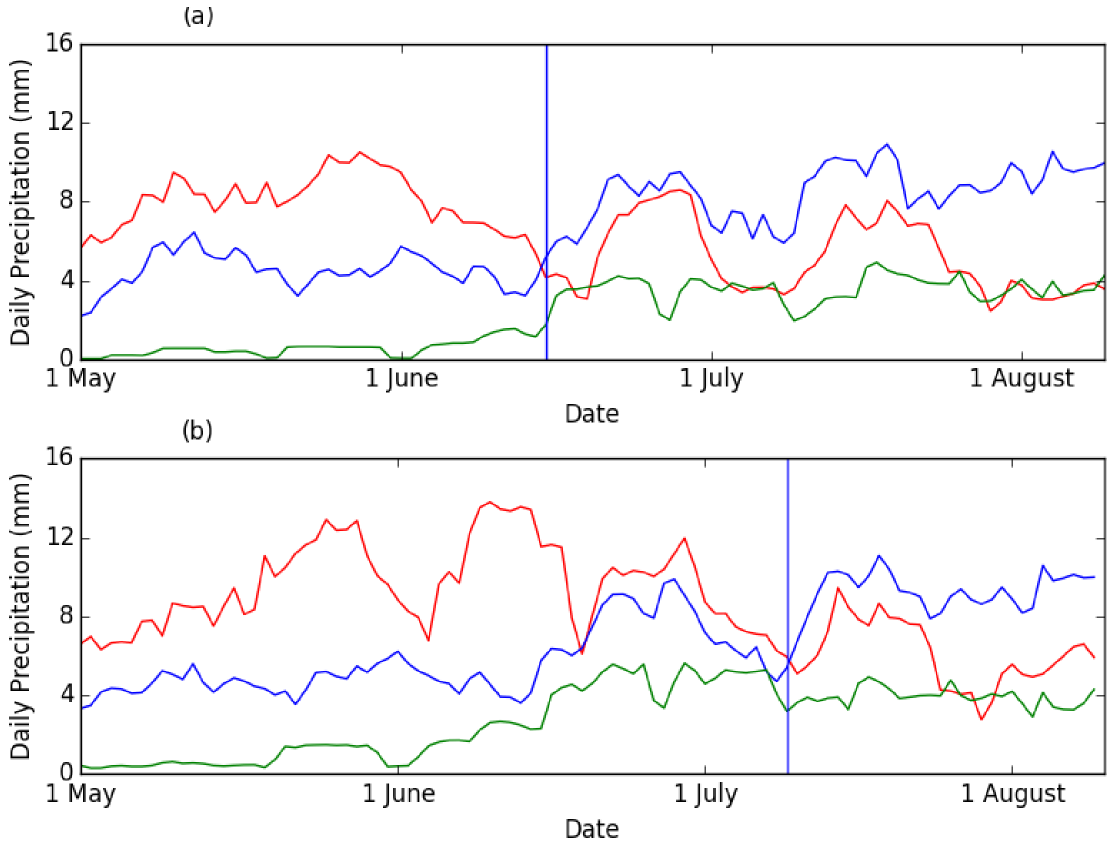

Figure 2.2 – (a) Example of the variability in *SJ_10* onset date. (a) GPCP time series of precipitation at 5°N (red), 10°N (blue) and 15°N (green) for the period 1 May – 10 August 2008. (b) Time series of precipitation at the three latitudes given by TRMM v7 for 2008. For both plots, blue vertical line denotes the date given for *SJ_10* onset.

Of interest is the fact that precipitation levels at 10°N and 15°N are similar across the entire observed period for both GPCP and TRMM v7. The reason for the difference in onset date is the variability in precipitation at 5°N. This example is representative of other comparisons between *SJ_10* onsets realised using different data.

Figure 2.3 highlights the inter-annual range of onsets found using different datasets. Comparing onset dates for the various datasets against *SJ_10* onsets for TRMM v7, it is found that the difference between TRMM v7 onset and ERA-I onset is greater than seven days for five of the fifteen years, likewise for GPCP this difference occurs in six of the fifteen years studied. In four years, the difference between TRMM v6 and v7 also exceeds seven days. There is no systematic year-to-year difference between pairs of datasets and therefore agreement cannot be reached through a simple bias correction.

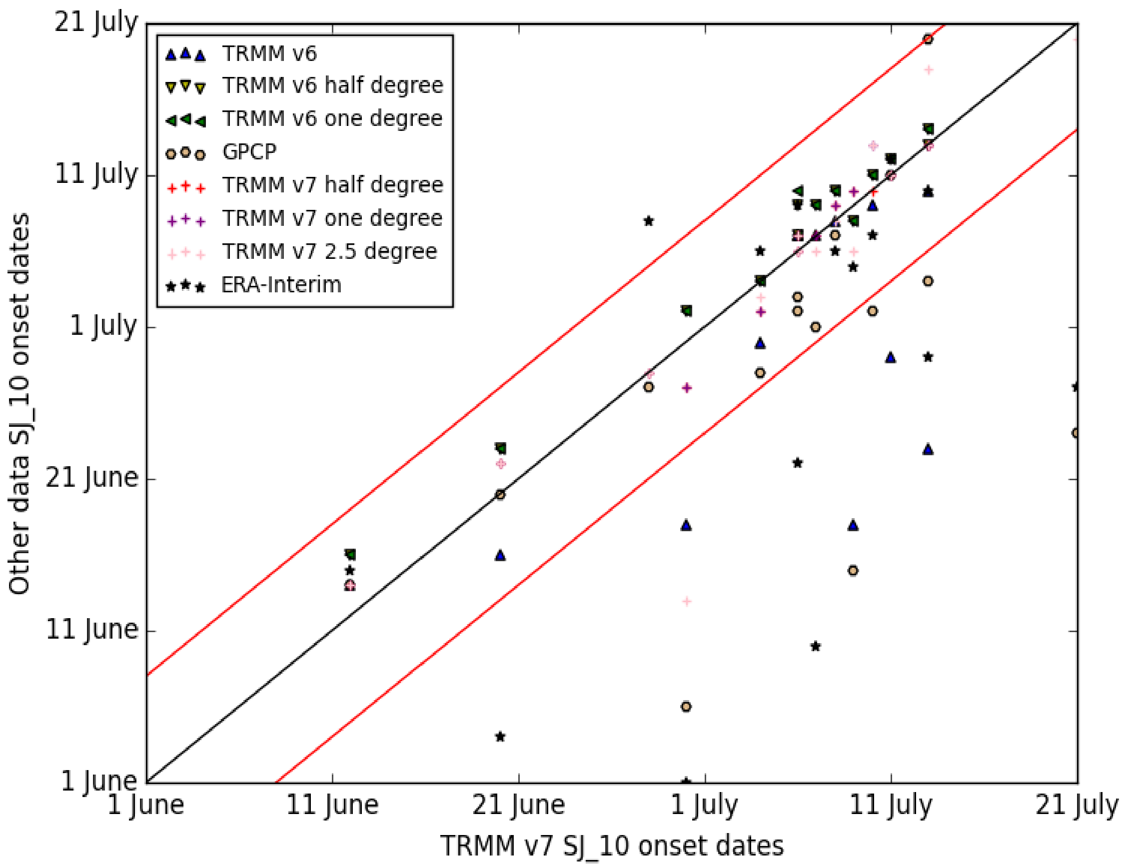

Figure 2.3 – *SJ_10* onset dates for all datasets plotted against TRMM v7 for observation period 1998-2012 where available. Black line denotes a perfect relationship between TRMM v7 onsets and onsets of other datasets. Red lines denote a 7-day margin between two observations.

The onset dates calculated across different datasets show statistically significant (to 5% level) positive correlation using Spearman rank correlation. Of note is the correlation between TRMM v6 and TRMM v7 (0.55) and TRMM v6 quarter-degree with its coarse-grained counterparts (0.63 and 0.67 for TRMM v6 half-degree and

TRMM v6 1-degree respectively). The GPCP onset dates are also well correlated with the other datasets (0.81 for TRMM v6, 0.76 for TRMM v6 1-degree data, 0.51 for TRMM v7 and 0.54 for TRMM v7 coarse-grained to 1 degree).

The onset definition SJ_10 does not appear to be sensitive to the resolution of observations used here. In particular, TRMM v7 shows very high consistency of onset dates across all resolutions. TRMM v7 quarter-degree onset dates are significantly correlated at the 5% level with the TRMM v7 half-degree onset dates (0.99) as well as the one-degree (0.99) and 2.5 degree (0.90) coarse grained version of TRMM v7. The northwards migration of the maximum rain belt can be reliably captured using high-resolution and lower resolution precipitation data.

Root mean square error (RMSE) analysis allows for comparison of onset dates given by each of the three precipitation datasets used. The RMSE is consistent between GPCP and the various resolution of TRMM v7 used (12.0 between TRMM v7 quarter degree resolution and GPCP, 12.1 between TRMM v7 one degree resolution and GPCP). The RMSE between TRMM v6 quarter-degree resolution and GPCP is lower (7.2) as well as the error between TRMM v6 and TRMM v7 at quarter-degree resolution (10.6). The fact that the RMSE is of similar order to the variability found in each dataset suggests that the variability of *SJ_10* is well constrained across datasets.

Whilst there is correlation between the *SJ_10* onset time series, the fact that there are certain years (up to 20% of those studied) where two datasets can disagree by over seven days suggests that dataset choice can still greatly impact the onset date found for certain years even though in most years this impact will not be too severe.

4.2. Regional onset definition by Fontaine *et al.* (2008)

Composites of annual OLR progression show a northward migration of regionally-averaged (10°W-10°E) deep convective activity from 5°N towards the Sahel during late June/early July (Fig. 2.4). This occurs concurrently with the annual movement of the ITCZ and maximum rain-belt into the Sahel. The regional definition *Font* expands on the information in Fig. 2.4 to establish the date at which the maximum convective belt shifts from 5°N to 10°N with annual onset dates of *Font* computed using the method in Table 2.1. The definition *Font* contains a level of subjectivity in the period of time required to establish the shift of the maximum convective belt to 10°N.

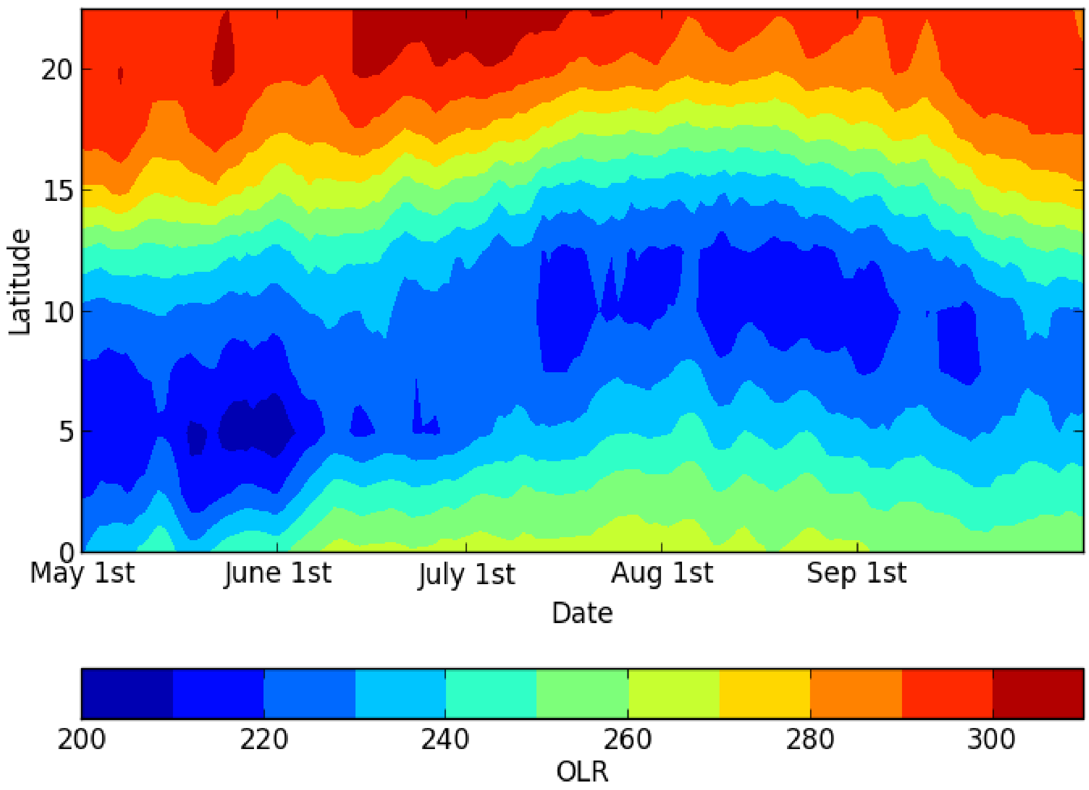

Figure 2.4 - Motivation for the onset definition *Font*. Annual mean (1998-2012) of zonally-averaged OLR progression throughout the monsoon season.

As with *SJ*, the lack of definitive threshold values for *Font* allows for potential ambiguity within the definition. In order to remain objective and to allow for repeatability of the results shown here, the onset *Font* has been interpreted as close to verbatim as is pragmatic. Onset dates for *Font* have been previously published in Gazeaux *et al.* (2011) for the years 1979 - 2004. Analysing the crossover between this study and our own, we find years in which the onset dates agree (1998, Fig. 2.5a) and ones with unclear results (1999, Fig. 2.5b). In 1998 a shift of the maximum convective belt from 5°N to 10°N around 1 July is evident, at which point convective activity remains at, or northwards of, 10°N for the remainder of the monsoon season (Fig. 2.5a). 1 July is also given by Gazeaux *et al.* (2011) as the onset date for this year. For 1999 (Fig. 2.5b) onset date is more difficult to determine. Gazeaux *et al.* (2011) determine onset 10 days later than for 1998, however there exists much more frequent, low OLR coverage (indicative of deep convective activity) over the Sahelian region for 1999 during mid/late June. Although convective activity seems to diminish at about 5°N around 11 July, part of the convective maximum has already established itself over 10°N prior to this time. It is quite possible to make a case for the onset occurring prior to 11 July; however given the exact wording of the definition, 11 July would be the most appropriate date.

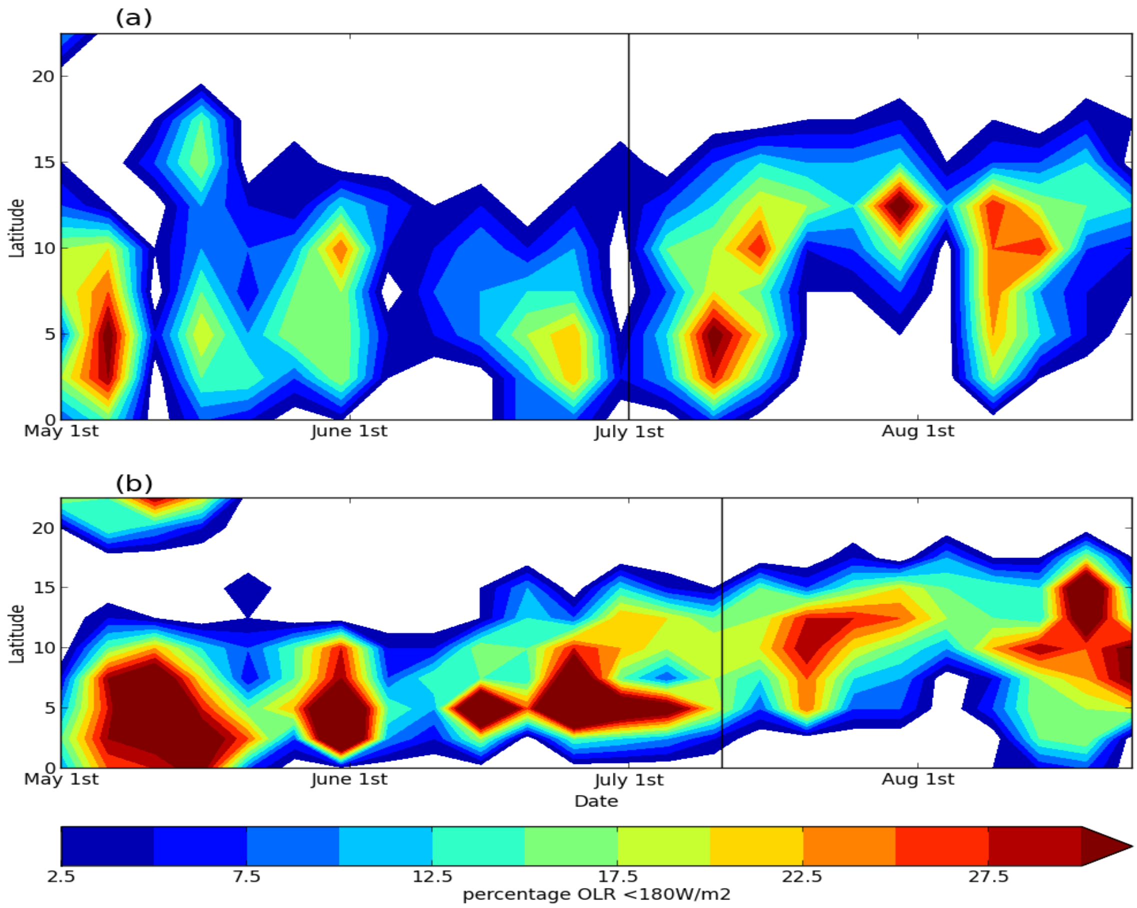

Figure 2.5 - Illustrative examples for the onset definition *Font*. Zonally-averaged, 5-day smoothed percentages of grid cells with OLR less than or equal to 180 Wm^{-2} for (a) 1998 and (b) 1999. The black lines mark onset dates given in Gazeaux *et al.* (2011).

Font is open to interpretation and difficult to objectively calculate making this an unsuitable metric for sole use in evaluating onset prediction for West Africa. Despite this, the use of OLR data represents a significant benefit of the definition *Font*, due to the long and reliable dataset (NOAA 1979-present) and data not being reliant on satellite retrievals. *Font* could be used along with other regional definitions such as *SJ_10* and *LeB_Reg* in order to observe the large-scale shift of the monsoon system.

4.3. Regional onset definition based on Le Barbé *et al.* (2002)

4.3.1. Summary Statistics

The regional definition *LeB_Reg* determines a representative date for the seasonal northwards shift of the ITCZ similar to *SJ* and *Font*. Similar to the two previous definitions there is room for subjectivity in explicit onset date identification. In 2002 for example, there is a clear shift in the location of the maximum rain event frequency from near 5°N to 10°N during mid-July (Fig. 2.6a). By contrast, in 1999 the maximum in rain event frequency does not reach 10°N until mid/late June. However as early as 1 June 1999, rain event frequencies at 10°N are greater than 0.5 (i.e. at least 5 rain events per 10 days; Fig. 2.6b). It is open to interpretation which date should be taken as the precise onset date for this year highlighting the flexibility in the calculation and comparison of *LeB_Reg.* It should be noted that the result found here may be closely tied to the ambiguity found in *Font* for 1999 (Fig. 2.5b).

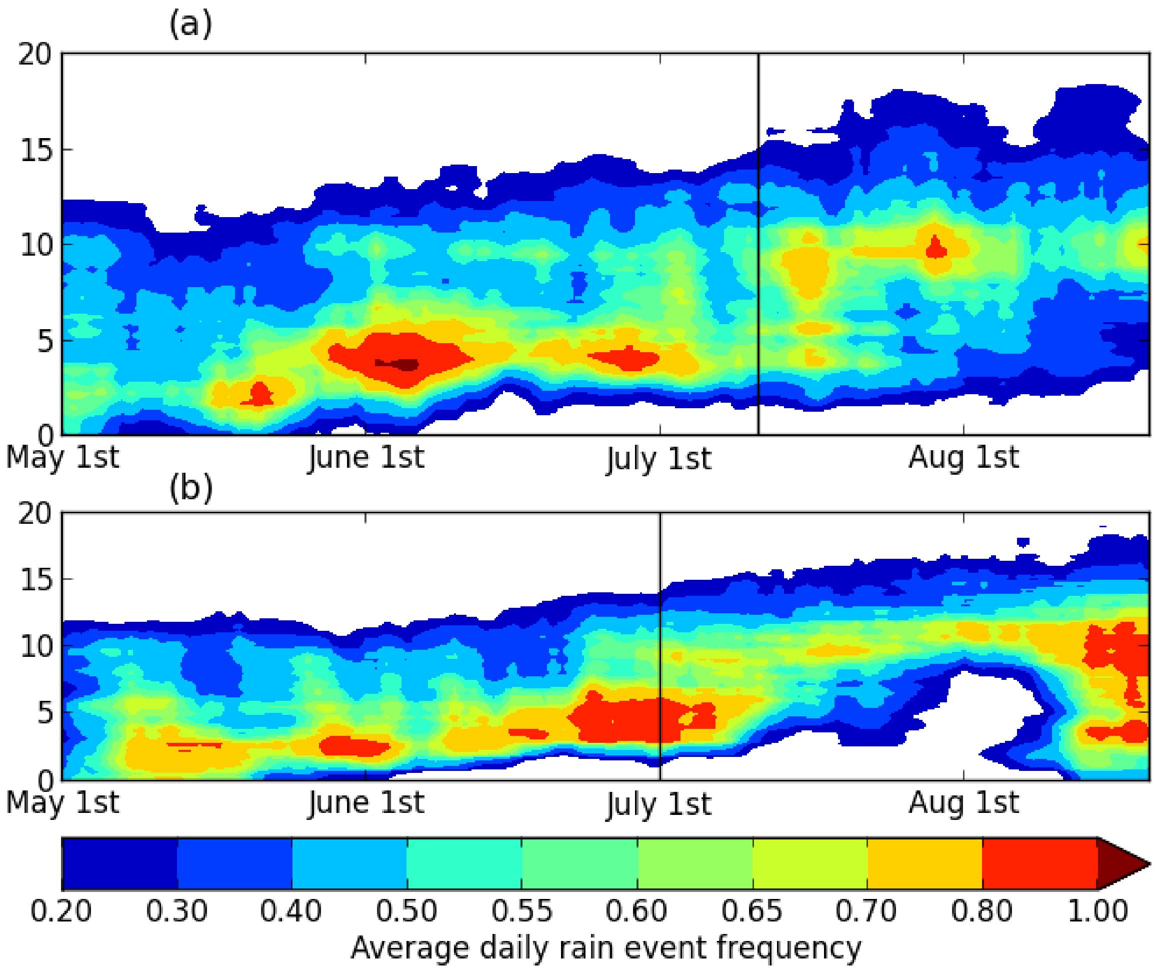

Figure 2.6 - Illustration of regional onset definition *LeB_Reg*. TRMM v6 3-hr daily rain event frequency for the zonally averaged (10°W – 10°E) monsoon region in (a) 2002 and (b) 1999. Black lines mark identified onset date for given year.

<u>4.1.2. Comparison between *SJ_10* and *LeB_Reg*</u>

Figure 2.7 highlights the comparison between onset dates for the various *SJ_10* representations using different datasets and *LeB_Reg.* For TRMM v6 several *SJ_10* onset dates agree closely with their complimentary *LeB_Reg* onset date with 2004 marking the largest temporal gap between the two definitions for these datasets. This is due to the existence of a double peak in rain event frequencies occurring at

10°N during July affecting the *LeB_Reg* onset but not the *SJ_10* onset (not shown). There exist more frequent large outliers found when comparing *LeB_Reg* to *SJ_10* onsets using other datasets. In all datasets comparisons, there are years when the difference between onset dates is greater than seven days.

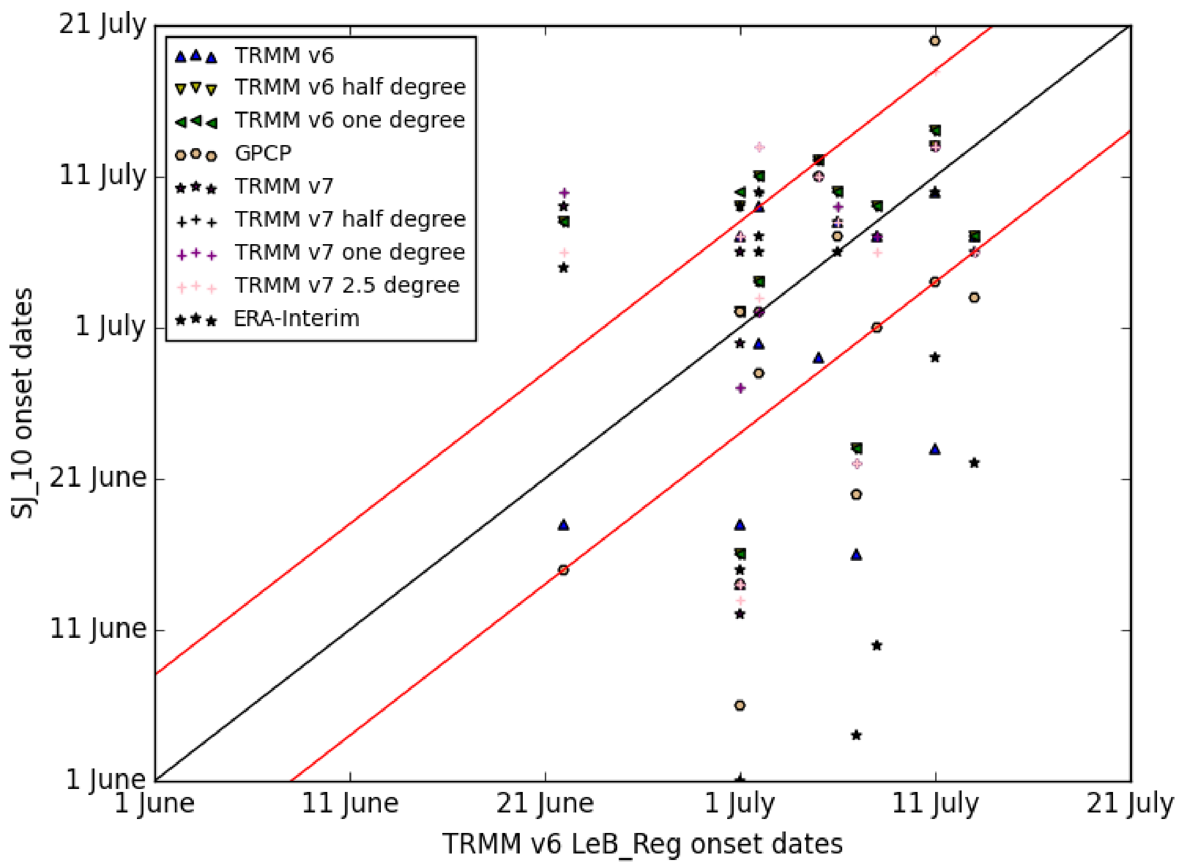

Figure 2.7 – Inter-annual variability in onset observations for different onset definitions. Comparison of *LeB_Reg* with *SJ_10* onset dates for different datasets. Black line denotes the line of exact agreement of onset dates and red lines show expected inter-annual variability.

The mean onset date for *LeB_Reg* using TRMM v6 over the period 1998-2010 is 3 July with a standard deviation of six days. This is comparable with the onset mean found for *SJ_10* (28 June for TRMM v6, 5 July for TRMM v7) and consistent with the observed pattern of *Font*. Despite the mean onset dates being comparable between *SJ_10* and *LeB_Reg*, there is little inter-annual correlation between the two definitions with no correlations significant at the 5% level found. Different onset definitions have disparate perceptions of which years have late and early onsets.

Overall there is moderate agreement between the mean patterns of all regional definitions used here implying that the same large-scale dynamical process is being measured by all three regional definitions using different metrics. However, the lack of inter-annual correlation between onset dates calculated using different datasets poses a significant problem for practical seasonal forecasting. Without agreement between datasets there is limited use in evaluation of forecast models due to the lack of clarity on what an accurate prediction of monsoon onset would be for any given year. Forecasts should therefore be compared to multiple datasets with the forecasted regional onset date expected to lie within the spread of observable onset dates. Finally, onset definition used must be relevant to the goals of the forecaster and give practical implications to users. For tracking the seasonal ITCZ movement, the inclusion of definitions that do not use precipitation intensity data, such as *Font* and *LeB_Reg* should also be considered whilst care is taken to understand the limits of definition subjectivity.

5. Local definitions

Unlike the regional definitions analysed above, the three local definitions examined in this study all use the same observational parameter (precipitation) but capture different aspects of the local seasonal precipitation time series. *Mart* captures the onset of persistent rainfall, *Omo* is triggered by heavy rainfall and *Yam* identifies the commencement of local rainfall at the grid cell level.

The motivation behind and construction of *Mart* makes the definition directly relevant to local, agronomic stakeholders. In contrast, the definition given by *Yam* is, by the authors' admission, readily modifiable. It is expected that the beginning of local rains (i.e. *Yam*) at a given grid-cell will occur before or simultaneous with the onset of *persistent* local rainfall (*Mart*). Therefore potential strong correlation between *Mart* and *Yam* would provide a useful window of prediction for the agronomical onset of local rainfall with practical benefits for local farmers.

5.1. Geographical patterns of local onset in TRMM v7

Figure 2.8 compares the three local definitions studied here using the TRMM v7 dataset. Both *Omo* and *Yam* show widespread onset prior to the middle of June (day 169, Fig. 2.8b and 2.8c). *Mart* (Fig. 8a) has onset dates occurring later than the other two local definitions and shows a rough southerly progression of onset dates through the West African region. For some locations, onset dates in *Mart* occur over 28 days after local triggering of *Omo* (Fig. 2.8d) and *Yam* (Fig. 2.8e) with little difference in the average timing of onset for *Yam* and Omo except over the northern Sahel (Fig. 2.8f). It is apparent that it is far easier to trigger *Yam* or *Omo* than *Mart* over most of the analysed domain.

There is sporadic statistically significant (at the 5% level) inter-annual correlation between the three datasets studied at the grid cell level (Figs. 2.8g, 2.8h, and 2.8i, white areas denote regions where no significant correlation is found). This lack of widespread correlation shows there is generally little inter-annual consistency between the local commencement of rainfall (*Yam*), the commencement of heavy rainfall (*Omo*) and the local commencement of persistent rainfall (*Mart*). The local onset definition chosen can significantly alter the onset pattern observed across the West African region and therefore impact the relationship between local and regional onsets considered.

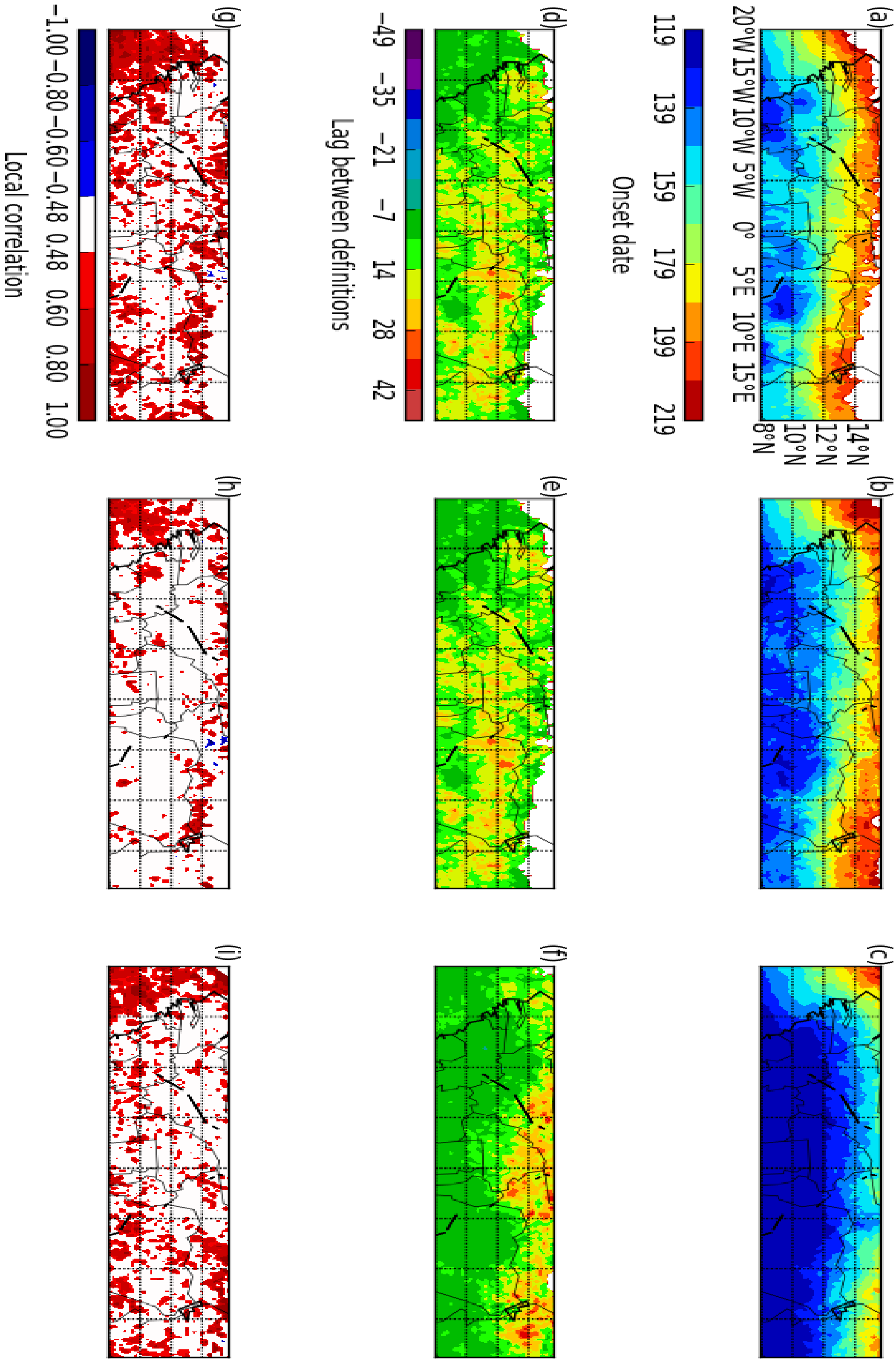

Figure 2.8 - Local onset comparisons for TRMM v7 0.25° for the period 1998-2012. Mean onsets for (a) *Mart*, (b) *Omo* and (c) *Yam*. Lag between (d) *Mart* and *Omo* onsets (red denotes *Mart* later than *Omo*) and (e) *Mart* and *Yam* (red

denotes *Mart* later than *Yam*), (f) *Omo* and *Yam* (red denotes *Omo* later than *Yam*). Correlations between (g) *Mart* and *Omo*, (h) *Mart* and *Yam* and (i) *Omo* and *Yam*. White values denote regions where local correlation between definitions is not significant. Large scale rivers and lakes within the study domain are included for reference.

5.2. Comparison of local onset patterns in different datasets

5.2.1. Comparison of TRMM v6 and TRMM v7 onset composites

Figure 2.9 compares the onset dates found for the three local onset definitions using TRMM v6 and v7 data. In general, local onsets dates for *Mart* and *Yam* agree closely across TRMM v6 and v7 (compare Fig. 2.9a and 2.9c with Fig. 2.8a and 2.8c), with little difference in mean onset dates across datasets (Fig. 2.9d, 2.9f); the notable exceptions occur around 7-15W°, 8-12°N and 5-12°E, 8-11°N. The onset date *Omo* occurs earlier in TRMM v6 than in TRMM v7 by about two weeks or more across the entire West African region (Figs. 2.9b and 2.9e). It is possible that the difference found between onset dates using the two datasets is due to the different representation of intensive rainfall (Seto *et al.* 2011).

There is statistically significant correlation (at the 5% level) across datasets for *Mart* and *Yam*, but poorer correlation for *Omo* (Fig 2.9g and 2.9i for *Mart* and *Yam,* Fig. 2.9h for *Omo*)*.* This suggests that both TRMM datasets agree with their retrievals of light rainfall (<10mm), and potentially have differing retrievals of heavier precipitation, with TRMM v7 less likely to observe the heavy early season rainfall required to trigger *Omo*.

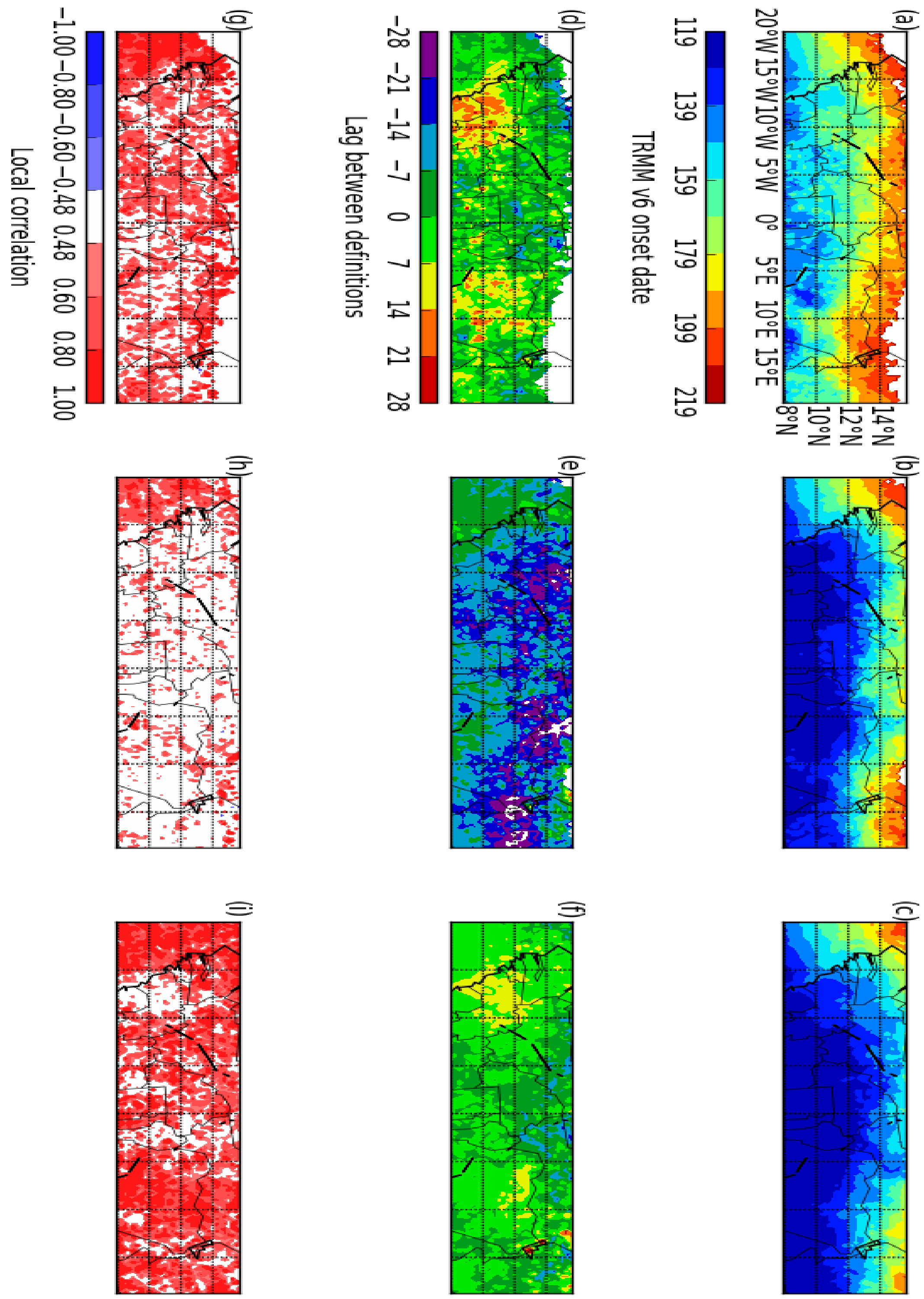

Figure 2.9 - Local onset composites for TRMM v6 and comparison with TRMM v7. Mean onsets for (a) *Mart*, (b) *Omo* and (c) *Yam* from the TRMM v6 dataset. Lag between (d) TRMM v6 and v7 *Mart* onsets (red denotes v6 later than v7) and (e) TRMM v6 and v7 *Omo* onsets, (f) TRMM v6 and v7 *Yam* onsets. Correlations between datasets for (g) *Mart*, (h) *Omo* and (i) *Yam*.

In both TRMM versions, there is a zonal maximum in onset date *Mart* for low latitudes around 10°W and in the longitude region 5°W-0°E. Around these regions it is possible that there exists significant coupling between African Easterly Waves and local rainfall, which potentially explains the later onset dates observed (Bain *et al*. 2014 their Fig 4). As this paper does not focus on the dynamical triggers for onset this potential link has not been investigated further here but is worthy of further research.

5.2.2. Comparison of TRMM v7 and GPCP onset composites

Onset composites for *Mart, Omo* and *Yam* using GPCP show earlier onsets than for TRMM v7 for almost the entire West African region. In particular, the agronomic onset *Mart* is triggered during May for almost all longitudes in the latitude range 8°N-12°N with the north-eastward progression of onset dates apparent in TRMM v7 observations not present in GPCP (not shown).

Furthermore, there is little to no statistically significant (at the 5% level) inter-annual local correlation between onsets in TRMM v6 or TRMM v7 and those in GPCP for any of the three definitions studied. Whilst it is possible that this disparity is due to the different spatial resolution of TRMM and GPCP this lack of correlation is of concern with regard to the *Mart* definition. Poor correlation between GPCP and TRMM v6/v7 suggests an inherent disagreement as to the optimal time for effective planting of crops at a local scale and suggests that observational dataset choice can greatly affect the onset dates found. A potential reason for this is that GPCP has a wet bias of greater than 1 mm/day over the study region during boreal summer making it easier for GPCP to satisfy the dry-test restriction of *Mart* than for either of the TRMM products (Adler *et al.* 2012 their Fig. 7).

5.2.3. Comparison of TRMM v7 and ERA-I onset composites

The three local definitions studied here are triggered over a much smaller spatial area of West Africa within the re-analysis data of ERA-I than in the higher resolution TRMM datasets (not shown). There is very poor coverage of both *Mart* and *Omo* using ERA-I data; this pattern is not consistent with composites of coarse grained TRMM data (not shown). There is little correlation between ERA-I onsets and TRMM onsets regardless of version used or the level of coarse-graining used. Due to the lack of onset triggering it is clear that ERA-I struggles to calculate local onsets *Mart, Omo* and *Yam* without modification of thresholds.

5.2.4. Summary of local onset comparisons

The local onset pattern of the West African Monsoon is very sensitive to the onset definition calculated and observation dataset used. The two onset definitions which do not require a prolonged period of sustained precipitation (*Yam* and *Omo*) both occur earlier than the agronomic definition *Mart* in TRMM datasets. There is good intra-dataset agreement for the local definitions *Mart* and *Yam* across TRMM v6 and v7 consistent with their agreement for regional onsets. TRMM v6 and v7 quarter-degree onset dates do not agree closely with those found using the coarser dataset GPCP for any of the three local definitions. Likewise the re-analysis data does not appear to be able to satisfy the thresholds needed for local onset to be triggered. The local onset pattern found for West Africa is highly dependent on definition and dataset choice. Thresholds used in local onset definitions may need to be modifiable given potential biases across different datasets and forecast models.

5.3. Sensitivity of onset definitions to thresholds

5.3.1. Sensitivity of *Mart* to dry-test period

False onset poses the largest agronomical risk for local stakeholders in West Africa. Premature planting of crops before persistent rainfall can lead to near-total crop yield loss and widespread famine. It is therefore vital that onset definitions are robust and not overly sensitive to parameter thresholds.

In order to test the local precipitation threshold definitions, *Mart* was subjected to a modified dry-test period. A comparison between a 20-day and 30-day dry-tests was performed for the TRMM v7 dataset. Figure 2.10 shows the mean onset patterns for both realizations of *Mart* and the correlation between the two. The mean onsets for 20 and 30 day dry-tests exhibit approximately the same general spatial pattern, suggesting that the definition is robust (Fig. 2.10a and 2.10b). However, there are several areas in which onset dates occur substantially later for a 30-day dry-test. Most notably, parts of Ghana and Burkina Faso (5°W-0°E, 8°N-14°N) have onset dates occurring 25-30 days later with the more restrictive onset definition. Although in places the timing of mean onset differs, there exists significant correlation at the 5% level between the onset definitions of *Mart* with 20 and 30-day dry-tests across the entire region studied (Fig. 2.10c). It is possible therefore that in regions of difference between the two dry-test plots the definition *Mart* can be calibrated on a local scale. *Mart* can be considered a stable onset definition which is not overly sensitive to the length of dry test employed.

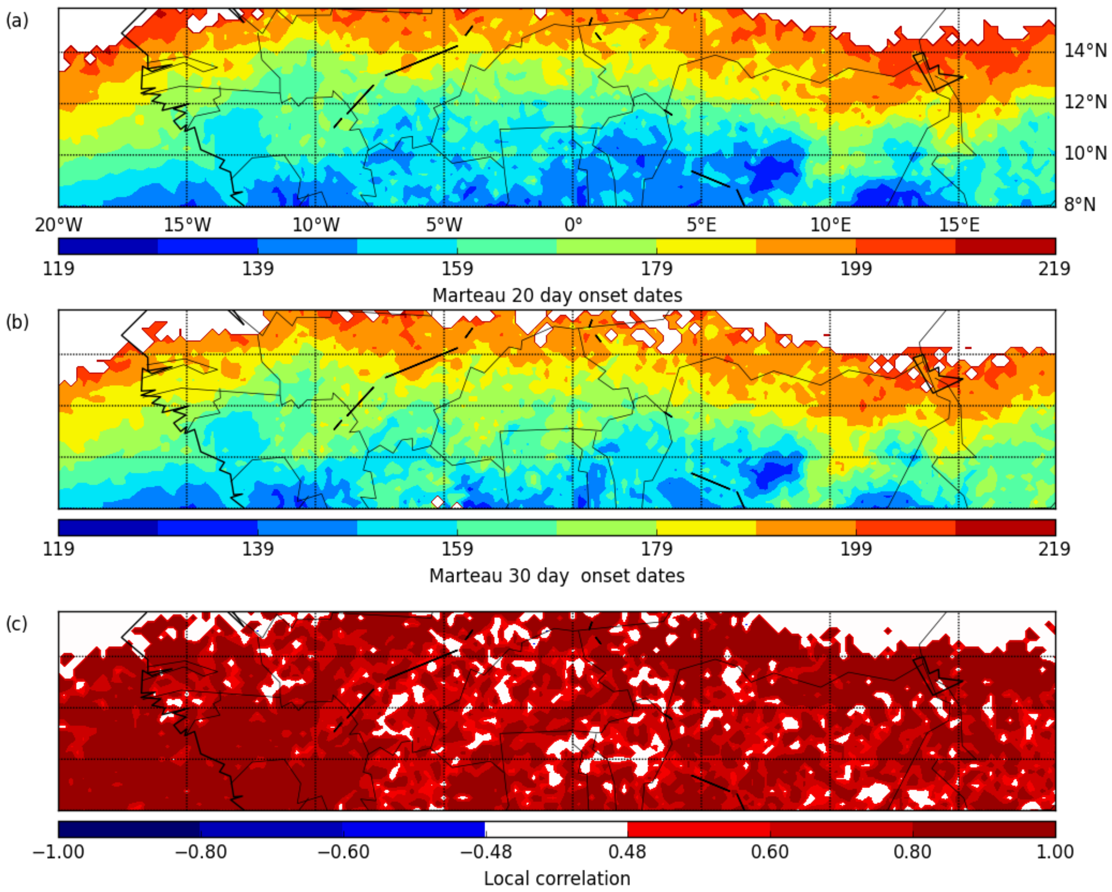

Figure 2.10 - Evaluation of sensitivity of *Mart* to dry-test duration. Mean *Mart* onset patterns for (a) 20-day dry test and (b) 30-day dry test. (c) Local inter-annual correlation between the two definitions.

5.3.2. Sensitivity of *Omo* to dry-test selection

The lack of a dry-test within the definition of *Omo* means that a short, isolated, intense rain event could trigger onset prior to persistent rain necessary for crop growth being installed over local regions. In order to highlight the risk of this occurrence, *Omo* was modified to include the same dry-test found in *Mart* (i.e. no seven day spell with less than 5mm of rain in the subsequent twenty days of initial rain event).

The inclusion of a dry-test to the *Omo* definition drastically changes local onset dates observed across West Africa (not shown). Onset dates are much later across the entire region with very few onsets triggered in May. There is little to no significant local correlation (at the 5% level) between the definitions of *Omo* with and without a dry-test across the entire region studied.

Due to the lack of agreement found, it is suggested that the local definition *Omo* should not be used to calculate onset for agronomic purposes unless a dry-test of at least 20 days is included in calculation of the definition.

5.3.3. Sensitivity of *Yam* to observation period and precipitation intensity

The local onset definition *Yam* was subjected to an extended observation period to ascertain its sensitivity to false onset. In order for onset to be triggered, it was required that the average rainfall for twenty days was greater than 2 mm/day as opposed to the original window of six days. In low latitudes, there is little change between the two definitions (not shown). Onset dates are still triggered in May/early June across the entire West African region and there is significant correlation between the two definitions for most of the region 8-12°N.

The onset dates given by *Yam* are more sensitive to the intensity of precipitation required for triggering compared to the length of observation period. Figure 2.11a and 2.11b respectively display the onset distribution given by *Yam* with requirements of 2 mm/day and 4 mm/day needed in the initial six day period. The onsets seen in the more restrictive definition still occur during May/mid-June, but they are more closely representative of the onset seen in *Omo* (Fig. 2.8b). Despite this, Fig. 2.11c shows that there is statistically significant correlation at the 5% level between the two

Yam realisations over a large part of the region considered, implying that inter annual onsets patterns are consistent across both onset requirements.

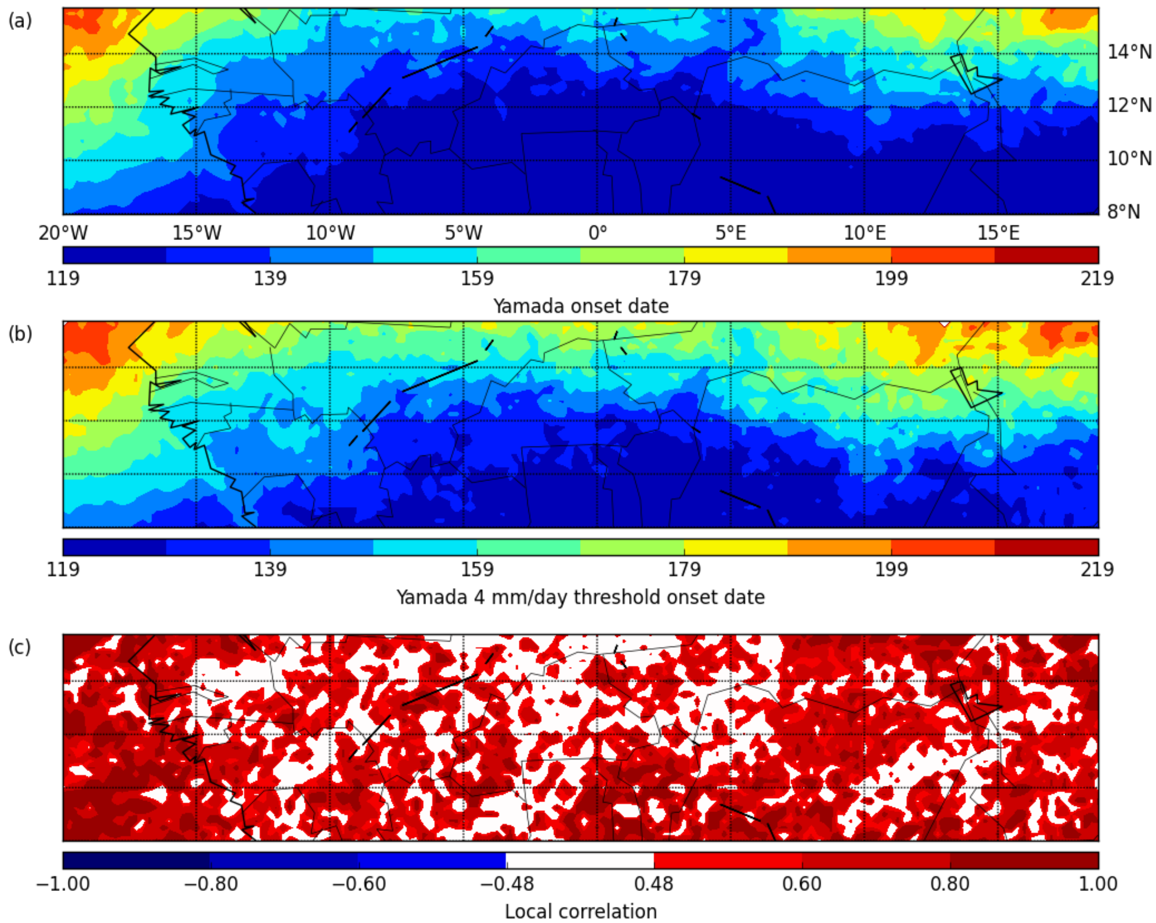

Figure 2.11 - Sensitivity of *Yam* to precipitation threshold required. (a) *Yam* composite for 2 mm/day threshold, (b) *Yam* composite for 4 mm/day threshold, (c) correlation between the two definitions.

5.4. Semi-local onset distribution given by *LeB_Loc*

The definition *LeB_Loc* provides an onset value for each full degree of longitude with direct comparison to *LeB_Reg*. The temporal and latitudinal variation in rain event frequency differs depending on the longitude observed giving further information on the possible reasons behind the contrast from local and regional onsets. This is evident by observing patterns at two locations in 2002 (Fig. 2.12). At 8°W, an appreciable shift in the maximum of rain events from near 5°N to about 10°N can be seen to occur around late June/early July (Fig. 2.12a). Further east this shift is not evident. Instead, rain event frequencies around 5°N remain approximately constant throughout the monsoon season, with rain event frequencies in higher latitudes showing a seasonal pattern (Fig. 2.12b). It is possible that at the edges of the monsoon region, the influence of moisture transport from the Gulf of Guinea and the eastern Atlantic (western boundary) and progression of meso-scale convective systems from the Ethiopian Highlands (eastern boundary) on rain event frequency is high. Furthermore, topography could influence the patterns shown in Fig. 2.12. These regions also display the highest variability in local onset date *Mart*.

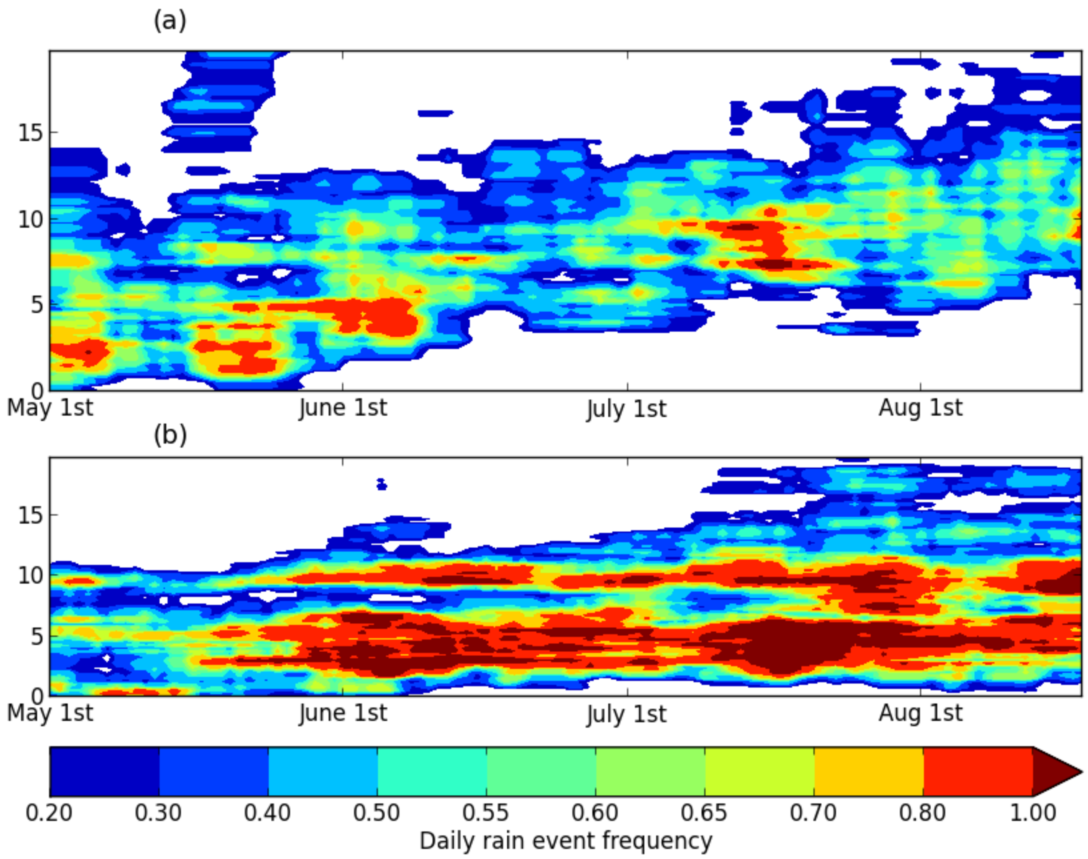

Figure 2.12 – Semi-localised realizations of *LeB_Loc*. TRMM v6 3hr observations of daily rain event frequencies for (a) 8°W 2002 and (b) 8°E. Both figures are taken from 2002, a similar pattern is found in most years.

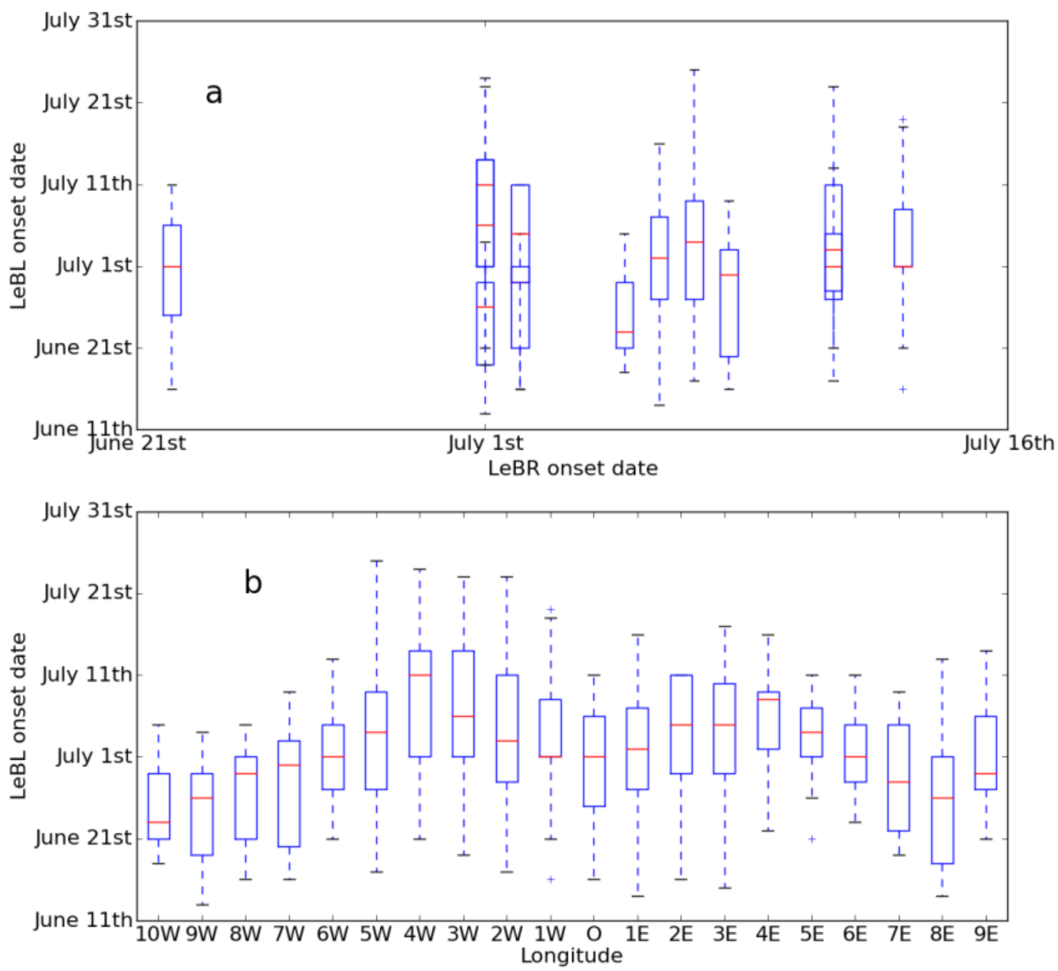

Figure 2.13 – (a) inter-annual comparison boxplots between *LeB_Reg* (horizontal axis) and spread of *LeB_Loc* onsets (vertical axis). (b) boxplots of *LeB_Loc* onset dates grouped by longitude. For each boxplot there are 13 *LeB_Loc* onset dates represented covering the years 1998-2010.

There appears to be little inter-annual consistency between the regional definition *LeB_Reg* and the semi-local definition *LeB_Loc* (Fig. 2.13a). No apparent link between the range of *LeB_Loc* dates for a given year and that year's *LeB_Reg* onset date is present in our results. However, there is a discernible spatial pattern of *LeB_Loc* onset dates across the thirteen years when dates are grouped by longitude (Fig. 2.13b). Onset dates occur earliest near the western boundary of the studied region with latest dates occurring from 5°W-0°E (the region that is most likely connected to AEW activity). Although earlier dates are also observed across the eastern boundary of the monsoon region (5°E-10°E) there is generally a wider range of onset dates observed than around the western boundary implicitly highlighting higher inter-annual variability in onset dates around the eastern half of the monsoon region that further west. This suggests potentially that drivers that affect *LeB_Loc* over the western extent of the monsoon region are more consistent year-to-year than those which affect onset across the eastern part of the monsoon region.

The semi-local definition *LeB_Loc* suggests propagation of onset coming into the Sahel from both the east and west of the monsoon region. This is in agreement with findings for the local definition *Mart*. Semi-localised onset dates given by *LeB_Loc* occur predominantly in late June or early July which is concurrent with the regional dates given by *SJ* and *LeB_Reg* but after *Mart* for the latitudes 8-10°N. The semi-localised onset can therefore be seen as a middle ground between the regional and local onset definitions mentioned.

5.5. Correlation between local, semi-local and regional definitions

It is already known that there is no correlation between the migration of the zonal maximum rain belt and the beginning of the Sahelian rainy season (Sultan and Janicot 2003). However the explicit link between local and regional onsets has not been assessed previously.

Figure 2.14 shows the local correlation between local and regional onsets within the pre-defined monsoon region. We find that there is no considerable section of the West African region that shows statistically significant (at the 5% level) correlation between regional onset dates (*SJ_10*) and local onset dates (*Mart*). North of 10°N, correlation is largely positive; here later regional onset is concurrent with later local onset on average. In lower latitudes, there exists a region of typically negative correlation between the two definitions. The local onset *Mart* precedes regional onset *SJ_10* for the latitudes 8-12°N, with the opposite occurring northwards of this point. Coupled with the poor correlation between the two definitions this implies that regional onset cannot be used as a predictor of local onset for latitudes 8°N-12°N.

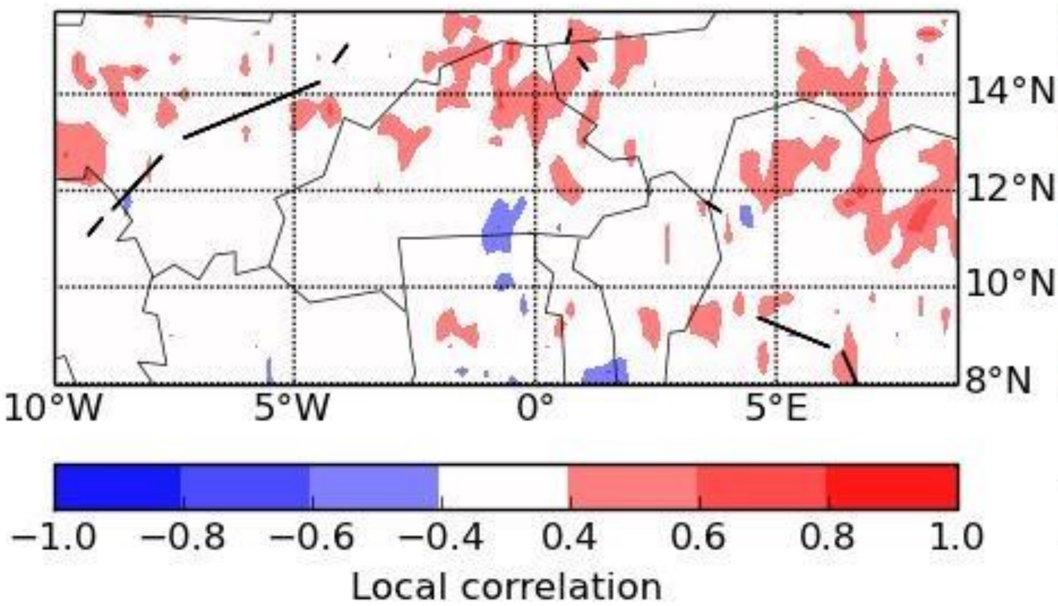

Figure 2.14 – Correlation between local and regional onsets within the monsoon region. Local inter-annual correlation between SJ_10 and Mart using the TRMM v7 dataset.

The semi-localised definition *LeB_Loc* was also assessed to test whether a link exists between localised onset patterns and latitudinal shifts in rain event frequency. We find that there is little significant correlation between the localised and semi-local metrics across the West African region.

We conclude from these findings that local and regional onset dates are not linked on an inter-annual level at the local scale. It is possible that different dynamics are affecting local and regional onset on a year-to-year basis. This result is disconcerting as it suggests that progress in understanding the regional shift of the ITCZ will not necessarily aid in understanding of what affects local onset.

6. Conclusions

The West African Monsoon onset can be viewed as a two-stage seasonal progression. During April and May, the Inter-Tropical Front gradually moves northwards increasing available moisture within the West African region. About 200 km behind the front, societally-useful rainfall occurs (Lélé and Lamb 2010) marking the approximate start of the local rainy season. During late June/ early July, the zonal maximum rain-belt rapidly shifts from one quasi-stationary location at 5°N to 10°N. This sudden shift (or jump) marks the regional onset of the West African Monsoon. Our work provides a comparison between different local and regional onset definitions and their observations in different datasets.

Nine definitions (including three realisations of Sultan and Janicot 2003) of the West African Monsoon onset have been calculated using four observational datasets and one re-analysis product for the period 1998-2012. Five regional definitions have been calculated across the monsoon region (10°W-10°E) with all definitions showing a shift of the West African Monsoon from near the Guinea Coast into the Sahel around the end of June or the beginning of July.

The regional definition given by Sultan and Janicot (2003) measures the annual shift of the maximum rain belt in West Africa from near the Guinea Coast (~5°N) further inland (~10°N). The mean onset date given by this definition is consistent across the four precipitation datasets studied here, as well as in the original work occurring in late June with a standard deviation of eight or nine days in all datasets. Although the mean patterns agree, there is poor inter-annual correlation between onsets calculated using different datasets. The inter-annual variability of regional onset is dependent on dataset choice despite similar long term patterns found. This result is disconcerting; if observational datasets cannot agree on regional onset dates year-to-year, even if their mean onset dates are similar, then it is unclear which dataset should be chosen to evaluate seasonal forecasting of monsoon onset. For forecast evaluation this means that the skill with which a model appears to predict onset is inherently tied to the observations the model is evaluated against.

The OLR definition given by Fontaine *et al.* (2008) shows an annual shift in convection from the Guinean coast to the continental region as does the rain event frequency definition given by Le Barbé *et al.* (2002). Due to the subjectivity of the definition, specific calculation of onset dates using OLR was not completed. The mean rain event frequency onset is consistent with the definition from Sultan and Janicot (2003), however inter-annual correlation between definitions varies dependant on dataset choice.

Local onset definitions are more spatially and inter-annually variable than their regional counterparts. The three definitions calculated (originally found in Omotosho *et al.* 2000, Marteau *et al.* 2009, and Yamada *et al.* 2013) each require different precipitation patterns in order to be triggered. All three definitions identify widespread onset occurring before regional onset. There is poor correlation between the agronomic definition presented by Marteau *et al.* (2009) and the other two local definitions analysed, but there is statistically significant (at the 5% level) correlation between Omotosho *et al.* (2000) and Yamada *et al.* (2013).

In order to test robustness, the local definitions were modified with more restrictive triggering conditions. It was found that the definition from Marteau *et al.* (2009) was not strongly affected by the inclusion of an extended dry-test with significant (at the 5% level) local correlation found across the region. The inclusion of a 20-day dry-test onto the Omotosho *et al.* (2000) definition greatly altered the local inter-annual pattern of onset with little significant correlation (at the 5% level) found implying that the definition may be susceptible to the risk of false onset. Yamada *et al.* (2013) is not sensitive to the length of observation period required or to the intensity of precipitation needed for triggering suggesting that the use of an arbitrary threshold does not seem to affect the expected onset pattern. We would therefore argue that the specific selection of threshold value for agronomic purposes requires further study.

Due to the variability found in local onset dates, a link between regional and local onsets was explored. We found that there is minimal inter-annual agreement between the local and regional definitions studied. For local stakeholders, there may be little use in knowing the regional onset date. Furthermore, there is no link found between local onset dates and the semi-localised onset definition inspired by Le Barbé *et al.* (2002), nor between the semi-local definition and regional onsets. Local definitions appear to be triggered in isolation to the regional dynamic shift portrayed in regional onsets. Skill in predicting the seasonal progression of the maximum precipitation band will not necessarily imply skill in predicting local precipitation onset. Other local and regional definitions have been tested with similar results.

Focus on local onset prediction and associated dynamics is therefore necessary for local stakeholders.

For evaluation of seasonal prediction of the West African Monsoon onset, it is apparent that the definition chosen and dataset used will greatly affect assessment of forecasts. Local and regional onset definitions must be considered, the subjectivity found within regional definitions must be taken into consideration and multiple observational datasets should be used. Although a lot of research exists evaluating the potential dynamical triggers for regional onset, local onsets require considerable future study as these are of more pressing need for local stakeholders and are uncorrelated with regional onset.

The concept of West African Monsoon onset is not a straightforward issue. While the monsoon system is clearly defined, picking a singular point at which onset occurs is reliant on understanding what onset means to the end-users. For regional climatology an understanding of when the maximum rain belt and convection zone reaches the Sahel is of interest. For local stakeholders it is more important to identify when local rainfall sufficient for their needs begins. There is no necessary right or wrong onset definition but care must be taken in future studies of onset sensitivity to understand what the scope of findings is for local and regional stakeholders.

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Chapter 3

On What Scale can we predict the Agronomic Onset of the West African Monsoon?

On what scale can we predict the agronomic onset of the West African Monsoon?

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Abstract

Accurate prediction of the commencement of local rainfall over West Africa can provide vital information for local stakeholders and regional planners. However, in comparison with analysis of the regional onset of the West African Monsoon, the spatial variability of the local monsoon onset has not been extensively explored. One of the main reasons behind the lack of local onset forecast analysis is the spatial noisiness of local rainfall. A new method that evaluates the spatial scale at which local onsets are coherent across West Africa is presented. This new method can be thought of as analogous to a regional signal against local noise analysis of onset. This method highlights regions where local onsets exhibit a quantifiable degree of spatial consistency (denoted local onset regions or LORs). It is found that local onsets exhibit a useful amount of spatial agreement, with LORs apparent across the entire studied domain; this is in contrast to previously found results. Identifying local onset regions and understanding their variability can provide important insight into the spatial limit of monsoon predictability. Whilst local onset regions can be found over West Africa, their size is much smaller than the scale found for seasonal rainfall homogeneity. A potential use of local onset regions is presented that shows the link between the annual Inter-Tropical Front progression and local agronomic onset.

1. Introduction

Accurate forecasting of the West African Monsoon (WAM) is a topic of great importance for local stakeholders and the wider forecasting community. More than 65% of the West African workforce works in the agricultural sector providing about 32% of gross domestic product (Fitzpatrick, 2015). The majority of farmland in West Africa is not irrigated; meaning the success of a harvest is strongly dependent on continuous and sufficient rainfall suitable for crop growing (Ingram et al. 2002; Ewansiha and Singh 2006).

In addition to agricultural impacts, previous work has linked the seasonal cessation of meningitis infections to the advancement of monsoon related moisture (Molesworth et al. 2003; Sultan et al. 2005a) as well as the link between seasonal increase in malaria and dengue fever cases and precipitation increase during boreal spring and summer (Mera et al. 2014). Compounding the risk of disease is the clear link between malnutrition and mortality rates of common diseases (measles, cholera, mumps etc.; West Africa Regional Health Working Group 2012, see http://www.who.int/hac/sahel_health_strategy_21june2012rev.pdf). The need to provide societies across West Africa with accurate, relevant and usable information on the local and regional monsoon condition is evident.

Of particular interest to local stakeholders is the timing of the WAM onset (Ingram et al. 2002; Sultan et al. 2005b), as well as the timing of *societally-useful* local precipitation (defined as more than 4 mm/day by Lélé and Lamb 2010). Over seventeen definitions for the WAM onset have been published (Fitzpatrick et al. 2015, their Tables 1 and 2). Definitions have been created over different length scales, using different metrics and analyzed with different datasets over various time periods (see for example Sultan and Janicot 2003; Marteau et al. 2009; Gazeaux et al. 2011).

Local, agronomic onset definitions such as that proposed by Marteau et al. (2009) can provide the most relevant information for local and national planners in West Africa. The agronomic onset definition given in Marteau et al. (2009), henceforth AODM, was made in conjunction with local and regional stakeholders in Senegal, Mali, and Burkina Faso. The AODM requires a pre-determined and relevant set of rainfall thresholds to be met in order to be triggered.

There exists a particular disparity in the literature between the timing and inter-annual variability of regional onsets (onsets calculated on a super-national scale following the zonal maximum of precipitation and convection) and local onsets (threshold based onsets evaluated at the sub-national scale). In particular, there appears to be little to no correlation between the annual transition of the zonal maximum rain belt and agronomic onsets across West Africa at the local scale (see Section 2; also Fitzpatrick et al. 2015). This presents an interesting conundrum for forecasters and stakeholders when trying to disseminate how useful regional onset forecasts are for more localized needs. Here focus is given exclusively to local onset variability.

In the current literature on WAM dynamics, the effect of dynamical drivers on local onsets has been vastly under-researched. Over West Africa there is research into how seasonal precipitation totals or the annual shift of the maximum precipitation belt are affected by many drivers. These include but are by no means limited to: sea surface temperatures (e.g. Caniaux et al. 2011; Rowell 2013), the Saharan Heat Low (Lavaysse et al. 2009) and associate modulation in forcing by mid-latitude Rossby waves (Roehrig et al. 2011), the phase and intensity of the Madden-Julian

Oscillation (Maloney and Shaman 2008; Lavender and Matthews 2009), dry-air intrusions from the Mediterranean tied to the Rossby wave response of the Indian Monsoon onset (Flaounas et al. 2012a,b), or African easterly waves (Berry and Thorncroft 2005; Bain et al. 2014) among other examples. However, how these drivers affect local onset variability has rarely been explored.

The most likely reason for the dearth in local onset variability studies is that local precipitation and local onsets are deemed too spatially and inter-annually variable to warrant detailed study (eluded to in several papers, e.g. Maloney and Shaman 2008). Indeed, Marteau et al. (2009) conclude that their local onset definition does not seem to be driven on a large scale by any coherent meso-scale, synoptic, or planetary scale features. There is little spatial or inter-annual agreement in onset date variability found across their study region. However, given that Marteau et al. (2009) also finds a clear increase in meso-scale convective activity over rain gauges after local onset is triggered it seems natural that local onset has some larger scale mode of variability. Here we hypothesize that there is some degree of spatial coherence present that can be measured using a different approach to those used in Marteau et al. (2009). It is not possible to begin assessment of the inter-annual variability of local onsets before quantification of the spatial limits of local onset predictability is known.

In this paper we attempt to answer the question “On what spatial scale can the commencement of local precipitation onset be viewed as sufficiently homogeneous for practical purposes?” Clearly if local variability in precipitation dominates over regional coherence across all West Africa, predictability of local onsets is likely to be poor and of little use to forecast users. Once the spatial limit of local onset homogeneity is known, it may be possible to assess the causes for local onset variability over clearly defined boundaries. This will provide the most useful data for local forecast users and regional planners directly affected by the timing of local onset.

In order to achieve our aims, a new approach to quantifying onset coherence is introduced. To quantify the spatial limit of temporal homogeneity of local onset, sub-regions of West Africa are sought for which either the year-to-year timing of, or inter-annual variability of, local onsets are consistent. It is desired that a representative time-series of onsets, such as annual median onset over the sub-region, can be used to describe inter-annual variability across the sub-region. This allows for local onsets to be represented within defined boundaries, much the same way current research constructs regional onset (such as Sultan and Janicot 2003; Fontaine et al. 2008; Vellinga et al. 2012). The homogeneous regions found are termed local onset regions (LORs) and all grid cells within an LOR are termed the LOR's constituents. Due to the lack of research on local onset variability, predictors for local onset have not been studied extensively. One potential predictor is the seasonal advancement of moist cool monsoon winds into continental West Africa (Ilesanmi 1971; Hasthenrath 1991; Lélé and Lamb 2010). The northernmost extent of the south-westerly monsoon winds is characterized by the Inter-Tropical Front (here referred to as ITF but also referred to as Inter-Tropical Discontinuity (ITD) in literature), sometimes thought of as the northernmost extent of the monsoon (Walker 1957; Lélé and Lamb 2010). An assessment of the potential link between ITF advancement and local onset variability is offered in this article providing information on a potential necessary condition for monsoon onset to occur.

Section 2 will give a brief overview of the onset definitions used and datasets employed with Section 3 highlighting the methods for identifying LORs and for the

ITF onset. Section 4 and 5 will give results for the spatially-uniform (year-to-year onset date homogeneity) and inter-annual (year-to-year onset variability coherence) methods, respectively. Section 6 highlights the use of inter-annual LORs in finding a link between the ITF and local precipitation onset. Section 7 summarizes the identification of LORs for use in analyzing the WAM.

2. Data and Definitions used

In order to identify and appreciate the level of spatial homogeneity of local onset, the definition chosen has to be applicable across the whole West African domain (taken here as 8°N–16°N, 20°W–20°E), and identify an important time in the local precipitation time series. For this study, the AODM is used, although the methods employed in this paper are also valid for other local onset definitions (e.g., Omotosho et al. 2000; Yamada et al. 2013).

2.1 Data

Daily rainfall totals for the season April–August have been taken from the high-resolution (0.25° x 0.25°) Tropical Rainfall Measurement Mission 3B42 v7 precipitation dataset for the period 1998–2014 (TRMM v7, Huffman et al. 2007). In order to study the seasonal ITF movement, 2-metre dew-point temperatures for 0600 UTC have been taken from the ERA-Interim reanalysis dataset for the months March–July, 1998–2014 (Dee et al. 2011). In order to use data on a comparative length scale to precipitation observations, the interpolated 0.25°x0.25° dataset from ERA-Interim was chosen as opposed to the native T255 horizontal grid. The earlier period for dew-point observations allows for identification of whether the ITF is a climatological precursor to local agronomic onset with pragmatic lead time for local and regional planners. Hence, the ITF is observed prior to the local agronomic onset of rain for this assessment.

One potential issue with using the TRMM v7 dataset is the relative briefness of available data compared to more coarse datasets (such as the Global Precipitation Climate Project or a rain gauge network). The decision to use TRMM v7 data was made due its higher resolution compared to other datasets which was considered sufficiently advantageous for analyzing the spatial variability of local onset over West Africa. An assessment of whether the results presented can be considered representative of longer term AODM homogeneity is provided in section 3.3.

2.2 Local West African Monsoon Onset Definition – Marteau *et al.* (2009)

The AODM is defined as the first rainy day (precipitation greater than 1 mm) of two consecutive rainy days (with total precipitation greater than 20 mm) and no seven-day dry spell with less than 5 mm rainfall during the subsequent twenty days. Figure 3.1 shows the mean onset dates and local variability of the AODM across West Africa for the period 1998–2012. The mean onset date for the AODM ranges from early May in the southern-most parts of our observed region to mid/late-July further north (Fig. 3.1a). The AODM is triggered every year across most locations in West Africa except towards northern West Africa (14–16°N). Inter-annual variability in the AODM is high over much of continental West Africa with local standard deviations of more than two weeks common (Fig. 3.1b). Conversely, in the longitude bound 20–10°W, local standard deviation of the AODM is generally lower than elsewhere within our studied region. The high variability of the AODM found over much of West Africa suggests that climatological local onset dates are not useful for local stakeholders in these regions. A clear understanding of the limits of predictability is therefore sought.

A considerable issue for local and regional planners is the lack of inter-annual agreement between local and regional WAM onset dates at the local scale. The most popular regional onset definition applied comes from Sultan and Janicot (2003). Fitzpatrick et al. (2015) examine the inter-annual correlation at the local scale between the AODM across West Africa and the regional onset date (averaged across 10°W–10°E), from Sultan and Janicot (2003) for the years 1998–2012 using TRMM v7 data. It is found that there is minimal significant correlation at the 80% level across West Africa between the two definitions. This result implies that understanding the inter-annual variability of regional onsets will have minimal use for understanding local onset variability. This result provides the motivation for this paper to exclusively focus on the AODM.

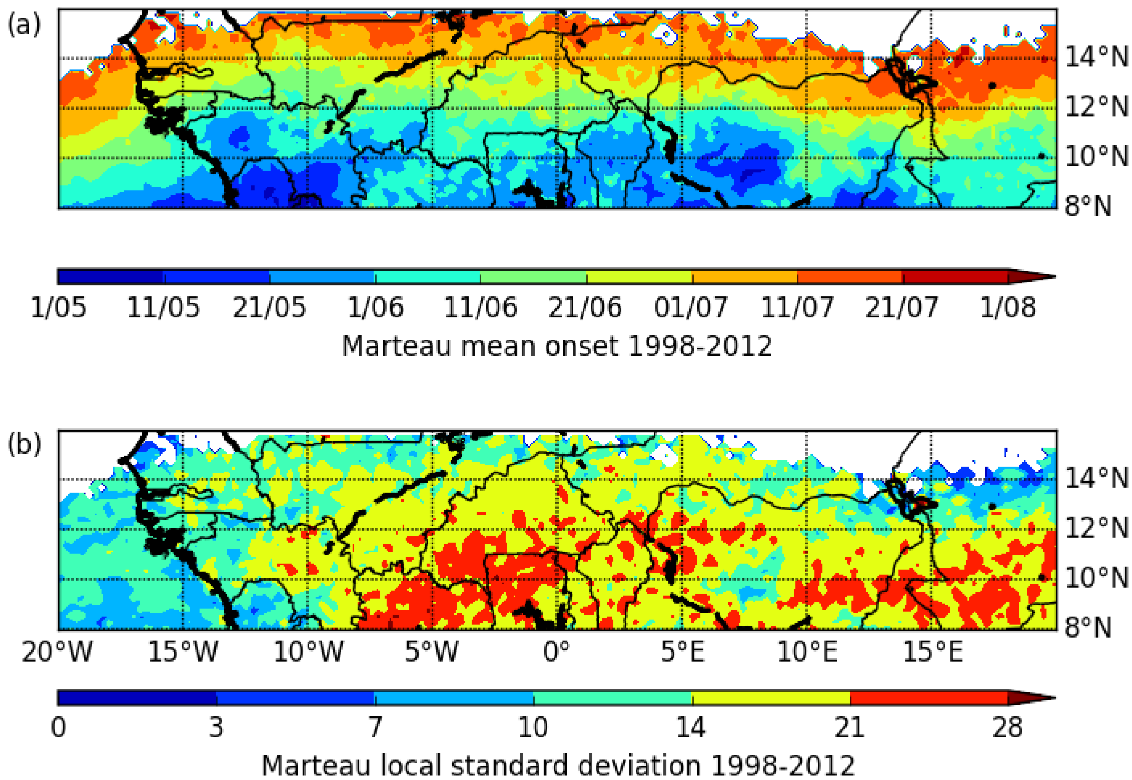

Figure 3.1 – Statistics for *AODM*. (a) Mean onset dates of *Mart* using TRMM v7 dataset for the years 1998–2012. (b) Standard deviation in days of local onset *Mart* from local average onset for the period 1998–2012 using TRMM v7 precipitation data. White regions denote locations where *Mart* onset date was found for less than 5 of the 15 years studied. Large-scale rivers and lakes within the study domain are included for reference.

2.3 Inter-Tropical Front onset

The ITF marks the northernmost limit of the moist, cool monsoon winds into continental West Africa and is defined here following Lélé and Lamb (2010) by observing the northwards extent of the 15°C 2-metre dew-point temperature isodrosotherm. We wish to establish whether there is a link between the median AODM date of a LOR and the progression of the ITF towards and beyond that LOR.

Therefore, a local ITF onset metric measured for every LOR (denoted ITFL) is given as:

- ITFL at LOR ***L*** occurs when the zonally averaged (across the longitudinal limit of ***L***), 10-day averaged 2-metre dew-point temperature at a given distance (denoted **D**) northwards of ***L*** is equal to 15°C.

The distance D is readily modifiable in order to assess the spatial difference in the link between the ITF and local onsets. The results shown here are figurative of the general link between local onsets and the ITF. A regional version of the local pre-onset (ITFL) has also been computed. This regional definition (denoted ITFR) follows the same method as the ITFL, but also zonally averages the 2-metre dew-point temperature across 10°W–10°E prior to computation of the onset date.

The definition of the ITFL has spatial limitations. As the 15°C isodrosotherm is representative of the location where cool moist winds from the Gulf of Guinea meet dry warm air from the continent, this definition is not valid over the western extent of the region studied (roughly 20°W–10°W). Therefore the ITFL analysis is done on the shortened longitudinal range 10°W–20°E. As the ITFR is defined between 10°W and 10°E, such a restriction is not required.

There is a need to distinguish the timing at which dew-point temperature data is taken. During the day, sensible heating allows for vertical mixing of the boundary layer across West Africa giving a well-established ITF, suggesting that 1200 UTC data is preferable. By contrast, cooling overnight allows for the ITF to penetrate further northwards near the surface partially due to the influence of gravity currents (Flamant et al. 2007; Bou Karam et al. 2008). Forecast centers often track the ITF location at 0600 UTC, when the convergence line is sharpest. The link between the

ITF and local onset has been assessed using both 0600 UTC and 1200 UTC dew-point data. As results for both times are similar, only 0600 UTC is presented here.

3. Method for identifying Local Onset Regions

Regions are sought where there is spatial coherence of local onset variability (hence local onset regions or LORs). These LORs can provide practical forecast skill for local and regional stakeholders. Two general modes of variability are assessed.

For regional planners, it is useful to identify regions where local onsets consistently occur around the same time each year (or where local onset anomalies are consistently bounded). These regions allow for forecast users to give a window when local onsets occur across the LOR with a reasonable amount of confidence given knowledge of what affects local onset variability within the LOR. The first LOR method is termed the *spatially-uniform* LOR method.

Additionally, regions are sought where regardless of the range of onset dates within the LOR the inter-annual variability of onsets is consistent. This information would allow regional planners and forecast users to gain insight on whether an onset will be relatively early or late across a defined region for a given year. This second LOR method is henceforth referred to as the *inter-annual* LOR method. The two methods should be treated independently.

The main advantage of the inter-annual LOR method is the ability to identify regions where onsets occur over a wide temporal range. The location of an LOR where variability is consistent despite a wide temporal range of AODM onset dates along topographic or climate gradients gives the potential for inherent prediction of onset within an LOR. In effect, observing the variability of the earliest onset dates within a LOR could give insight into the variability of later onsets across the LOR.

To identify LORs, we have devised a relatively simple method designed to be repeatable and practical for dependent stakeholders in contrast to more statistically complex methods such as cluster analysis. The methods used to identify spatially-uniform and inter-annual LORs follow the same pattern with different criteria. For each grid cell in the tested domain we first take the onset dates and spatial median of those dates within a three-by-three grid point LOR centered about the chosen grid cell. The LOR is tested using the spatially-uniform or inter-annual criterion (see sections 3.1 and 3.2, respectively). In principle, a given grid cell can have both types of LORs centered about it. Upon passing the chosen criterion, the LOR is expanded and tested again. If the criterion is not met, the LOR size and location are recorded. Expansion of LORs is done first by testing whether the LOR would pass the criterion with latitudinal extension (one row of grid cells added to the north and the south) and longitudinal extension (one column added to the east and west). If this new LOR does not pass the criterion, we test whether a latitudinal or longitudinal extension would provide a valid LOR. Failing this, the LOR is allowed to extend along any of the four axes. The order of testing chosen for this analysis is to add from the north, east, south, then west of the LOR. Re-ordering of these criteria has nominal effects on the results (not shown). If any of the above extensions pass the criterion tested, we repeat the process from the start.

It is inherently implied that a grid cell can belong to multiple LORs. Intuitively if a grid cell has coherent onset variability with its neighbours, then some of the neighbours will also have coherent variability with the original grid cell. We therefore note the largest LOR each grid cell is contained within as well as the location of all LORs. Using the method presented here, there is opportunity for LORs to overlap (this is in contrast to other methods such as cluster analysis). General grouping of LORs gives insight into the level of spatial homogeneity and provokes further discussion and analysis as opposed to the exact locations of single LORs, which may be too isolated to have a substantial impact for forecast users.

For both methods presented, there is an inherent requirement for LORs to be identified over regions where onset frequently occurs. Therefore it is required for both spatially-uniform and inter-annual LORs to have at least 80% of grid cells exhibit an AODM onset date for at least ten of the fifteen years assessed. Comparing LORs found with and without this restriction shows that many of the LORs over the region 14–16°N are not present when one demands that onsets frequently occur (not shown). Outside of this area, there is minimal difference between the LORs found (not shown). For the rest of this paper, the restriction is therefore applied.

3.1 Spatially-uniform LOR methods

Spatially-uniform LORs identify sub-regions of West Africa where the timing of onset is largely in agreement across the LOR each year. Two potential methods are provided for spatially uniform LORs; one using absolute onset dates and one using onset anomaly data.

First, we highlight regions where the absolute onset dates are consistently bounded, i.e., onset dates across the LOR occur within a pre-set range of each other year-to-year. The exact timing of onsets is allowed to vary inter-annually as long as the range of onset dates remains consistent.

Secondly, we highlight regions where the onset anomalies across the LOR are bounded (i.e., removal of the local mean onset date prior to LOR assessment). In some circumstances it will be more important to assess consistency of relative onset dates (anomalies), rather than absolute dates and thus both methods are considered.

For spatially-uniform LORs, we identify areas where onset dates (or anomalies) for a certain percentage of grid cells (**P**), taken as 50% but modifiable (see Section 4.1), lie within a given range (**R**) of the LOR median onset (median local anomaly) for **Y** years. The variables **R** and **Y** are modifiable. Understanding the balance between maximizing the trustworthiness of spatially-uniform LOR formation for stakeholders in West Africa, whilst not being too restrictive in creating LORs is important in making practical advances for onset comprehension. Whilst in an idealized setting there would be clear regions where all onset dates lie within a strict threshold for all years, in reality this is not the case (see section 4.1). Here we investigate the variability of spatially-uniform LOR coverage over West Africa for different values of **R** and **Y**.

3.2 Inter-annual LOR method

3.2.1 Outline of general method

The spatially-uniform LOR methods presented in Section 3.1 focus specifically on the absolute range of LOR constituent onset dates or anomalies each year. By contrast, the inter-annual method finds regions where LOR constituent onset dates share similar inter-annual variability. The inter-annual method can therefore be thought of as a natural extension to the spatially-uniform method using anomaly data.

For each grid cell across the observation region we identify the largest possible LOR centered at that location for which the following criterion is met:

- The onset time series of at least $\mathbf{n_{crit}}$% of all grid cells show correlation (at the **x** confidence level) with the median onset date time-series of the LOR.

The parameter **n_{crit}** is a modifiable percentage of the total number of grid cells within the LOR (denoted as **N**). The threshold **x** is also modifiable.

Inter-annual LORs are allowed to expand even if the test criterion is not passed as long as a larger LOR containing all the grid cells currently included passes. This allows for LORs up to 1.5 degrees larger to be considered when assessing whether LORs can be found. The number of LORs affected by this added level of complexity is approximately 10%, which tend to be smaller inter-annual LORs (not shown).

3.2.2 Sensitivity of probabilistic LORs to confidence interval selection

The probability that two random time series correlate at a given confidence level, **x** (e.g., 80%, 90%, or 95% level), is **p = (1-x)**. However, given the criterion presented in Section 3.2.1, the creation of an LOR encompassing many random time series is much less likely. Taking an LOR containing **N** grid points each with assumed random and independent time series of AODM and assessing the probability (**P**) that this LOR would pass our criterion, it can be shown using the binomial distribution that:

$$P = \sum_{r=n_{crit}}^{N} {}^{N}C_r (p)^r (1-p)^{N-r}, \qquad (3.1)$$

where **n_{crit}** is rounded up to the nearest integer. Table 3.1 shows a comparison of the expected number of random LORs for differing **N** and **x** with **n_{crit}** fixed at 80% if we accept the assumption that all grid cells have independent AODM triggering. For reference there are approximately 5500 grid cells in the studied domain. The number of expected random LORs is dwarfed by the total number of LORs found in Section 5.1.

Table 3.1 - Probability of getting a random inter-annual LOR of size N.

Number of grid cells in LOR (**N**)	Confidence interval (**x**)	$\mathbf{n_{crit}}$ (%)	Probability of random LOR	Expected number of random LORs
9	80%	80	0.0003	2
9	90%	80	3.0×10^{-6}	0.02
9	95%	80	2.6×10^{-8}	0.0001
25	80%	80	2.0×10^{-10}	1.0×10^{-6}

For regional planners the existence of an LOR implies that at least a given percentage of locations have inter-annual variability consistent with the median AODM variability with confidence **x**. Pragmatically this means that for every grid cell within an inter-annual LOR, a regional planner is able to give a probability that onset will occur later than, or earlier than average given knowledge of the median onset date variability (which can be attained through future research into local onset variability including our Section 6). Table 3.2 gives some example probabilities (here again we presume that the probability for each grid cell is independent).

Whilst it would be preferable to maximize **x** and $\mathbf{n_{crit}}$, in reality it is reasonable to expect some leeway. We therefore compare the size and coverage of LORs found using three different confidence intervals: 95%, 90%, and 80%. For these three confidence intervals the probability of the AODM variability at each LOR constituent grid cell following the median AODM variability is still greater than 0.5 meaning LORs can provide relative skill over a random forecast. Section 5.2 considers the variation of inter-annual LORs with respect to the parameter $\mathbf{n_{crit}}$.

Table 3.2 - Probability of LOR constituent having similar variability to median onset date for varying confidence intervals.

Confidence level (**x**)	$\mathbf{n_{crit}}$ (%)	Probability for each grid cell in LOR
0.95	80	0.76
0.9	80	0.72
0.8	80	0.64
0.8	100	0.8

3.3 Suitability of TRMM v7 as precipitation dataset for analysis of LORs

Precipitation over West Africa is known to have large decadal variability (see Fig. 1 in Lélé and Lamb 2010 and further references). Given the relative briefness of the TRMM v7 dataset, it is fair to ask whether TRMM v7 can be considered a sufficiently representative dataset from which to infer the variability of the AODM.

In order to test the robustness of dataset choice, the spatially-uniform and inter-annual methods were applied on two 7-year sub-periods of TRMM v7 data. LORs were found in the same locations using the shorter time periods and the full TRMM v7 dataset, although the size of LORs is often smaller for the former (not shown). We therefore posit that the results of this paper give a realistic representation of the spatial variability of the AODM, albeit with the restriction of observational biases.

4. Spatially-uniform LORs across West Africa

4.1 LORs found using absolute onset dates

Figure 3.2 shows the number of spatially-uniform LORs identified using absolute onset dates against different values of **Y.** The large number of LORs is consistent with the fact that each grid cell may have its own LOR. As expected, increasing **Y** decreases the number of LORs found. For example, when **R** = 7, the first large numerical decrease in the quantity of spatially-uniform LORs occurs between **Y** = 8 and **Y** = 9 years. Afterwards the number of LORs identified roughly decreases by 500 with each additional year **Y**. When **R** = 7, there are relatively few LORs for which onsets lie within a close range for many years (i.e., Y = 14), even at the three-by-three grid cell scale.

The number of LORs found is also affected by the size of the observation window, **R**. As would be expected, fewer LORs are identified when the variable **R** is reduced. In addition, the size of LORs is generally smaller for lower **R** (not shown). For higher values of **R** (such as **R** = 10 or **R** = 14 shown in Fig. 3.2), there appears to be little change in the number of LORs found for increasing **Y**, suggesting that the LORs found for high **R** are not sensitive to the impact of **Y** unlike those found for **R** = 7. The question must be asked whether LORs with such high values of **R** can be pragmatic.

In addition, the proportionate variable, **P**, also impacts the amount and size of LORs found. The number of LORs found for given **R** and **Y** roughly halves from **P** = 50% to **P** = 80% (not shown). The AODM across sub-regions of West Africa may exhibit some level of spatial coherence, but is evidently not universally coherent.

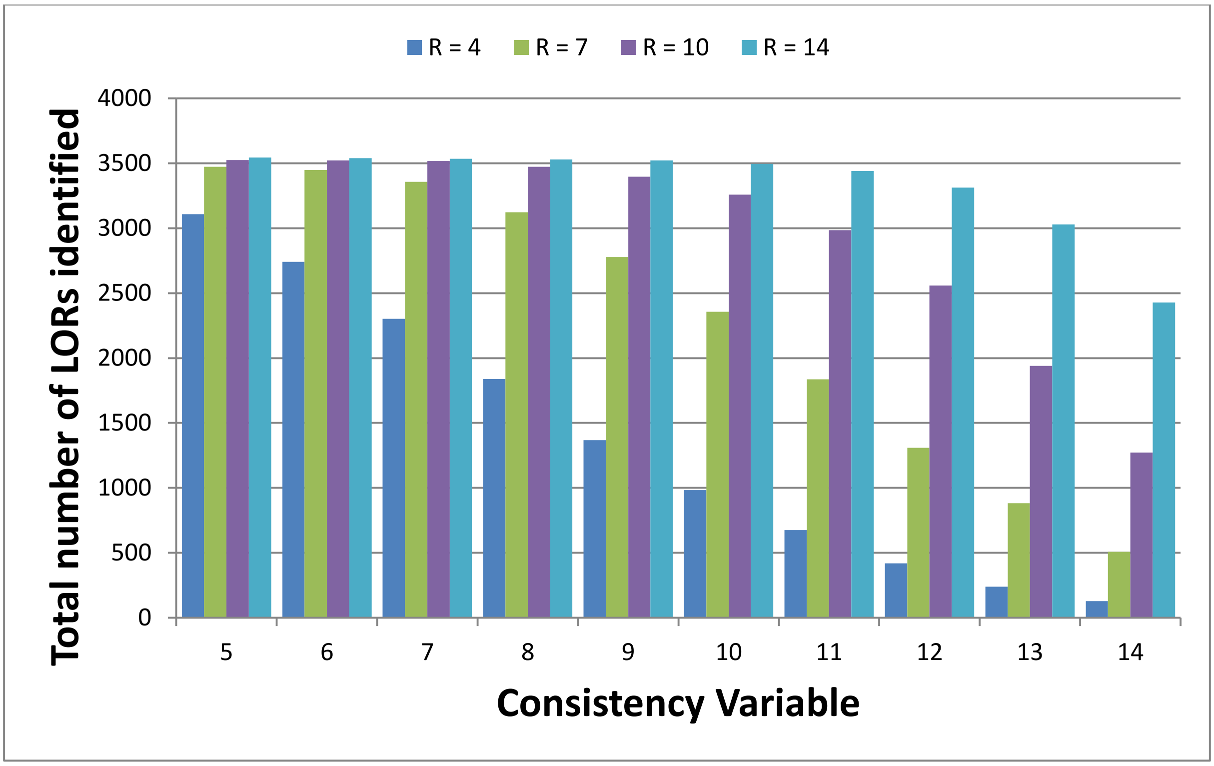

Figure 3.2 – Decrease in number of spatially-uniform LORs for increasing Y and decreasing R. Plot measures the number of grid cells for which at least a 3-by-3 (0.75°x0.75°) spatially-uniform LOR can be found against the number of years for which at least 50% of onset dates must lie within R days of the median LOR onset date (denoted Y). Different columns for each value of Y are for varying values for the temporal constraint R.

Figure 3.3a and 3.3b show scatter distributions of the spatial scale of LORs found for **Y**=7 and **Y**=9, respectively, with **R** = 7 days and **P** = 50%. Spatially-uniform LORs found using absolute onset dates tend to be “wide and short” (i.e., longitudinal scale > latitudinal scale). Given the latitudinal gradient of the AODM, as well as the geographical constraints of the study domain, this result is to be expected (see Fig. 1a). Figure 3 also shows that the distribution of LOR sizes remains roughly consistent between **Y** = 9 and **Y** = 7 despite the different quantity of LORs. This is due to the existence of a group of LORs, which consistently pass the spatially-uniform LOR criterion for almost all years. The understanding of how convective rainfall is triggered within these LORs could provide insight into practical prediction of the AODM. Given the findings of Marteau et al. (2009), this research may distill into determining the cause of early season meso-scale convective system genesis and development over LORs.

Figures 3.4a and 3.4b show the spatial scale of the largest LOR containing each grid cell for **Y**=7 and **Y**=9, respectively. The spatial distribution of LORs drastically changes with the increase of **Y** outside of a few "stable" regions. Large LORs are typically spatially restricted to the eastern Atlantic and coastal regions as well as low latitudes around Benin and western/central Nigeria (green and yellow LORs in Fig. 3.4). It can be concluded that these regions have the highest level of spatial uniformity in absolute onset date. Local variability in the AODM over the eastern Atlantic and Senegal is generally less than two weeks (see Fig. 3.1b). Therefore the most significant highlight of spatially-uniform LORs in terms of potential impact is over the longitude range 0–10°E.

Over the rest of West Africa there is minimal coverage of spatially-uniform LORs for large **Y**. This is particularly apparent around the region ~8–0°W and over the eastern extent of our study region (Fig. 3.4b). As the coverage of large spatially-uniform LORs within the monsoon region is minimal, regional averaging of precipitation for onset formation potentially overlooks natural localized sub-seasonal variability in precipitation.

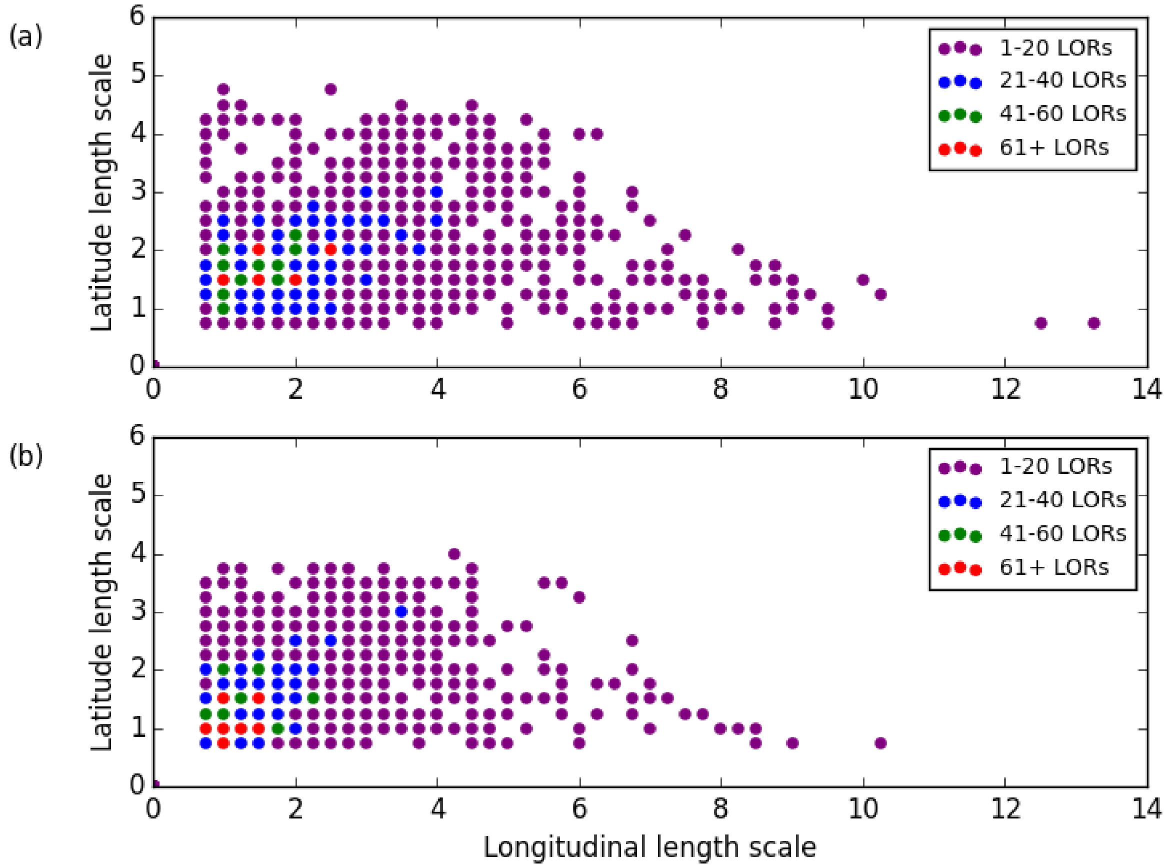

Figure 3.3 - Distribution of size of spatially-uniform LORs. LORs are identified where at least 50% of onsets lie within 7 days of median LOR onset for (a) Y = 7 years and (b) Y = 9 years. Longitudinal and latitudinal length scale is in degrees. The color of each circle denotes the amount of LORs found at each dimensional scale. For reference, the maximum possible latitudinal length scale is 8 degrees and maximum longitudinal length scale is 40 degrees.

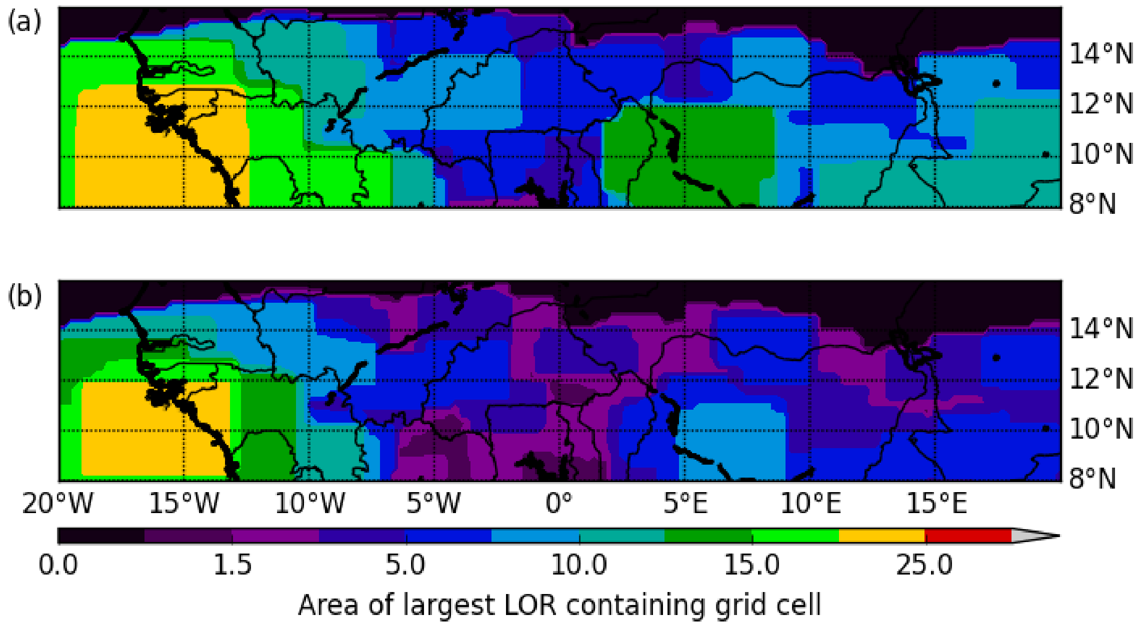

Figure 3.4 – Spatial comparison of spatially uniform LOR sizes calculated using absolute onset dates for with R = 7. Area of the maximum sized LOR containing each grid cell for (a) Y = 7 and (b) Y = 9. For both plots area is given in units of 10^4 km^2.

4.2 LORs found using onset anomaly data

As discussed in Section 3, it is possible to construct spatially-uniform LORs using local onset anomaly data instead of absolute onset dates. Figure 3.5 highlights the dimensions of the largest spatially-uniform LOR containing each grid cell for the anomaly method and is directly comparable to Fig. 3.3. Over the West African coast and the eastern Atlantic Ocean, there is a much larger region of spatial coherence for the anomaly method compared to the findings of Fig. 3.3. This result is not surprising given Fig. 3.1b. Large spatially-uniform LORs found with the anomaly method exist where there is low standard deviation of onset. Figure 3.5 shows that the largest LORs occur where local standard deviation of onset is lowest over a large area (namely ~20–10°W; see Fig. 3.1b). Probability density functions of onset anomalies over sub-regions of West Africa validate this fact (not shown). It is found that this region of high spatial coherence over Senegal and Guinea is not solely dependent on high agreement over the ocean (not shown).

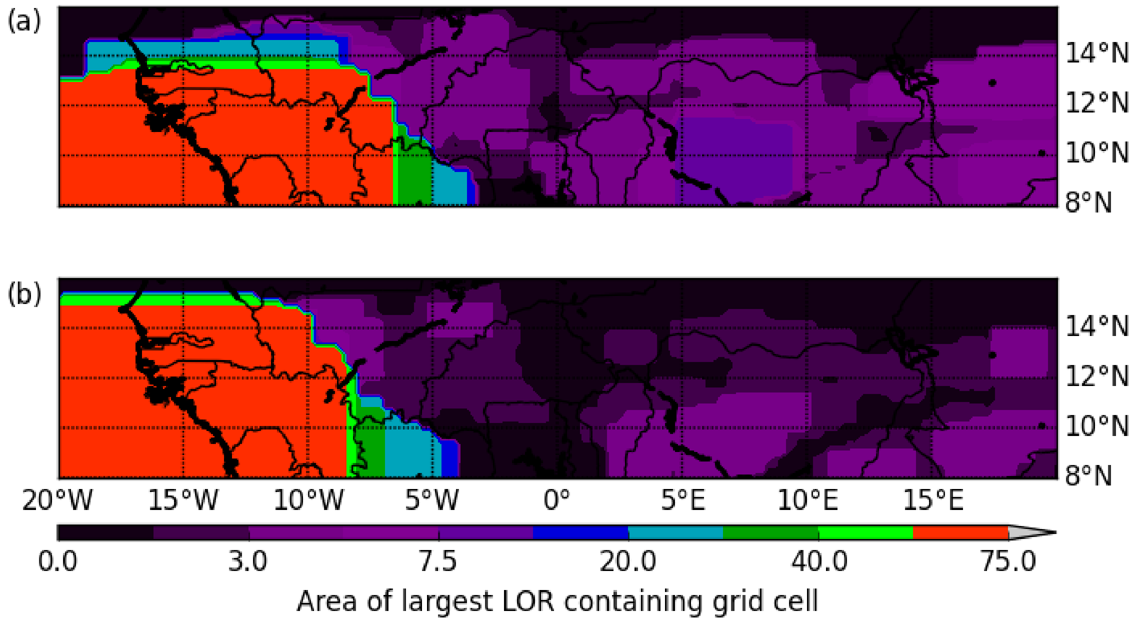

Figure 3.5 – As for Fig. 3.4 but calculating spatially-uniform LORs using onset anomaly data.

There are broad similarities between both spatially-uniform methods over the rest of West Africa. As seen in Fig. 3.4, Fig. 3.5 highlights relatively large areas of coherence over the eastern parts of Benin and Nigeria. The consistency between Figs. 3.4 and 3.5 suggests that there exist regions where onset dates are bounded but also have consistent anomalies. However, there exist large regions where the size of spatially-uniform LORs is small for both methods presented, suggesting that there are regions where local variability dominates absolute onset timings and relative anomalies. This information is important for forecaster users, as it identifies where local onsets may be less predictable.

The distribution of spatially-uniform LOR shapes found using the anomaly method is similar to that found when using absolute onset dates (not shown). There are larger

LORs present when using the anomaly method; however the LORs are still typically wide and short. This similarity is present despite the removal of the latitudinal difference in mean onset dates when calculating LORs using the anomaly method. Figures 3.4 and 3.5 show that spatially-uniform LORs can be diagnosed over West Africa using different fundamental methods. This work does not stress a preference of method. Instead we highlight different techniques to identify spatial coherence of local onset for planners and forecast users in West Africa. The most suitable LOR method should therefore be decided on a case-by-case basis by forecast users. For example, local agronomic stakeholders may prefer the information given by the absolute onset date method over information on onset anomalies.

Spatially-uniform LORs provide information on the year-to-year agreement of onset timing. Whilst there is not continent-wide agreement in onset date on an inter-annual basis, local onsets do show some level of spatial homogeneity. This challenges the conclusion of Marteau et al. (2009) that local onsets are too spatially variable for application on a wider scale although the difference in data used in Marteau et al. (2009) and this work must be considered.

5. Inter-annual Local Onset Regions over West Africa

5.1 Local Onset Region coverage for different confidence intervals

Figure 3.6 shows the location of all inter-annual LORs identified at three confidence intervals: 95% (Fig. 3.6a), 90% (Fig. 3.6b), and 80% (Fig. 3.6c), where 80% of grid cells are required to correlate with the median onset time series. It is noticeable many inter-annual LORs exist in contrast to the expected findings from Marteau et al. (2009).

The number of inter-annual LORs found is inversely proportional to the confidence level tested (compare Fig. 3.6a with Fig. 3.6c). There are five distinct regions where LORs are clustered. These five regions, their spatial limits, and the largest LOR within each region at the 80% confidence level are given in Table 3.3. Outside of the five regions found, the lack of LORs implies that local variability of the AODM dominates over any regional coherence. It can be seen that even at 80% confidence, LORs are not found within the region 1°W–1°E, 8–10°N (Fig. 3.6c). In this region we reason that it is currently not possible to give reliable information on the cause of AODM variability, as local noisiness of precipitation dominates onset variability. The same conclusion can be proposed for other areas where few or no LORs are present in Fig. 3.6.

The majority of inter-annual LORs in Fig. 3.6a cover less than 30,000 km^2 and so are relatively small in size compared to the range used for regional onset assessment. At lower confidence intervals the quantity of LORs and the scale of LORs increases. Figure 3.6b shows that at the 90% confidence interval large (blue) LORs are present over the coastal (CT), Niger/Nigeria (NN), and Cameroon highland (CH) regions defined in Table 3. This is more pronounced in Fig. 3.6c where large (blue) LORs are also found over the Mali/Burkina Faso (MBF) and Benin/Nigeria (BN) regions (also in Table 3.3). The existence of large regions where local onset exhibits homogeneity suggests that the inter-annual variability of local onsets can be reliably assessed with regard to regional and synoptic-scale processes using representative onset dates across pre-defined regions. These processes may include: sea-surface temperature teleconnections, African easterly wave activity modulating rainfall, and the impact of the Madden-Julian Oscillation among other features.

Table 3.3 - Location of five main regions of inter-annual LORs.

Region (abbreviation)	Spatial limit	Latitude and longitude of largest LOR within region	Area of largest LOR within region (‘000 km^2)
Coastal (CT)	20–10°W 8–16°N	20–13.25°W 8–13°N	337.5
Mali/Burkina Faso (MBF)	8–3°W 8–14°N	7.5–4°W 12.5–15.5°N	105
Benin/Nigeria (BN)	0–7°E 8–14°N	2–5°E 10–12.25°N	67.5
Niger/Nigeria (NN)	7–15°E 12–15°N	7.25–10.5°E 11–14°N	97.5
Cameroon Highlands (CH)	8–20°E 8–12°N	11.5–20°E 8–11.25°N	268.125

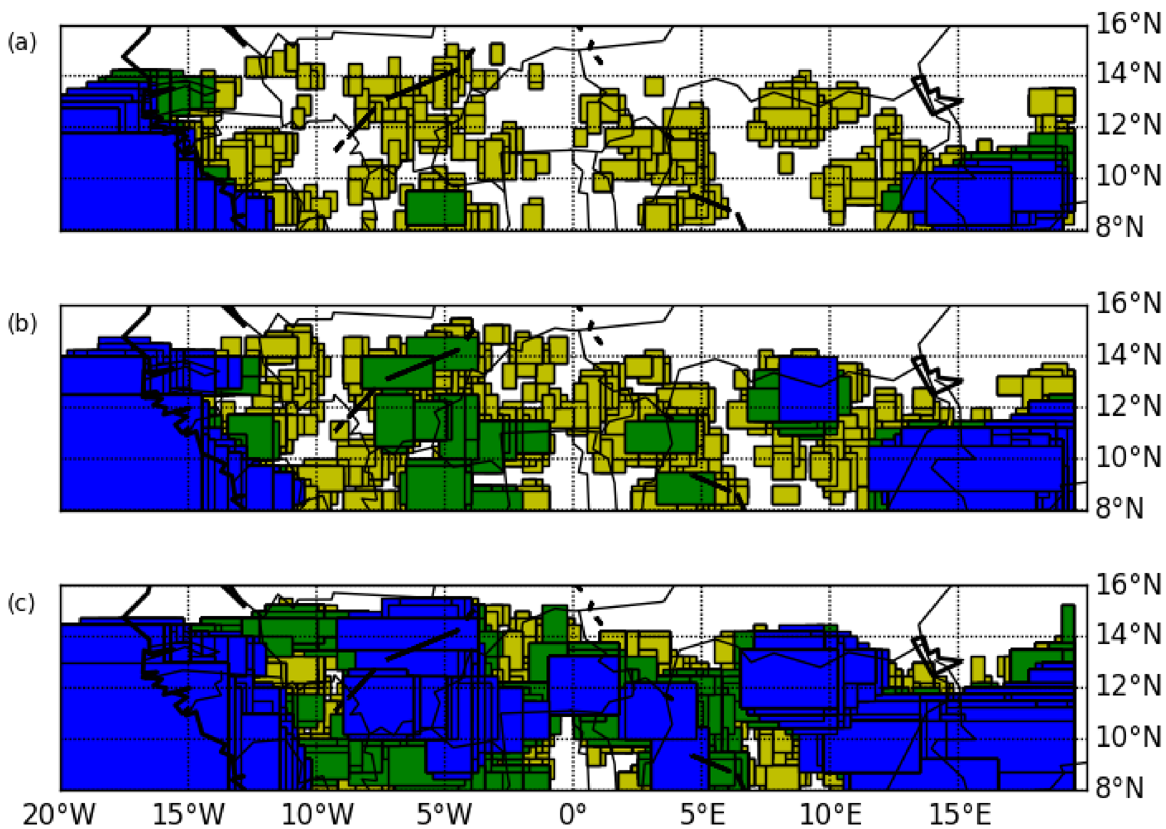

Figure 3.6 – Location of inter-annual LORs found at different confidence levels. Locations of local homogeneity of Mart onset found at (a) the 95% confidence interval, (b) the 90% interval, and (c) the 80% interval. Color of LOR signifies the size of LOR. LORs of area less than roughly 30,000 km^2 are colored yellow, green LORs cover an area between 30,000 and 60,000 km^2, and blue LORs cover area greater than 60,000 km^2.

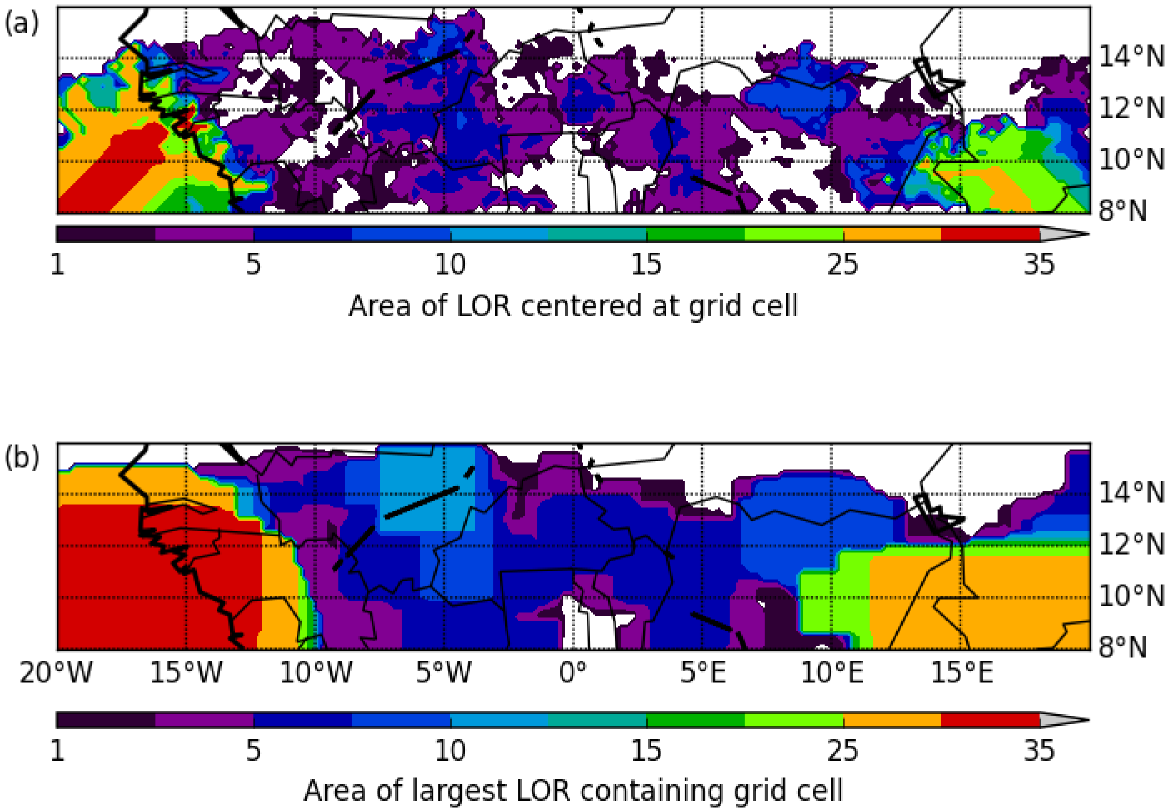

Figure 3.7 – Area of inter-annual LOR (found at the 80% confidence interval) (a) centered at and (b) containing each grid cell. Units for area are 10^4 km^2.

Figure 3.7a shows the area covered by inter-annual LORs, found at the 80% confidence interval, for every point across the study domain. It is possible to distinguish the five main regions in Table 3.3 as the locations where the largest inter-annual LORs are centered. Figure 3.7b highlights the largest LOR that each grid cell is contained within. Given the findings of Fig. 3.7b we suggest that the spatial homogeneity of local onset is sufficiently large to be analyzed on a wider scale than previously thought.

The existence of LORs across much of West Africa at the 80% confidence interval suggests that some drivers operating over 100’s of kilometers or greater are affecting local onset across the entire region. The exact processes responsible for local onset variability are not currently confirmed, however inter-annual LORs give a method by which these processes can be identified and analyzed.

Using inter-annual LORs, it is pragmatic to give relevant information on agronomic onsets across the entire West African domain studied given clear understanding of the spatial constraints of local onset agreement. Local onset regions allow for regional planners to give relevant information on onset timing to people dependent on such information with a built-in threshold of risk. Likewise, local stakeholders are able to know with a certain probability, expressed in Table 3.2, the relative timing of onset at their location (here correct to a quarter-degree square limit) compared to the local climatological mean. This is a large advantage over current regional onset forecasts.

5.2 Dependency of inter-annual LORs to restrictions in their formulation

Figure 3.8 shows the scatter distribution of inter-annual LORs found for the three confidence levels (95%, 90%, and 80%) for four values of $\mathbf{n_{crit}}$. It is apparent that either an increase in confidence interval tested or $\mathbf{n_{crit}}$ leads to smaller and fewer inter-annual LORs identified (compare across rows in Fig. 3.8 for the variability due to $\mathbf{n_{crit}}$ or down columns for the variability due to confidence interval). It is seen that inter-annual LORs exist even with the most stringent restrictions tested here (Fig. 3.8d). It can therefore be concluded that the AODM does exhibit spatial coherence in local inter-annual variance over West Africa even at the highest levels of specification presented here. With the exception of a few wide and short LORs, inter-annual LORs tend to be more “square” (similar longitudinal and latitudinal scales) compared to the spatially-uniform LORs (Fig. 3.3). Given the latitudinal variability of the AODM seen in Fig. 3.1a, this leads to the conclusion that inter-annual LORs are capable of capturing variability over a greater range of onset dates than spatially-uniform LORs. This is an advantage of inter-annual LORs, indicative of their ability to capture the general variability of early monsoon flow instead of one specific moment in the monsoon season. For the remainder of this paper, unless stated otherwise, analysis is done on LORs found at the 80% confidence interval with $\mathbf{n_{crit}}$ = 80%.

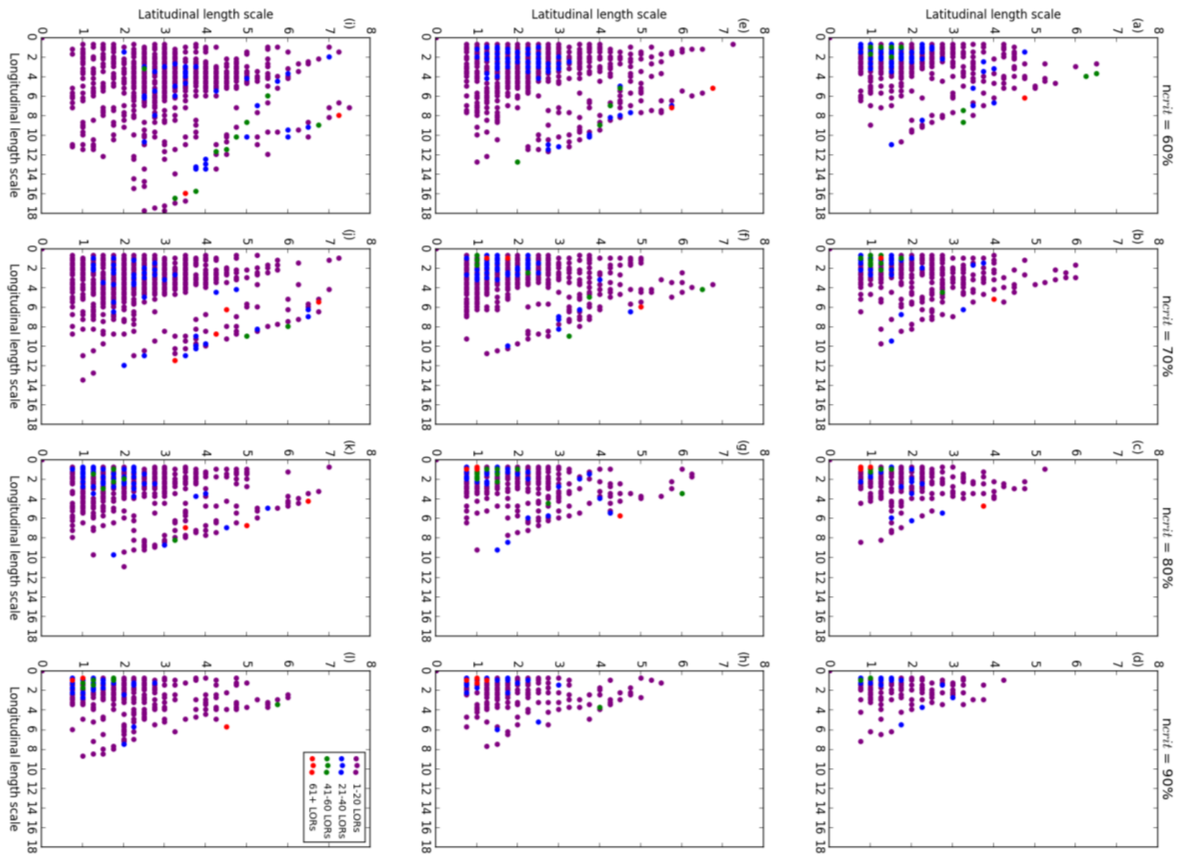

Figure 3.8 - Comparison of inter-annual LORs found for different n_{crit} at different confidence intervals. Scatter distribution of the spatial dimensions for inter-annual LORs found at all confidence intervals and values of n_{crit} tested. Panels a–d show LORs at the 95% confidence level, panels e–h show LORs at the 90% confidence level, and panels i–l show LORs at the 80% level. Columns are sorted by values of n_{crit} written above panels a–d. The color of each circle represents the number of LORs found at each dimensional scale (legend in 8d holds for all panels). Longitude and latitude scale are in degrees.

5.3 Consistency of inter-annual LOR existence for 2013 and 2014

In order to verify the inter-annual LOR results, we have assessed whether the LORs found for the time period 1998–2012 also display onset variability for the years 2013 and 2014. To test this, we consider each LOR found for the period 1998–2012 individually and analyze whether the inter-annual criterion would hold for 2013 and/or 2014. In practice, if the median onset date for an LOR for 2013 is later than the climatological median onset date of that LOR, we assess whether the constituent onset dates are also later than their respective local long-term mean onset dates and vice versa. Figures 3.9a and 3.9b show the LORs that validate for 2013 and 2014, respectively. The majority of LORs found for the period 1998–2012 are validated in 2013 and 2014 with LORs in four of the five main regions highlighted in Table 3.3 present in Figs. 3.9a and 3.9b. Figure 3.9a highlights that variability in the NN region in 2013 does not follow the pattern found for 1998–2012 with the entire region absent of LORs. The fact that all NN LORs disappear shows the stability of the method (it is expected that for 20% of years the LOR would not be validated). This is also true for the MBF region in 2014. In both years the reason for this lack of homogeneity is a high spatial variability of AODM anomalies within the regions (not shown).

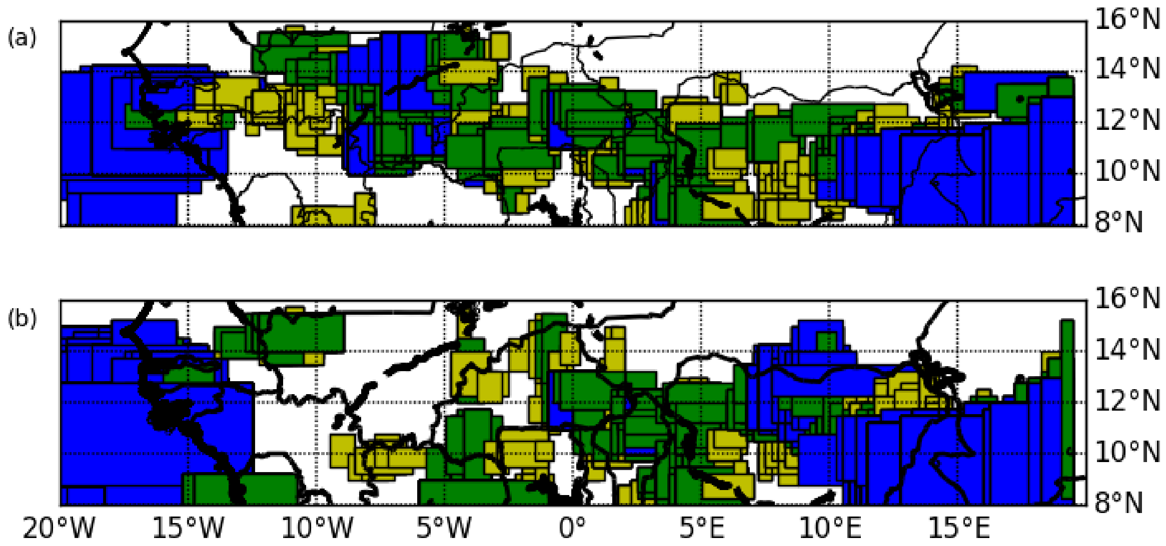

Figure 3.9 - Verification of inter-annual LORs for 2013 and 2014. LORs found at the 80% confidence interval for 1998–2012 are tested for the years (a) 2013 and (b) 2014. LORs highlighted show regions where at least 80% of grid cells have onset variability relative to the grid cell mean onset dates consistent with the relative variability of the median LOR onset date compared with median LOR onset dates for 1998-2012. Shading of LORs is consistent with Fig. 3.6.

In conclusion, inter-annual LORs appear to have some usefulness in highlighting areas where onset variability is consistent each year. Understanding what causes the modulation of LOR median onset in a given year will allow for predictability of local onsets across defined parts of West Africa. Identification of the drivers behind local onset variability within the regions highlighted in Table 3.3 should be an area of key importance for West African research.

5.4 Cross correlation of inter-annual Local Onset Regions

Figure 3.6c and Table 3.3 show that there are large-scale LORs found in the five distinct regions. We investigate here how independent the inter-annual variability of each region is relative to the other regions.

Figure 3.10 shows the level of cross-correlation present between LORs across West Africa. Each of the five regions identified previously have been assessed separately. Figure 3.10a shows all LORs that cross correlate at the 95% confidence level with the largest LOR in the CT region with panels b–e each showing the same correlations for the largest LOR within the MBF, BN, NN, and CH regions, respectively. The inter-annual LORs between the CT and MBF regions tend to correlate, suggesting a connection between the dynamical effects on monsoon onset variability across these two regions (Figs. 3.10a and 3.10b). The exact reason for this link is currently unknown, but there are indications that westerly moisture flux from the eastern Atlantic coast and other factors could play a role (Lélé et al. 2015). Likewise there appears to be a link between onset variability over the NN region and the variability over the MBF and BN regions (Figs. 3.10b–d). This again suggests that there is a possible underlying connecting driver or combination of drivers of local onset variability across a large section of West Africa. A potential explanation of the connection between the MBF and NN regions is the development and westward migration of fast moving squall lines generated over the Jos Plateau. There does, however, appear to be a disconnection between variability of onset across the NN and CH regions, suggesting that the factors that control onset variability are different. This is likely due to the topographical features in the CH region governing local onset.

Cross correlating LORs highlight that there may be large-scale underlying causes for local onset variability across sections of West Africa. For example, it may be that the connection between the CH and MBF regions is due to the African easterly jet and associated African easterly waves bringing intense precipitation towards the MBF region. This link has not been explicitly proven with regards to local onset, but in a more climatological sense (e.g., Fink and Reiner 2003; Bain et al. 2014).

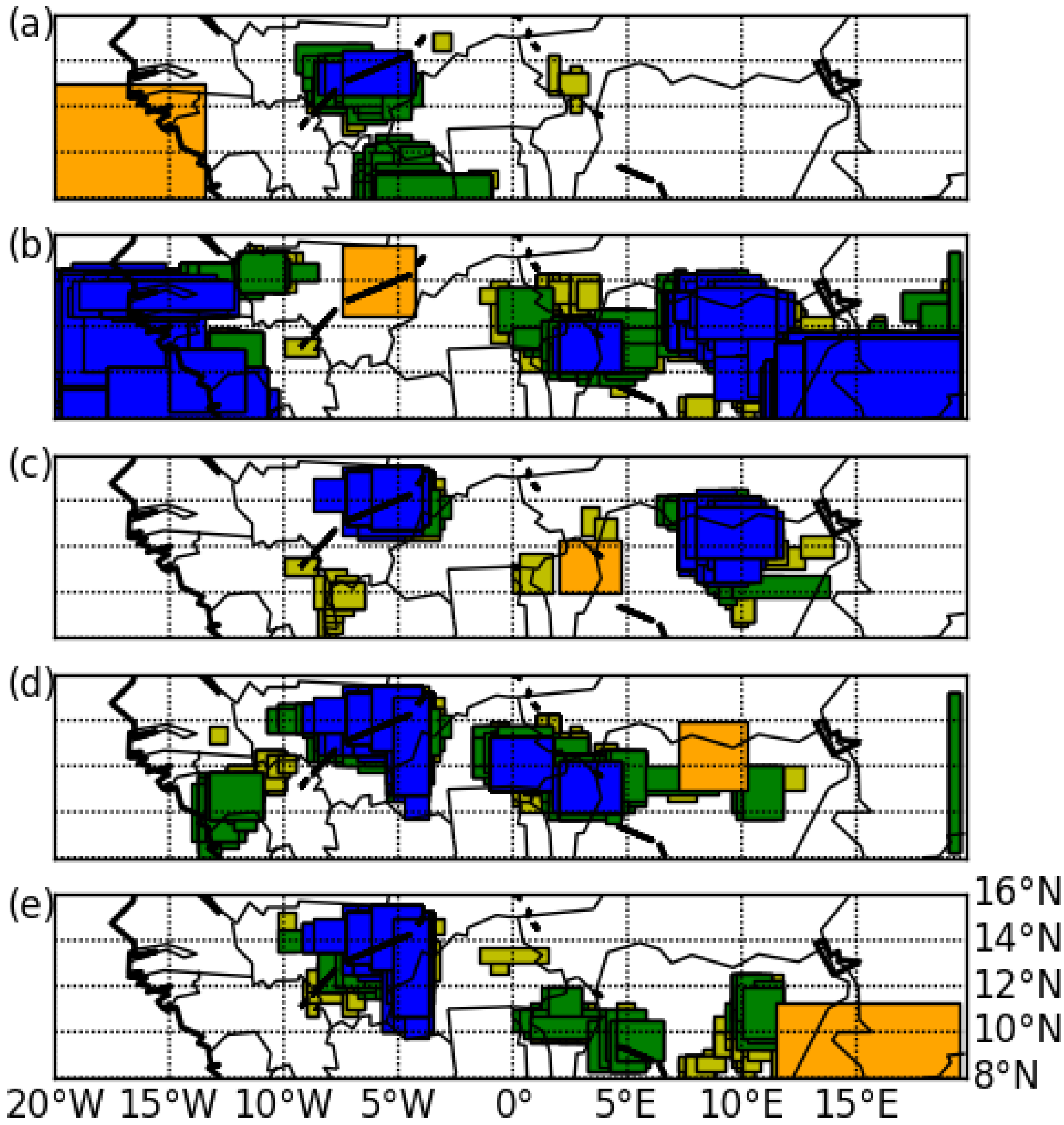

Figure 3.10 – Cross correlation of the five main locations of inter-annual LORs (found at the 80% confidence interval). Location of LORs that cross correlate at the 95% confidence interval with the largest LORs found within (a) the CT

region, (b) the MBF region, (c) the BN region, (d) the NN region, and (e) the CH region. Orange LORs are the largest LORs found within each region with dimensions listed in Table 3.3. Other colors of LORs are consistent with Fig. 3.6 (i.e. yellow, green and blue LORs are representative of LOR size).

6. Correlation between Local Onset Regions and the Inter-Tropical Front

Figure 3.11 shows the location of inter-annual LORs which correlate (at the 90% level) with the ITFR onset date at 1.5 degrees latitude north of the northernmost latitude of the LOR (i.e., ITFR at 14°N for an LOR with northernmost extent at 12.5°N; Fig. 3.11a) and the point when the ITF reaches 15°N (i.e., ITFR at 15°N; Fig. 3.11b). Both Fig. 11a and 11b show that the majority of LORs that correlate with the ITFR onset are within the longitude band 10°W–10°E, which coincides with the region where the ITFR is calculated. The ITFR at 15°N primarily correlates with LORs across the MBF region (Fig. 3.11b). This could highlight the fact that different dynamics modulate agronomic onset within the five distinct regions highlighted in Table 3. The link between the ITFR at other distances north of each LOR have also been investigated. It is found that the link between the ITFR and local onsets in the MBF, BN, and NN regions is stable, however there is a more variable link found across the CT and CH regions (not shown).

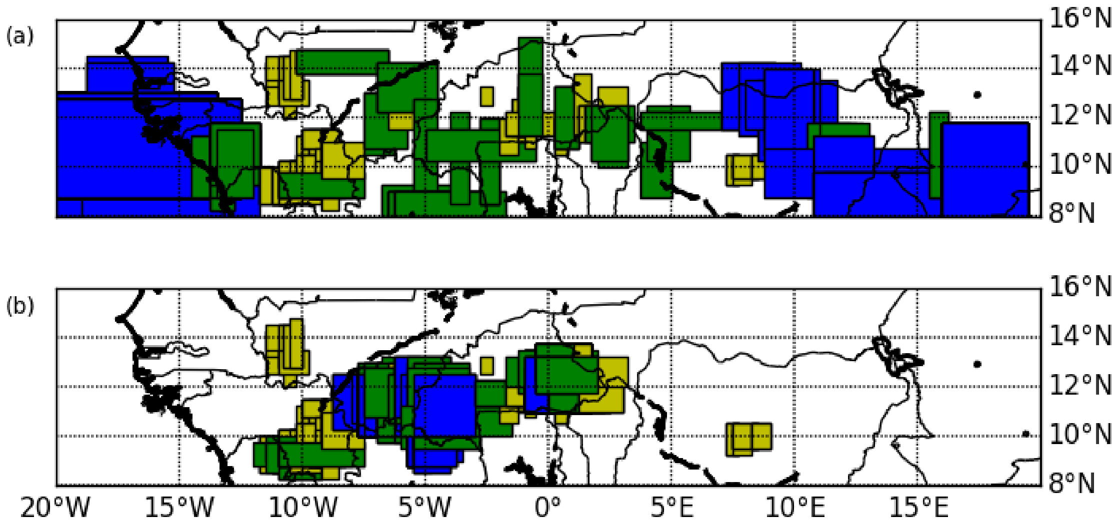

Figure 3.11 - Location of inter-annual LORs (found at the 80% confidence interval) that positively correlate with regional ITF onset (i.e., later regional ITF implies later local onset). (a) Significant correlation at the 90% confidence interval between ITFR onset at 1.5 degrees latitude north of the northernmost latitude of each LOR and median LOR onsets. (b) Significant correlation between ITFR onset at 15°N and median LOR onset. Color scale of LORs consistent with Fig. 3.6.

Later-than-average ITFR advancement is typically concurrent with later-than-average AODM. Given that a link between the ITF advancement and societally-useful rainfall has already been found (Lélé and Lamb 2010), the apparent link between ITFR and the AODM across West Africa provides a potential necessary condition for local onset to occur. Figure 3.11b may also provide a missing link between local and regional onset variability in the MBF region. Sultan and Janicot (2003) define monsoon pre-onset across the region 10°W–10°E as the date when the ITF reaches 15°N. The authors find minimal correlation (0.01) between the timing of the pre-onset and their regional onset date. This result, coupled with the findings of Fitzpatrick et al. (2015) and Fig. 3.11b, suggests that the timing of the monsoon pre-onset is a better indicator for local onset variability than the timing of regional monsoon onset within correlating LORs shown in Fig. 3.11b.

Finally, in Fig. 3.11a, a link between the AODM and the ITFR can be seen over the coastal region. The potential for a teleconnection between local precipitation over the coast and the advancement of moisture into continental West Africa is intriguing. The dynamical understanding of this link across all regions warrants further investigation (with the work of Lélé et al. 2015 providing motivation).

Figure 3.12a compares the median onset of the AODM within each LOR with the timing of the ITFL at 1.5 degrees north of the northernmost latitude of that LOR (i.e., ITFL at 15°N for an LOR with northernmost latitude of 13.5°N). As for the ITFR, different latitudinal gaps between the ITFL and LORs have been examined with consistent results (not shown). As mentioned in Section 2.3, the definition of the ITFL over the CT region is not calculated. Over the four regions analyzed, there exists a link between the inter-annual variability of the AODM and the advancement of the ITFL. This result suggests that measurements of dew-point temperature over clearly defined regions can give meaningful insight for local planners into the variability of monsoon rains with sufficient lead time for practical purposes.

Figure 3.12b shows that the lead time between the ITFL onset and the AODM onset across LORs is frequently much larger than two weeks, although the lead time may differ even across overlapping LORs. The standard deviation of this link is generally between seven and fourteen days (Fig. 3.12c). There are however LORs where the variability in the lag can exceed three weeks. Nevertheless, the standard deviation in Fig. 3.12c is often lower than the high local variability of the AODM (Fig. 3.1b). It can be proposed that the ITFL onset date can be used as a predictor of local onset variability of the AODM with sufficient lead time for practical purposes. Given the variability in lead time seen in Fig. 3.12c coupled with the existence of neighbouring regions where the lead time can differ, the ITFL may not be suitable for explicit onset date prediction. Conversely for probabilistic or tercile analysis, the link shown here would be of practical use. The fact that a link exists between the ITFL and AODM dates for many LORs is an improvement over using regional onset dates to predict local onsets.

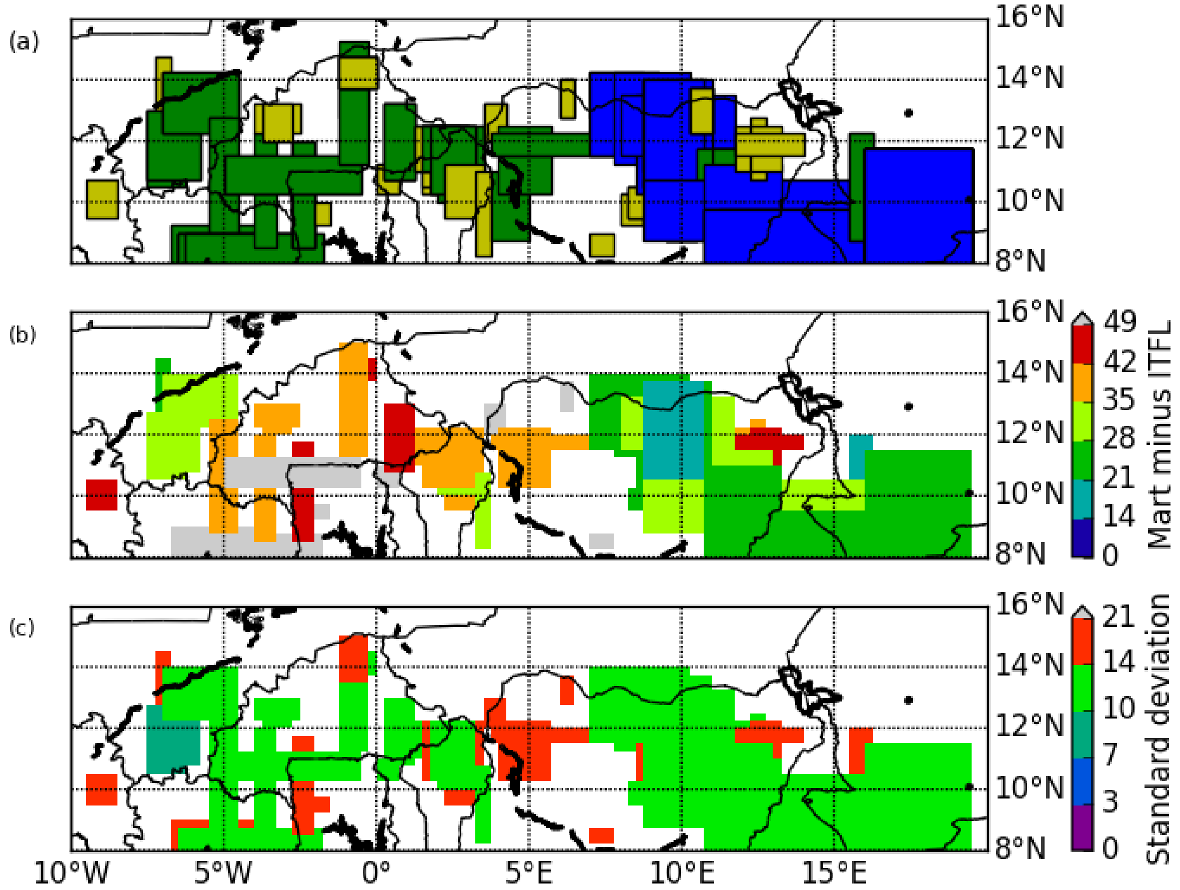

Figure 3.12 – Correlation between ITFL and *Mart* and key statistics. (a) Location of inter-annual LORs (found at the 80% confidence interval) that correlate with the ITFL onset 1.5 degrees north of the northernmost latitude of the LOR to the 90% confidence interval. Color scale of Fig. 3.12a is consistent with Fig. 3.6. (b) Average lead time (days) between ITFL onset and median

Mart onset within each LOR. (c) Standard deviation of the lead time between the two onsets.

Apparently (and intuitively), the movement of moisture towards and beyond correlating LORs is a necessary condition for local onset to occur, however it is unclear whether the ITFL or ITFR onset is a sufficient condition for onset. The dynamical link between the deepening of the continental monsoon layer across West Africa and local agronomic onset requires further study. This finding gives precedent for assessment of local onset predictability across most of West Africa.

7. Summary

The local onset of the West African Monsoon is under-used by both the science community and in forecast practices due to the complexity and inhomogeneity of local rainfall. It is shown here that local onsets have spatial coherence across sections of West Africa. These areas are termed as local onset regions (LORs). There exist several local onset definitions applicable over West Africa (Omotosho et al. 2000; Marteau et al. 2009; Yamada et al. 2013). The definition proposed by Marteau et al. (2009) was selected for analysis here.

Local onset regions have been identified using two methods, one focused on absolute onset dates or local anomalies (spatially-uniform LORs) and one centered on local inter-annual variability of onsets (inter-annual LORs). Both methods identify sub-continental regions of local onset consistency across West Africa but also highlight a distinct lack of widespread spatial agreement in onset. The fact that so little of the *monsoon region* (10°W–10°E from Sultan and Janicot 2003) can be captured within large LORs suggests that there are potentially multiple combinations of dynamical and topographical factors affecting local onset within this region. This is in contrast to, but does not contradict nor controvert earlier findings for regional onset variability. Local and regional onsets occur over different regions and over different observational time periods and should be considered as separate entities.

There are clear advantages and disadvantages to the spatially-uniform LOR method. The identification of regions where onsets occur at a similar time highlights locations where a temporal trigger of onset may exist. However, by setting a strict limit for proximity to the median value of an LOR, the method inherently limits LOR coverage and size across regions of high local variability and where the gradient of local onsets is high. As a result, spatially-uniform LORs tend to be “wide and short” (longitudinal length scale > latitudinal length scale). Computing spatially-uniform LORs using onset anomaly data does not change the size or location of LORs found with the exception of the region 20°W–10°W. By contrast, Inter-annual LORs cover larger latitudinal length scales than spatially-uniform LORs and therefore can give a useful view of homogeneity of onset not observed in spatially-uniform LORs.

LORs have been constructed to allow the median onset date for each year to be considered as a representative onset across the LOR. This makes practical sensitivity assessment of local onset possible using a finite set of locations (for instance a rain gauge network). This is one of the main advantages of identifying LORs.

It is suggested here that the level of spatial agreement between onset dates gives some insight into the nature of potential dynamical or topographical onset triggers. In theory, processes occurring on the synoptic scale (such as the response to the Indian Monsoon onset) will affect onset dates over a large region if indeed they have any effect on local onsets. By contrast, more localized processes (such as topographic triggering of convection) will control coherence of onsets over a smaller area. The interaction of different local onset triggers occurring over varying scales (both temporal and spatial), needs further investigation for accurate prediction of local agronomic onset over West Africa to be feasible. The location and size of LORs might give insight into the features that modulate onset.

The inter-annual LORs found using precipitation data from 1998–2012 are also verified using local onset dates for 2013 and 2014 with the exception of one region in each year. This suggests that despite the high temporal and inter-annual variability of local onset dates, LORs have much more consistent inter-annual variability.

Finally, the seasonal progression of the ITF, taken here as the northward extent of the 15°C isodrosotherm, is shown to be directly linked to onset dates across West Africa. Across almost all correlating LORs the average lead time between the localized ITF advancement and median local onset date is greater than two weeks, although the exact dynamics for this link are not currently understood. This result provides a link between local agronomic onset and a readily measurable metric that occurs prior to agronomic onset. The seasonal transition of the ITF is less spatially and temporally noisy than local precipitation and also less dependent on dataset choice (compare Fig. 5 in Roberts et al. 2015 to the findings of Fitzpatrick et al. 2015). The link shown here supports the findings of Ilesanmi (1971) who shows that station rainfall totals are well correlated with the positioning of the ITF. The identification of other similar links could help improve local onset prediction.

The work presented here provides a first step in bridging the gap between regional climate dynamics and local onset variability. A better understanding of the limits of predictability of local onset as well as the cause of inter-annual variability of local onset will provide relevant information for local stakeholders across the region and help provide a platform on which future research into local onset variability can be performed.

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Chapter 4

The Influence of the Madden-Julian Oscillation on local agronomic onset across West Africa

The influence of the Madden Julien Oscillation on local agronomic onset across West Africa

For submission to the Quarterly Journal of the Royal Meteorological Society

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Abstract

The timing of local agronomic onset marks a key date for farmers across West Africa. However, given the nature of localised precipitation in this region, accurate forecasting of local onset dates requires identification of large-scale and well-understood climatological triggers. The influence of the Madden-Julian Oscillation (MJO) on agronomic onset dates and the wider West African climate is explored here for the period 1979-2014.

It is seen that when the MJO enhances deep convection over the Guinea Coast, there is a weaker pressure gradient between the Gulf of Guinea and the Sahara leading to reduced northwards moisture flow towards the Sahel. This is coupled with subsidence and divergence over the Sahel and less precipitation than climatology. By contrast, when the MJO supresses convection around the Gulf of Guinea (south of 5°N), a stronger northwards flow of moisture into the Sahel and greater early season precipitation is seen.

The MJO influences the state of the West African climate during late May and early June and therefore could be an indicator of relatively early or late agronomic onsets across this region.

1. Introduction

The accurate prediction of localised and societally-useful precipitation is an important problem for the West African community (Ingram et al. 2002; Marteau et al. 2009; Lélé and Lamb 2010). In particular, it is vital that a reliable and relevant West African Monsoon (WAM) onset date is given to local forecast users at a timescale that allows for successful implementation of decision making strategies (Ingram et al. 2002; Sultan et al. 2005). Given the complex nature of accurately predicting precipitation at user-relevant spatial scales with pragmatic lead time, it is important to understand how large-scale and measurable features of tropical meteorology affect the WAM system. This work provides insight into how the Madden-Julian Oscillation (MJO; Madden and Julian 1971) affects the inter-annual variability of precipitation based local onsets and associated metrics across West Africa.

The latitudinal shift of the regionally-averaged maximum precipitation and convergence zone over West Africa (sometimes referred to as the Inter-Tropical Convergence Zone or ITCZ), has been the most common onset date studied (e.g., Sultan and Janicot 2003; Fontaine and Louvet 2006; Gazeaux et al. 2011; Vellinga et al. 2012). However, there are many subtly different metrics used to give an explicit WAM onset date that occur over a variety of length scales and use different data (a summary of which can be found in Fitzpatrick et al. 2015). The most valuable information for local farmers and forecast users is the onset of sufficient precipitation at their respective location (i.e. a local onset date). Prior work has suggested that inter-annual variability of local onsets differs from the regional variability and thus must be considered on its own merits.

Local onset dates typically focus on precipitation thresholds relevant for farming. The agronomic onset definition from Marteau et al. (2009), hereafter referred to as "the local onset”, is used in this study however other local onset definitions can also be applied (e.g. Omotosho et al. 2000). The local onset uses precipitation thresholds that are relevant for agricultural management and can be thought of as the commencement of persistent, user-relevant precipitation. By design, the local onset can only be explicitly calculated *a posteriori* making an understanding of conditions prevalent before local onset important.

Recent work suggests that there exists some useful level of spatial coherence for local onsets across West Africa allowing for further investigation into the causes of inter-annual variability (Fitzpatrick et al. 2016). Regions where the inter-annual variability of local onsets is coherent are termed local onset regions (LORs). The use of LORs allows for analysis of the cause of local onset inter-annual variability over a length scale that is pragmatic for forecasters and regional planners.

The MJO is one the dominant planetary features affecting large-scale convection and precipitation within the tropics (Madden and Julian 1971; Madden and Julian 1994; Hendon and Salby 1994). Cyclical oscillations between enhanced and reduced convection over the Pacific warm pool impact tropical convection through large scale wave dynamic responses. With a standard period of 40–90 days the MJO can provide predictive information into sub-seasonal variability of convection and precipitation across the tropics including West Africa (Janicot et al. 2009; Pohl et al. 2009).

Previous work has explored the impact of the MJO on sub-seasonal to seasonal variations in regional precipitation totals across West Africa (Maloney and Shaman 2008; Lavender and Matthews 2009; Janicot et al. 2009; Mohino et al. 2012; Flaounas et al. 2012a,b) and the timing of regional monsoon onset (the date when the ITCZ shifts from the Guinea Coast to the Sahel; Matthews 2004). For localised, pre-monsoon onset, the impact of the MJO and the Indian Monsoon (IM) onset could have substantial impact (Flaounas et al. 2012b).

The onset of the IM has been well documented in literature (Moron and Robinson 2014; Parker et al. 2016). As opposed to the WAM onset which is rather abrupt, the seasonal migration of monsoon rains over the Indian Sub-continent is relatively consistent with onset dates ranging from early May until mid-July (Indian Meteorology Department). Flaounas et al. (2012b) find that up to ten days after the IM onset, a Gill-type Rossby wave progresses towards West Africa at the same time moisture flux convergence increases over the Sahel (10°N) and decreases over the Guinea Coast (5°N). Between 10 and 20 days after the IM onset, the Gill-type Rossby wave induces a zonal gradient of pressure anomalies around 300 hPa over the eastern Mediterranean, enhancing subsidence of high tropospheric air which is directed equator-wards. This dry air subsidence suppresses convection over the Guinea Coast potentially due to a temperature inversion in the middle troposphere. The Gill-type Rossby wave also accelerates the zonal shift of the maximum rain belt of the WAM through a negative pressure anomaly between the Gulf of Guinea and the Sahel. After 20 days, the maximum rain belt is shifted towards the Sahel and maintains this position throughout the summer monsoon season.

There is potential for a dynamical link between the MJO and precipitation variability prior to the regional onset. Subsidence over the Gulf of Guinea (GoG, ~0-5°N) and Guinea Coast is linked to increased northwards, low level, non-divergent flow from the coast towards the Sahel (Hagos and Zhang 2010). In turn, there is an increased flow of moisture into the Sahel which shifts the Inter-Tropical Front (ITF), analogous to the northernmost limit of cool-moist monsoon winds, further northwards. It is important to state however that other factors can help or inhibit northwards progression of the ITF such as cold pool outflows or Kelvin waves (Flamant et al. 2009). The relative annual location of the ITF is linked to precipitation variability (Ilesanmi 1971; Lélé and Lamb 2010; Lélé et al. 2015), and variability in local onsets (Fitzpatrick et al. 2016). Here we investigate how the MJO affects precipitation and onset-related metrics such as the ITF influenced by the findings of Berhane et al. (2015) who show that the MJO affects precipitation extremes and moisture advection in boreal spring.

Sections 2 and 3 describe the data and methods used within this work. Section 4 considers the influence of the MJO on the regional West African Monsoon climate. Section 5 focusses specifically on LORs and explores how the MJO impacts local onsets and onset-relevant variables in non-arbitrary regions. Section 6 will summarize the findings of this work and suggest possible extensions.

2. Data

The local onset date is calculated using precipitation data from the Tropical Rainfall Measurement Mission 3B42 version 7 product (TRMM v7; Huffman et al. 2007). TRMM v7 data are used for the years 1998-2014 inclusive at the native 0.25 x 0.25 degree resolution. Previous work has suggested that TRMM v7 gives the most realistic high-resolution representation of the local onset, although there are still potential biases in the data (see Seto et al. 2011 and Fitzpatrick et al. 2015).

The ERA-Interim re-analysis (ERA-I, Dee et al. 2011) product is used to assess the atmospheric response to different MJO conditions. The re-analysis is available for the years 1979-2014 and therefore provides a long duration over which different atmospheric conditions can be identified and investigated.

There must however be a degree of hesitation in using re-analysis products and care must be made not to assume that findings derived from re-analysis studies are guaranteed to represent truthful situations. In particular, ERA-I has been shown to poorly capture the mean local onset dates across West Africa (Fitzpatrick et al. 2015) as well as certain aspects of the ITF advancement and recession (Roberts et al. 2015) and more broad issues involving the global water, heat and momentum budgets (Dee et al. 2011). Despite the issues presented above, ERA-I is considered a bench mark re-analysis product and is suitable for the work presented here. Roberts et al. (2015) provide an overview of skill in representing the ITF across a variety of re-analysis products with ERA-I considered the most consistent representation of the ITF advancement during the early WAM season.

One of the long standing issues with WAM analysis is the lack of a spatially-dense network of reliable *in situ* measurements. ERA-Interim uses a 4DVAR data assimilation technique and variational bias correction techniques to adjust forecasted parameters closer to the observed background state seen using satellite data and in situ observations (Poli et al. 2010). Over West Africa, there is a lack of in situ recordings that can be used to bias correct ERA-I (see Ilesanmi 1971, Parker et al. 2008 and Fig. 1 in Fitzpatrick 2015). In practice, this means that over West Africa, the forecast given is less strenuously corrected (particularly over the Sahara where very few observations exist) and thus is potentially less reliable than over a heavily observed region (e.g. Western Europe). This issue is prevalent for other re-analysis products as well and speaks to an under-investment in soundings over West Africa that can potentially hamper constructive investigation into the causes of monsoon variability in the region. The findings given here must therefore be treated with caution as all re-analysis research must.

The most extensive dataset of the MJO is provided by the Bureau of Meteorology (BoM; see http://www.bom.gov.au/climate/mjo for full details). This dataset interprets outgoing longwave radiation from the NCEP-DOI 2 dataset and is considered a representative dataset for inferring the phase and intensity of the MJO. A single, planetary calculation of the phase and amplitude of the MJO is given for every calendar day. The daily phase and amplitude of the MJO is taken from 1979–2014.

Finally, outgoing longwave radiation (OLR) values are taken from the National Ocean and Atmosphere Administration (NOAA) interpolated dataset for the years 1979-2012 (Liebmann and Smith 1996; http://www.esrl.noaa.gov/psd/data/gridded/data.interp_OLR.html). Although the period used for OLR data does not cover the entire period of re-analysis data used, the results presented appear consistent with expected findings.

3. Methods

3.1 The agronomic onset date from Marteau et al. 2009

The local onset is defined as the first rainy day (> 1 mm) of two consecutive rainy days (with total precipitation greater than 20 mm) with no seven day period with total precipitation less than 5 mm in the subsequent twenty days (Marteau et al. 2009). The local onset date is assessed over a Sahelian study region (20°W–20°E, 8–16°N). Onset dates range from the beginning of May until mid/late July with an apparent northwards progression (Fitzpatrick et al. 2016, their Fig. 1a).

There are approximately 5500 quarter-degree grid cells within our study region. Instead of providing sensitivity assessments at the grid-cell level, representative inter-annual LORs are used (Fitzpatrick et al. 2016). Broadly speaking, an inter-annual LOR marks a spatial area over which the inter-annual variability of local onsets is consistent (a more detailed explanation can be found in the original work). Figure 4.1 shows the five LORs used within this work, taken from Table 2 of Fitzpatrick et al. (2016). The five distinct regions are denoted henceforth as (from west to east): the coastal region (CT), the Mali/Burkina Faso region (MBF), the Benin/Nigeria region (BN), the Niger/Nigeria region (NN) and the Cameroon Highlands (CH).

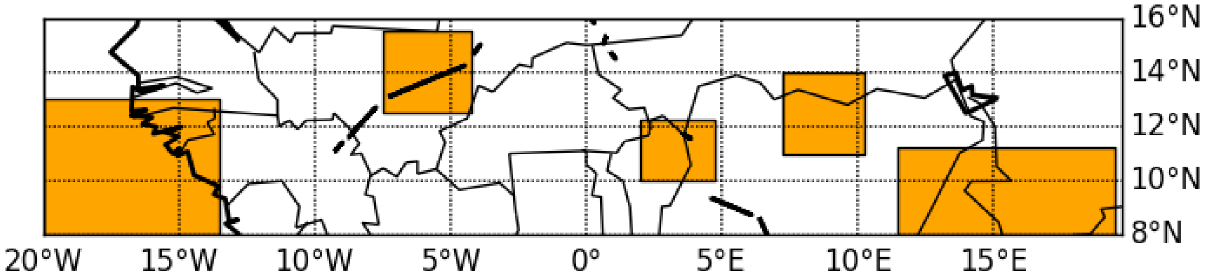

Figure 4.1 - Location of 5 LORs used in analysis. The largest inter-annual LOR found in each of the five LOR areas (from west to east: Coastal, Mali-Burkina Faso, Benin-Nigeria, Nigeria-Niger, Cameroon Highlands). Full details of LOR construction and statistics can be found in Fitzpatrick et al. (2016).

The median local onset across each LOR is used as a representative time series for onset within that LOR. The mean of the representative onset dates for each of the five LORs used in this study are given in Table 1. The average onsets of the CT, BN and CH regions occur almost a month earlier than the onsets of the MBF and NN regions. Part of the reason for this difference is the latitudinal gradient of the local onset across West Africa (Fitzpatrick et al. 2015). In order to determine the state of the environment conducive to agronomic onset, an assessment must therefore be performed on the WAM system in May and June. In this work, we use the observation period 23 May–12 June for assessment which covers median local onset in three of the LORs, the climatological WAM transitional stage (Flaounas et al. 2012a) and the climatological IM onset date (taken from the Indian Meteorological Department). The period 23 May–12 June is termed the “observation period”.

Table 4.1 - Mean onset date from 1998-2014 for the five LORs in Fig. 1

Region	Mean onset date (1998-2012)
Coastal (CT)	11 June
Mali/Burkina Faso (MBF)	1 July
Benin/Nigeria (BN)	5 June
Nigeria/Niger (NN)	24 June
Cameroon Highlands (CH)	6 June

<u>3.2 The MJO phase and intensity in May and June</u>

The phase of the MJO can modulate the level of convection over the GoG and Guinea Coast (approximately 5°S–5°N, termed collectively as coastal West Africa here) during the observation period of this work. As such, it is necessary to distinguish between the years when the MJO predominantly favours or inhibits deep convection over this location. Similar to the work of Flaounas et al. (2012b), and Mohino et al. (2012) among others, we state that MJO phases 2–5 are more conducive to convective inhibition over coastal West Africa, and phases 6–1 are more likely to enhance convection over coastal West Africa. When the MJO is in phase 2–5, this is termed an “inhibiting” day or “inhibiting conditions” for succinctness in our analysis. Conversely, phases 6–1 are associated with “favourable” days or “favourable conditions”. These terms relate solely to coastal West Africa; indeed given the structure of the MJO, favourable conditions over coastal West Africa are coupled with inhibited convection elsewhere in the tropics.

For the period 23 May–12 June we determine whether the MJO is predominantly favouring or inhibiting deep convection over West Africa. Figure 4.2 highlights the proportion of favourable and inhibiting days in this period for each year. Years in which there are at least 10 more inhibiting days than favourable days are denoted as “inhibiting MJO years” with the opposite (10 more favourable days than inhibiting days), termed “favourable MJO years”.

In the assessed period, there are ten inhibiting years (1984, 1987, 1989, 1990, 1991, 1992, 1993, 1996, 2005 and 2014), and five favourable years (1997, 1999, 2003, 2006 and 2009). The set of favourable and inhibiting MJO years are used to explore the different atmospheric conditions over West Africa during our observation period. There is potential evidence of decadal variability in the existence of favourable or inhibiting MJO conditions during our observation period; the reasons for this variability are not currently understood.

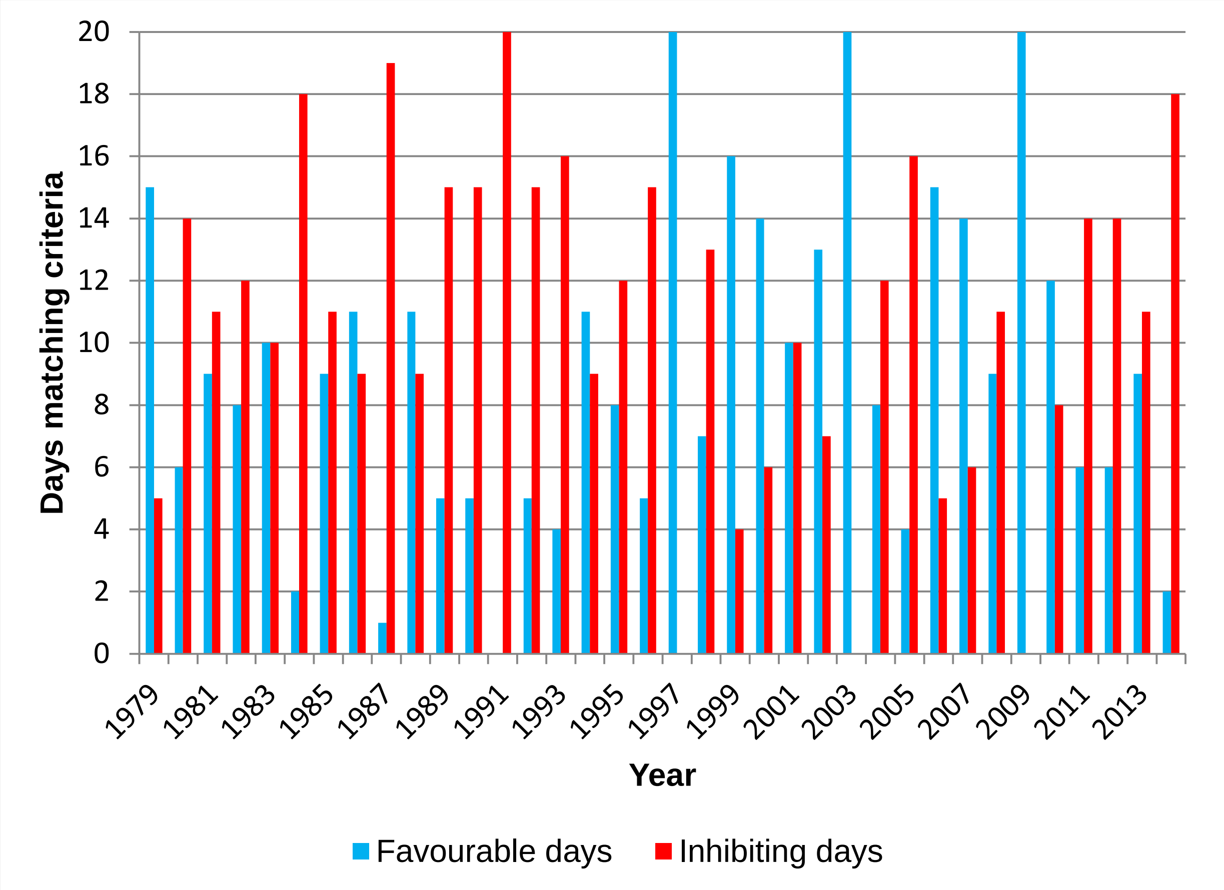

Figure 4.2 – Evaluation of the MJO status over the Guinea Coast for the period 23 May – 12 June, 1979-2014. The proportion of favourable days (MJO phase 2 – 5, blue values) to inhibiting days (MJO phase 6 – 1, red values) are compared. See accompanied text for more details.

3.3 Statistical method used for difference plots

For all metrics, it is important to highlight the difference between favourable and inhibiting MJO years. In order to separate potential MJO signals from noise a statistical test is required. A common test to determine whether two independent populations are significantly different is the Student t test. For meteorological purposes, this test has several flaws which can reduce the power (or reliability) of findings.

Firstly, the test requires that both populations are normal or have long tails. For a small population (such as metrics taken from the 5 favourable MJO years), it is not possible to determine long tails and a normality test (such as Wilks-Shapiro) is unlikely to give powerful results. Secondly, the Student t test assumes that the variance of both populations is the same. Whilst this can be readily tested for each metric, it is unnecessary to perform this calculation given that more powerful statistical methods exist.

The Welch t test can be thought of as a natural extension of the Student t test which provides similar power to results when the variance of the two populations is the same and superior power when the variance differs. Therefore, the Welch t test provides advantages over the Student t test with no drawbacks and has been chosen for this work.

All comparison figures in this work show differences which are significant to the 95% confidence interval using a Welch t test. The independent populations are (respectively): favourable years and non-favourable years, inhibiting years and non-inhibiting years, and favourable and inhibiting years.

Although the Welch t test provides advantages over the Student t test, it still assumes the populations are normal. In order to test whether this assumption affects the power of results shown, all figures have also been reproduced using methods that do not assume normality of populations. There are no substantial differences between the findings using the Welch t test and our alternative method (not shown); here only the Welch t test findings are shown.

4. The regional impact of the MJO on West Africa

Firstly, we consider how the MJO affects precipitation within the ERA-I dataset. Although local onset dates calculated using ERA-I do not compare well with observed onset dates (Fitzpatrick et al. 2015), it is of interest to see how the re-analysis model internally responds to the different MJO conditions. Fundamentally, precipitation is the most relevant metric to agronomic forecast users as onset and subsequent decision making depends on precipitation variability. Therefore the modulation of precipitation by the MJO is the most important result for decision makers across West Africa.

Figure 4.3 shows daily average precipitation rates for 23 May–12 June for the total period 1979-2014 (Fig. 4.3a) as well as anomalies in favourable (Fig. 4.3b) and inhibiting (Fig. 4.3c) MJO years, and the difference between inhibiting and favourable MJO conditions (Fig. 4.3d). For comparison, Fig. 4.4 shows the same results for the period 13 June–2 July.

The maximum rain belt can be distinguished around the Guinea Coast (~5°N) as can the region of substantially lower precipitation across most of North Africa and the Sahara (both Fig. 4.3a and Fig. 4.4a). The re-analysis dataset captures the large scale features of the WAM around the transitional monsoon phase and therefore further analysis is valid.

Figure 4.3b shows that during late May and early June there is significantly less rainfall (at the 95% confidence level) over continental West Africa (~5–10°N) compared to climatology when the MJO favours coastal convection. Conversely, over the GoG, rainfall is mostly greater than average in favourable MJO years. This pattern is reversed in inhibiting MJO years (Fig. 4.3c) where greater continental precipitation and lower oceanic precipitation are seen. The difference between inhibiting and favourable MJO years suggested in anomaly plots is confirmed in Fig.

4.3d, providing evidence of a dipole-type response of precipitation to the MJO during late May and early June. From Fig. 4.3 we suggest that inhibiting MJO conditions are more favourable for enhanced continental precipitation early in the monsoon season and vice versa. Such information could be of considerable value to farmers if accurately modelled and communicated.

For the latter observed period (Fig. 4.4), we see the same dipole in precipitation anomalies for favourable MJO years (Fig. 4.4b). As before, in inhibiting MJO years (Fig. 4.4c), this signal is reversed, with the magnitude of anomalies similar over both time periods (the exception being over the GoG in favourable MJO years). Differences between inhibiting and favourable MJO conditions suggest greater precipitation (up to 8 mm/day in some locations) present in years when the MJO inhibits convection over the continent (Fig. 4.4d). Over the GoG, there is less difference between inhibiting and favourable MJO years in the later observational period (compare Fig. 4.4d to Fig. 4.3d); this is potentially due to the lower precipitation over this region during the later period (seen in Fig. 4.3a and 4.4a). Given the thresholds used in calculating local onset dates, this difference is likely to have substantial impact.

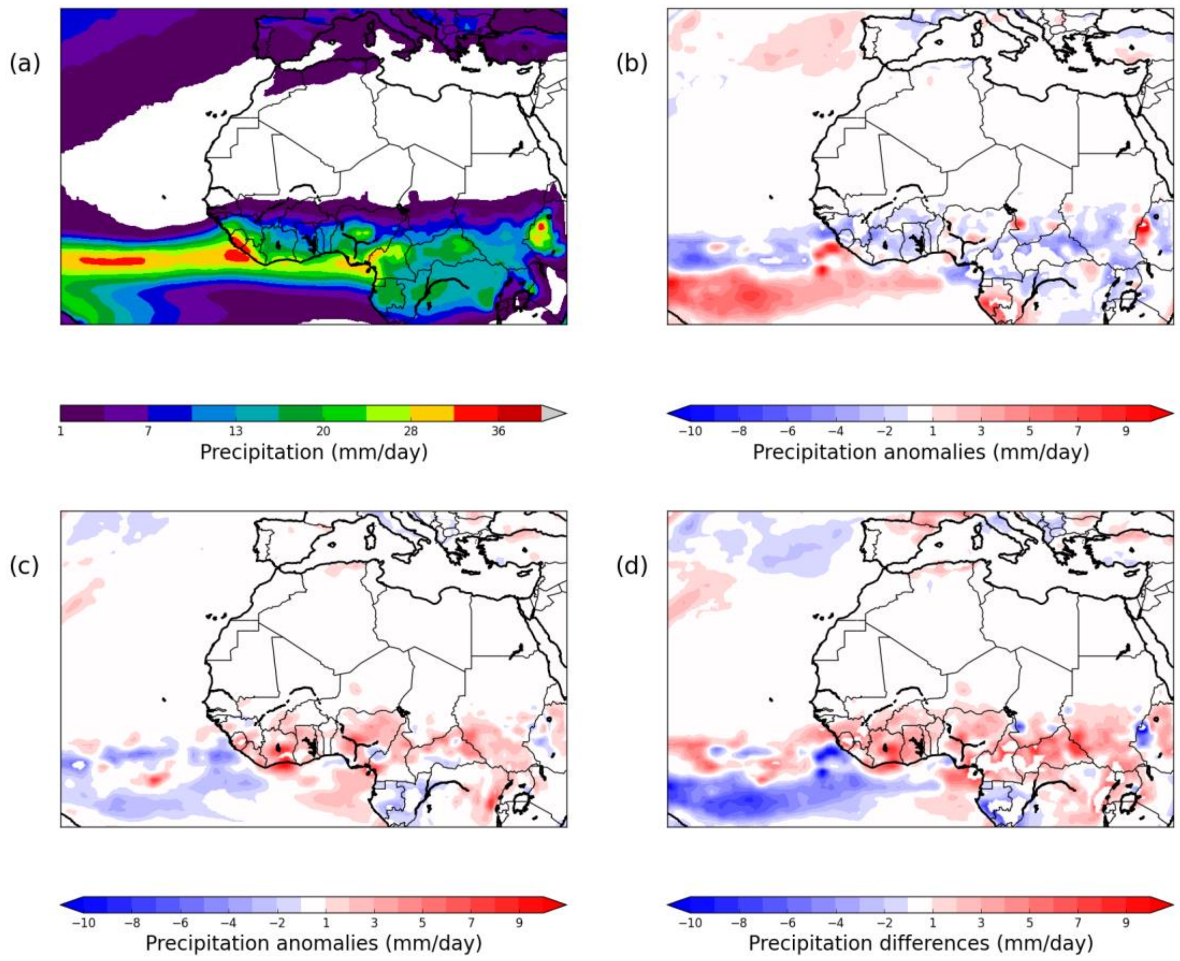

Figure 4.3 - (a) Mean daily precipitation values (mm) for the period 23 May–12 June 1979-2014 as well as anomalies for (b) favourable MJO years and (c) inhibiting MJO years. Differences between inhibiting and favourable MJO years are given in panel (d).

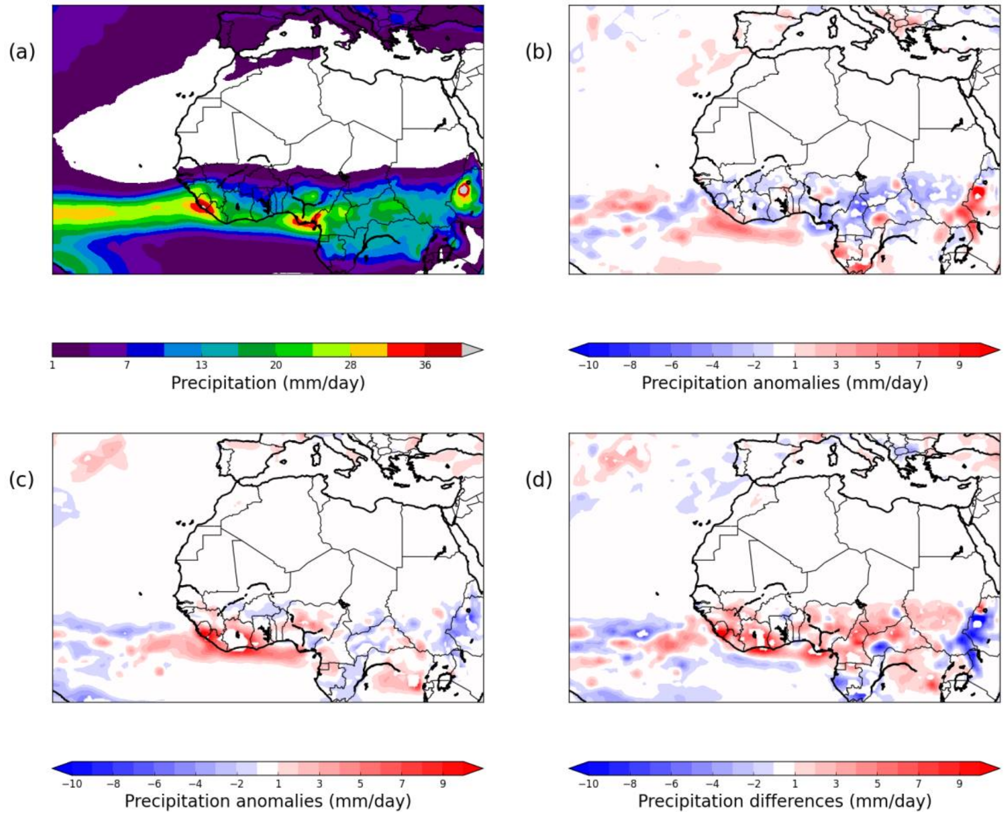

Figure 4.4 - As for Fig. 4.3 but for the period 13 June - 2 July.

From Figs. 4.3 and 4.4 it appears that the MJO substantially affects precipitation across West Africa. Favourable MJO conditions are likely to maintain the maximum precipitation zone about the GoG and thus less precipitation will occur over the continent leading to potentially later local onset dates. Although given known errors of precipitation estimates within re-analysis data, this result should not be taken verbatim. A comparison of precipitation totals from the ERA-Interim and the higher resolution TRMM v7 datasets over the two time periods studied shows that the inter-annual variability over the ocean is almost universally statistically significant (to at least the 90% confidence level, not shown). Over the continent, there is more variability in the agreement between datasets with little of the Guinea Coast showing statistically significant correlation (to at least the 90% confidence level). This result suggests that precipitation over the continent in ERA-Interim may not be representative of observational differences.

In order to further establish the nature of the dipole structure found in Figs. 4.3 and 4.4, OLR and dew-point profiles across West Africa have been assessed. This gives the added advantage of analysing whether the dipole found for precipitation data exists for other metrics and datasets.

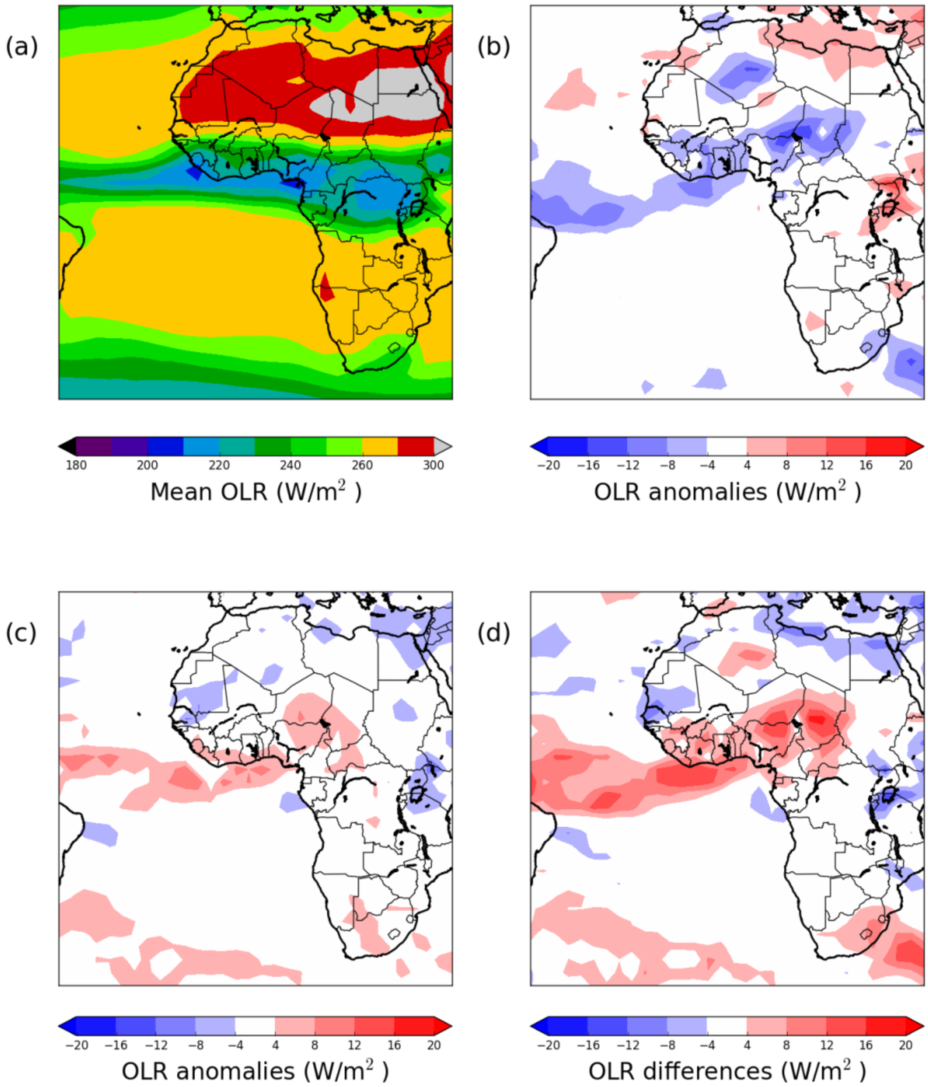

Figure 4.5 – (a) Mean OLR values (W m^{-2}) for the period 23 May–12 June 1979-2014 as well as anomalies for (b) favourable MJO years and (c) inhibiting MJO years. Differences between inhibiting and favourable MJO years are given in panel (d).

Figure 4.5 shows the mean OLR values for the years 1979–2012 (Fig. 4.5a), as well as anomalies in favourable MJO years (Fig. 4.5b), inhibiting MJO years (Fig. 4.5c) and the difference between inhibiting and favourable MJO years (Fig. 4.5d) across the observation period. As expected, the zonal minimum in OLR is coincident with the zonal maximum in precipitation (compare Figs. 4.3a and 4.5a) reaffirming the location of the ITCZ. Around the ITCZ, lower OLR values suggest that convection is enhanced in favourable MJO years (Fig. 4.5b) whereas in inhibiting years, convection over this region may be weaker (Fig. 4.5c). This is in agreement with the anomaly plots seen for precipitation around this time.

Interestingly, there are also lower OLR values present across the approximate position of the SHL for favourable years whilst the opposite is not seen for inhibiting years. This may suggest a spatial variability to the MJO impact on the West African climate for different MJO conditions. Finally, in agreement with Flaounas et al. (2012b), there are contrasting anomalies between the Mediterranean and coastal West Africa found in both Fig. 4.5b and 4.5c indicative of the teleconnection found previously.

Given the impact of the MJO on precipitation and OLR, it is important to assess how surface pressure and available column water are impacted by the MJO. At its most basic level, the WAM onset has been shown to be a response to the pressure gradient between the SHL and the Guinea Coast, bringing moisture into the Sahel, reducing convective inhibition and increasing the potential for convection and precipitation through the Sahel (Peyrillé et al. 2016). The MJO therefore can have a considerable impact on the whole WAM system by altering this pressure gradient.

Figure 4.6a shows the mean surface pressure and 10-metre wind fields across the studied period, Fig. 4.6b and 4.6c give anomaly plots for favourable and inhibiting MJO years respectively and Fig. 4.6d shows pressure and wind differences for inhibiting minus favourable years. Figure 4.7 shows the same plots for total column water (TCW).

The mean wind patterns (Fig. 4.6a) show southerly winds across the Gulf of Guinea towards to Guinea Coast feeding the maximum zone of precipitation which is centred on 5°N at this time (as seen in Fig. 4.3a). The maximum zone of TCW is also distinguishable about this latitude (Fig. 4.7a). Similarly, the regional minimum in TCW is located near to the SHL. The latitudinal range of particularly high TCW values is arguably wider than for high precipitation totals (compare Fig. 4.7a to Fig. 4.3a). Finally, there is evidence of the northerly trade winds across the eastern Atlantic Ocean which curve inland around Senegal and Guinea. This northerly to westerly wind pattern potentially feeds eastward moisture flux into continental West Africa which may be correlated to precipitation (Lélé et al. 2015; their Fig. 9).

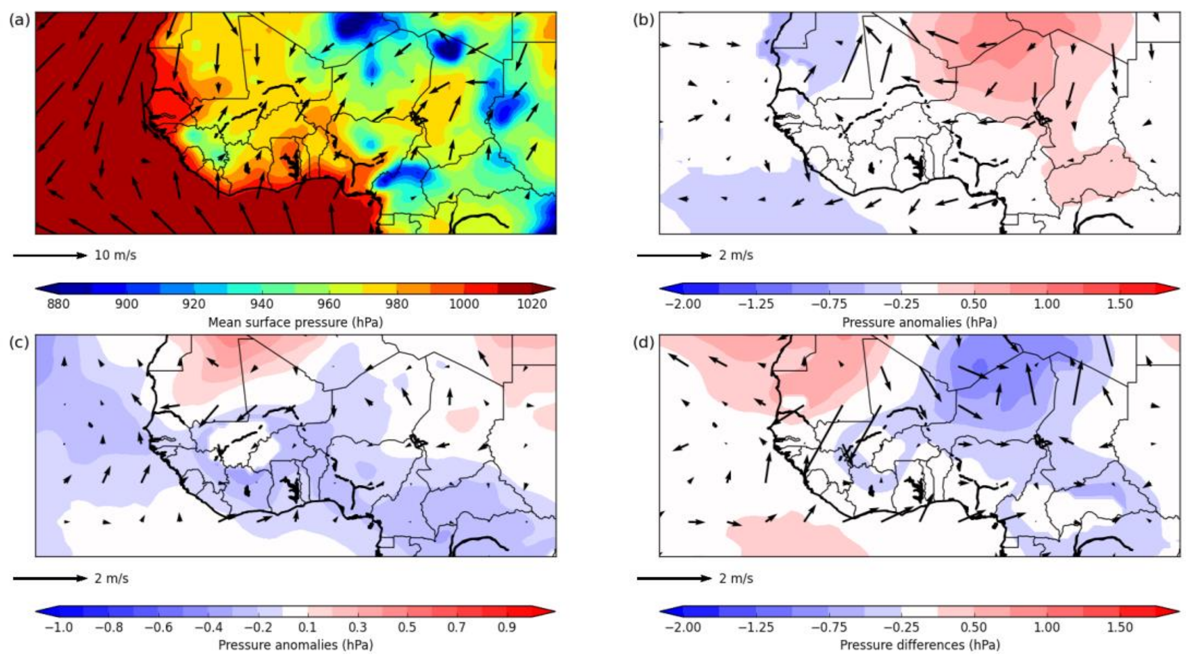

Figure 4.6 – Surface pressure and 10-metre wind anomalies for favourable and inhibiting MJO conditions. Panel (a) mean surface pressure and 10-m horizontal winds for period 23 May–12 June for the years 1979–2014. Panels

(b) and (c), mean surface pressure and horizontal wind anomalies for the period 23 May–12 June for favourable and inhibiting MJO conditions respectively. Difference between panels (c) and (b) are presented in panel (d).

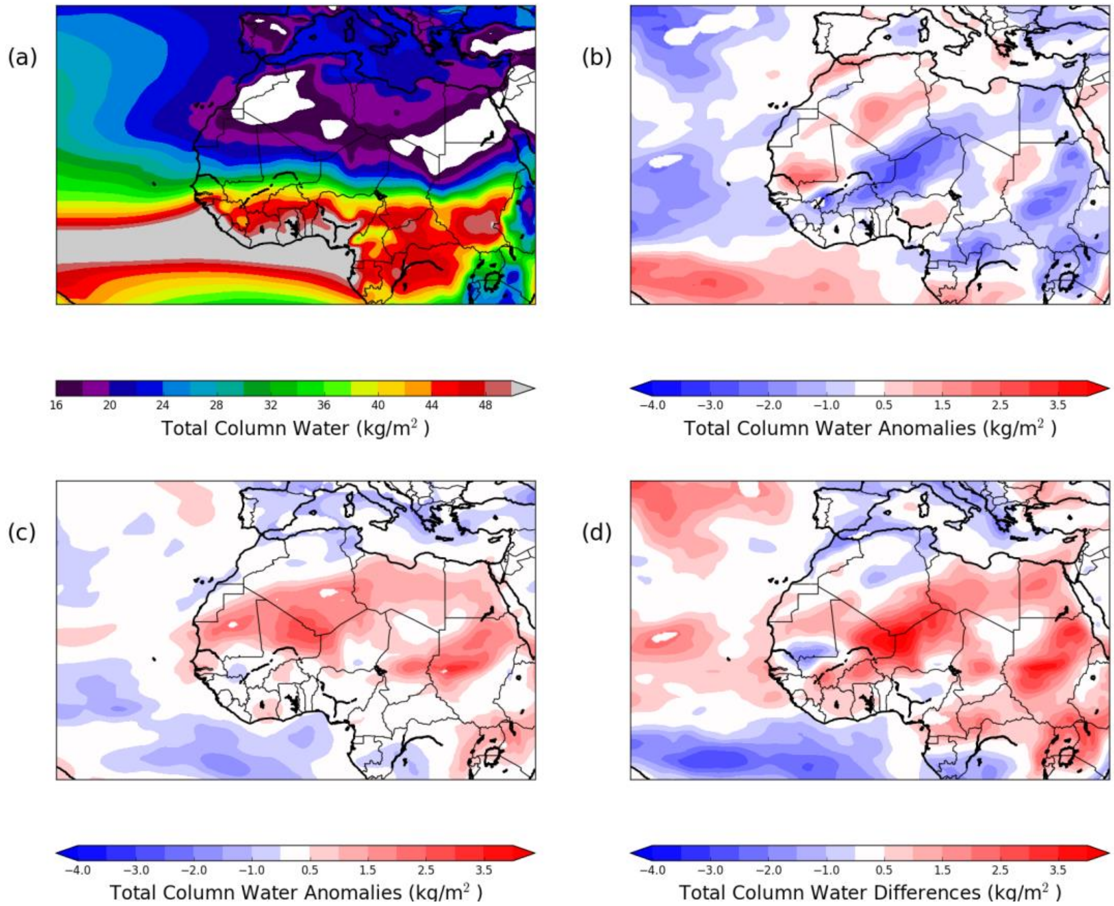

Figure 4.7 – (a) Mean total column water values (kg/m^2) for the period 23 May–12 June 1979-2014 as well as anomalies for (b) favourable MJO years and (c) inhibiting MJO years. Differences between inhibiting and favourable MJO years are given in panel (d).

Surface pressure anomalies show a sharp contrast between favourable and inhibiting MJO years (Figs. 4.6b and 4.6c). In particular, favourable MJO conditions appear to be synonymous with a high pressure over the SHL region and lower pressures over parts of the tropical eastern Atlantic Ocean (Fig. 4.6b). Wind anomalies for favourable years also suggest that there is slightly weaker southerly wind flow during the observation period compared to climatology. For inhibiting MJO years (Fig. 4.6c), whilst there is no significant change in surface pressure over the SHL region, there are lower surface pressure values over much of the continent (south of approximately 10-15N), and off the coast of West Africa. These pressure values are coupled with an implied stronger southerly surface wind flow. The dipole-type response seen in previous metrics is observed here (Fig. 4.6d). The differences seen in Fig. 4.6d suggest that MJO impacts the pressure gradient between the Guinea Coast and the SHL, potentially promoting increased low level flow into the Sahel when coastal convection is inhibited.

TCW anomalies are in agreement with other metrics, although the anomalies are more spatially variable than surface pressure or OLR anomalies. In favourable MJO conditions (Fig. 4.7b), there is higher TCW over the Gulf of Guinea than climatological average with the opposite seen in inhibiting years (Fig. 4.7c). Furthermore, in favourable MJO years there is a large region of lower than average TCW found from Mali to northern Niger. This lower than average moisture total could be a cause of later than average local onsets over this region as it is located slightly north of similar precipitation anomalies (see Fig. 4.3). Likewise, to the north of the TCW maximum, there are higher than climatological TCW values found when the MJO inhibits coastal convection. Again, this is similar to precipitation anomalies and may suggest that conditions suitable for local onset exist across the Sahel earlier when the MJO restricts deep convection over the Guinea Coast.

The difference between favourable and inhibiting MJO years shows an apparent land-ocean contrast (Fig. 4.7d). There are consistently greater TCW totals over the continent when coastal convection is inhibited with the opposite true over the Gulf of Guinea. Schematically, this suggests that favourable MJO conditions create a more compact ITCZ effectively starving the Sahel of early season monsoon moisture and associated potential for precipitation.

Figure 4.8 shows the low level (925 hPa) temperature anomalies for favourable and inhibiting MJO years as well as the long term average temperature during the observation period. The mean temperature pattern agrees with the pressure gradient presented in Fig. 4.6 with lower temperatures (high pressure) over the Gulf of Guinea and higher temperatures (coupled with lower pressure) further north into the continent (Fig. 4.8a). During favourable MJO years (Fig. 4.8b), there is an apparent increase in low level temperatures over the equatorial tropical Atlantic Ocean and aligned across the southern coast of West Africa. These positive temperature gradients cover a large part of the Sahel as well including Senegal and southern Mali. The opposite effect over this region is seen in inhibiting MJO years with lower temperatures across much of the same region (Fig. 4.8c). The difference between favourable and inhibiting MJO years (Fig. 4.8d) is most pronounced around the Gulf of Guinea and the coastal region around 5°N. Higher temperatures over the GoG in favourable years may act to reduce the pressure gradient between the GoG and the SHL and thus reduce the northwards transport of moisture towards the Sahel prior to the regional monsoon shift in late June. The results of Figs. 4.6 and 4.8 suggest that this situation may be in partially controlled by the MJO given the existence of significant differences in temperature and pressure profiles during different MJO conditions.

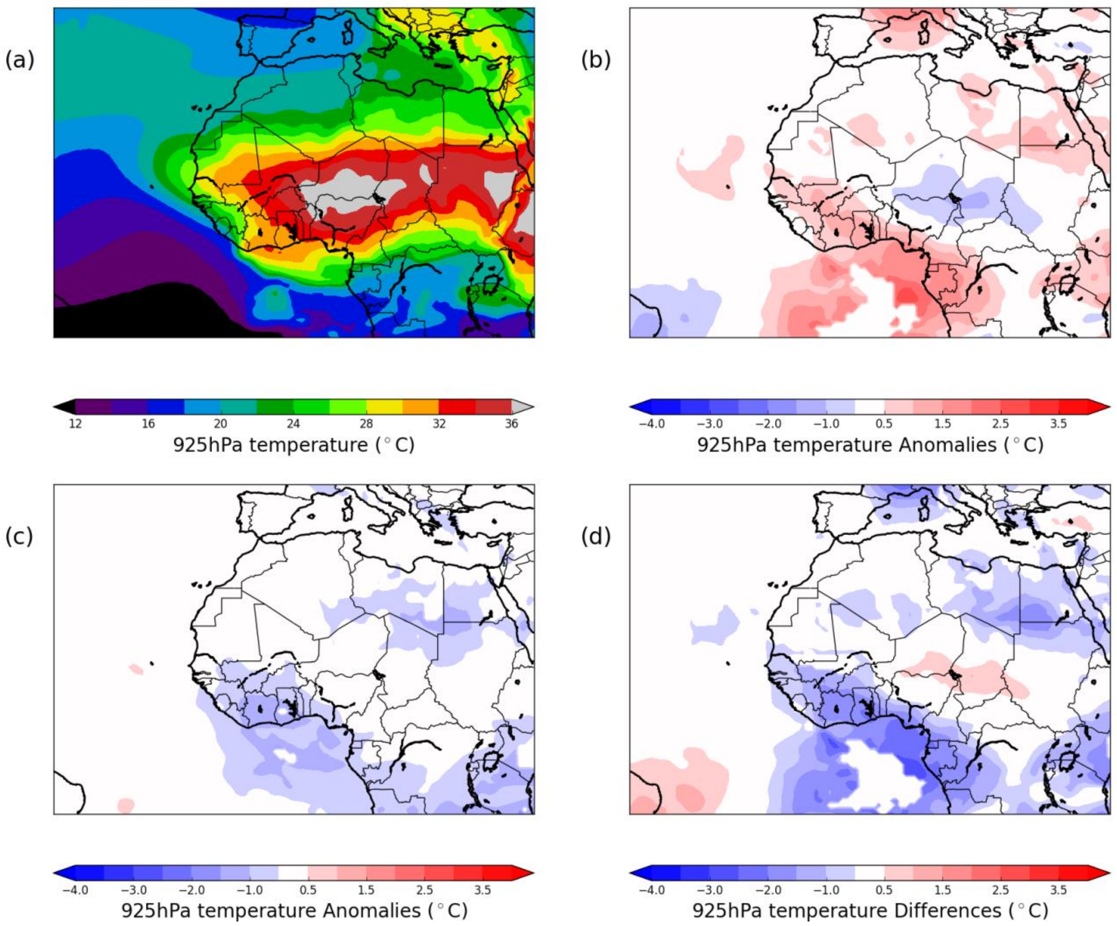

Figure 4.8 – (a) Mean 925hPa temperature values (°C) for the period 23 May–12 June 1979-2014 as well as anomalies for (b) favourable MJO years and (c) inhibiting MJO years. Differences between inhibiting and favourable MJO years are given in panel (d).

Finally, we observe the MJO's impact on convergence (or synonymously divergence) and vertical velocity (w) through the *monsoon region* (taken here as 10°W–10°E). It is important to stress that convergence and vertical velocity fields from re-analysis data will not be able to capture the complete impact of the MJO particularly on localised or sub-grid cell convergence (Birch et al. 2014a,b). There is also a cause and effect relationship between convection and convergence meaning that increased convergence by itself cannot be seen as a cause of increased convection or ultimately precipitation. The study of convergence and vertical velocity profiles here does allow for a more holistic view of the MJO impact on the WAM during the transitional stage however and is thus worth examination.

Figure 4.9 shows the mean vertical zonally-averaged cross section of divergence across the monsoon region during the observation period (Fig. 4.9a), favourable and inhibiting MJO year anomalies (Fig. 4.9b and 4.9c), and the difference between both sets of years (Fig. 4.9d). Figure 4.10 shows the same results for vertical velocity.

In Fig. 4.9a, there is a region of deep divergence through the troposphere between 5–10°N with an associated region of convergence located north of this denoting the maximum convergence zone. Note that the maximum convergence zone as shown here is located to the north of the maximum precipitation belt and closer to the zone of maximum TCW. There is also a region of downwards vertical movement through the atmosphere (analogous to deep suppression) seen across the entire pressure column around 5°S with negative w (deep convection) throughout the vertical column seen from 0–5°N (Fig. 4.10a). This is analogous to the structure of the coastal monsoon phase described by Thorncroft et al. (2011) and thus we consider ERA-Interim to be reasonably reliable at capturing the main vertical velocity features relative to the WAM.

Anomaly plots of convergence show that in general, favourable MJO years are associated with enhanced low to mid-level convergence south of 15°N which is the approximate northwards limit of the monsoon during this period (Fig. 4.9b; Sultan and Janicot 2003). By contrast, who the MJO inhibits convection over West Africa, there is much greater divergence over the region (Fig. 4.9c). This is consistent with the findings of Flaounas et al. (2012b) where the IM onset leads to dry air intrusions across the whole West African continent supressing deep convergence. Relating this result to precipitation anomalies (Fig. 4.3c) may suggest that the cause of increased precipitation in inhibiting MJO years across the Sahel is a result of isolated and violent storms rather than an increase in storm frequency.

Anomalies of vertical velocity in favourable and inhibiting MJO years suggest that there is a reduction in upwards transport near the ITF (15°N) in favourable MJO conditions coupled with an increase in upwards velocity near the equator (Fig. 4.10b). This reinforces the idea that the maximum rain belt and convergence zone may be more compact in favourable MJO years. In inhibiting MJO years (Fig. 4.10c), the magnitude of upwards velocity in the region 5–15°N is generally the same or greater than climatology suggesting increased upwards motion over continental West Africa between the GoG and the ITF. There is also a potential weakening of the subsiding branch of the Hadley circulation at 200–400hPa around 10–15°N. These anomalies suggest that there is less suppression over continental West Africa in inhibiting MJO years and the potential for increased convective activity. The fact that Figs. 4.10b and 4.10c are not directly opposite in sign suggests that the MJO may impact the WAM system differently depending on the phase of the MJO.

Figure 4.9d shows that in inhibiting years there is greater divergence and lower convergence seen across almost all of West Africa compared to favourable years. However, around 15°N (the approximate ITF location), there is greater convergence in inhibiting MJO years. This result is consistent with the strengthening of the pressure gradient between the Guinea Coast and the SHL seen previously (Fig. 4.6d). When considering vertical velocity, there is evidence of a three-region response to the MJO. Around the equator, inhibiting MJO years reduce coastal convection. Between 5 and 15°N, there is increased upwards velocity in late years.

Finally, north of the ITF (15°N), there is again increased suppression (or reduced convection) in inhibiting MJO years. Relating this to precipitation suggests that in favourable MJO years potential for societally-useful precipitation over the Sahel may be lower.

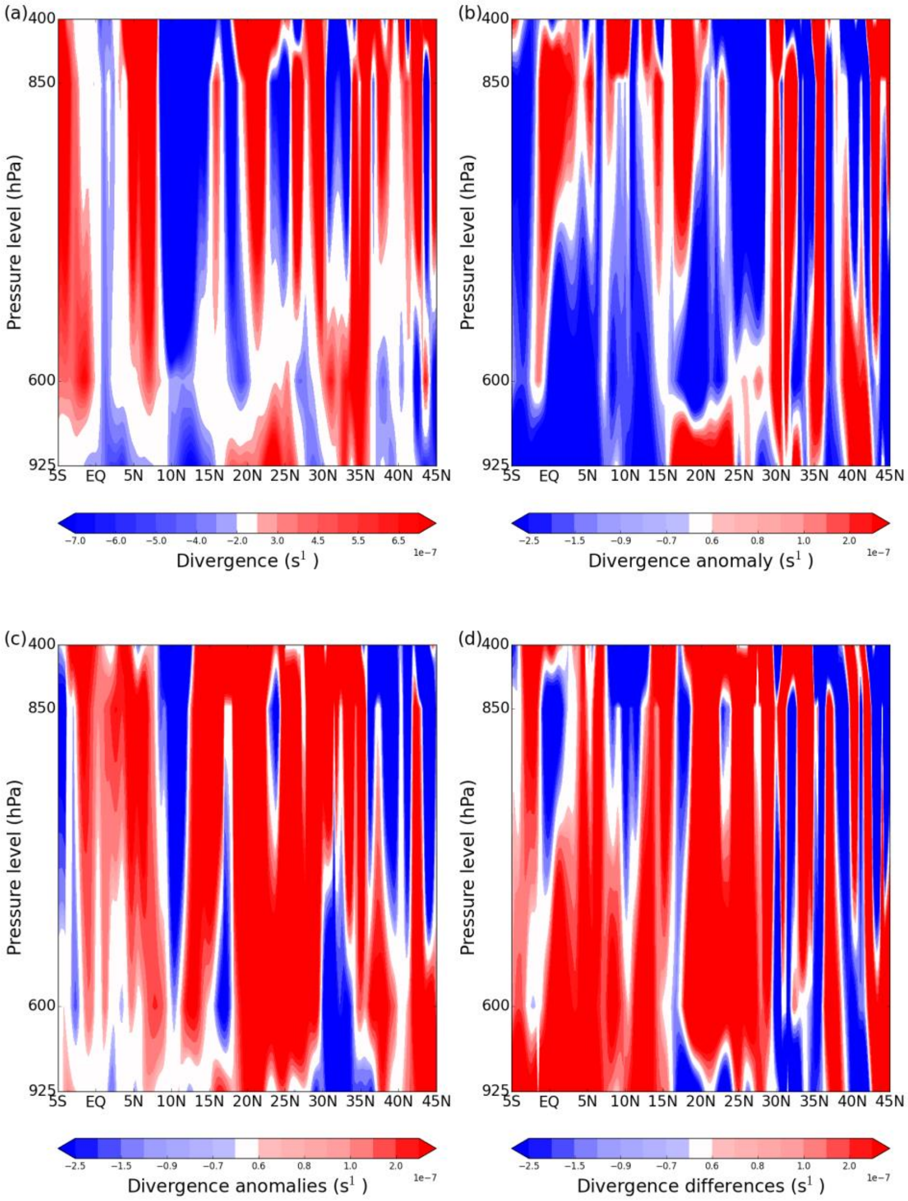

Figure 4.9 – Cross section of tropospheric convergence (blue) and divergence (red) for favourable and inhibiting MJO years. Panal (a) – mean zonally-averaged (from 10°W-10°E) divergence fields from 925–400 hPa for the West African region across all years studied. Anomalies from climatological means are given in panels (b) and (c) for favourable and inhibiting years. Panel (d) gives the difference between inhibiting and favourable MJO conditions.

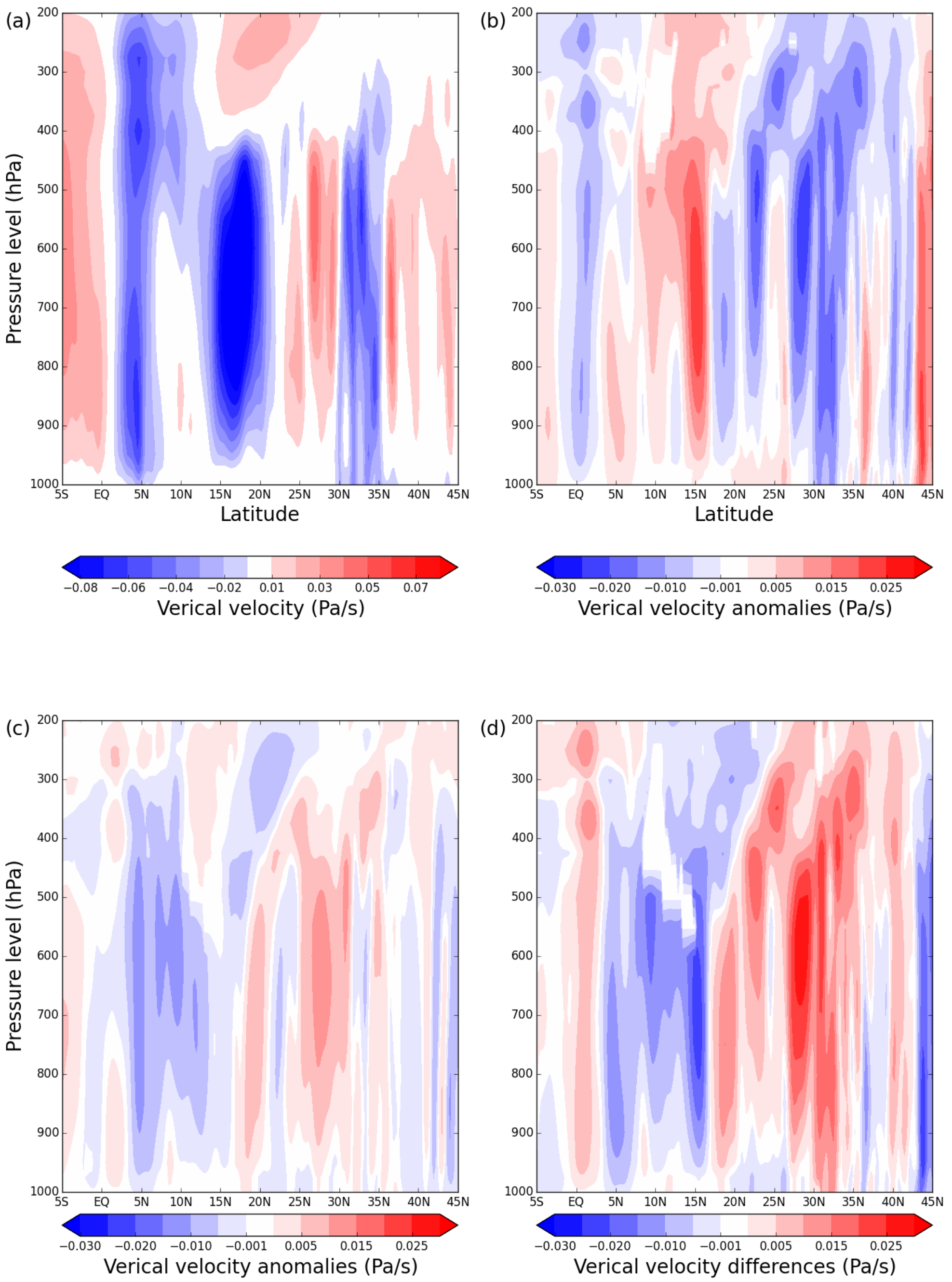

Figure 4.10 – Cross section of vertical velocity, *w*, (blue values for upwards velocity, red values for downwards velocity) for favourable and inhibiting MJO years. Panal (a) – mean zonally-averaged (from 10°W-10°E) vertical velocity from 1000 hPa to 200 hPa for the West African region across all years studied.

Anomalies from climatological means are given in panels (b) and (c) for favourable and inhibiting years. Panel (d) gives the difference between inhibiting and favourable MJO conditions.

4.1 Summary

The MJO can be seen to affect the state of the WAM around the time of the IM onset and transitional regional WAM phase. Between 5 and 15°N, there is decreased precipitation and lower OLR in favourable MJO years. The pressure gradient between the GoG and the Sahara also appears to be reduced in favourable years. There is an apparent contrast in favourable years between the tropical eastern Atlantic around the equator (where convection is enhanced) and the region between the GoG and the ITF (where convection is reduced) for favourable MJO years.

Schematics of how the MJO affects the WAM climate when in phases 2–5 (favourable years) and 6–1 (inhibiting years) are presented in Figs. 4.11 and 4.12 respectively. When the MJO favours convection over the GoG (Fig. 4.11), there is increased ascent at 5°N with higher rainfall at and to the south of this latitude. Lower OLR over this region is coupled with a lower surface pressure and higher total column water (TCW). There is a reduced pressure gradient between the GoG and the SHL leading to a weaker shallow meridional circulation (SMC) and less available moisture within the Sahel. There are few storms and little precipitation over the Sahel in favourable MJO years suggesting that local onset dates are likely to be later.

By contrast, when the MJO inhibits coastal convection (Fig. 4.12), there is less deep convection and lower precipitation south of 5°N. Higher surface pressure over this region drives a stronger SMC feeding moisture further northwards. Although there is increased moisture over the Sahel during inhibiting MJO years, there is still high descent and divergence over this region. Therefore, a high convective inhibition environment is still in place over the Sahel. Convective storms during this period are therefore likely to be relatively isolated, unorganised and potentially quite intense. Therefore, whilst conditions suitable for persistent rainfall necessary for local onset triggering may not be present during the observation period for inhibiting years, conditions suitable for earlier than average local onset may be installed over the Sahel during this time.

Previous works have suggested that the MJO and associated dry-air intrusions aid to “switch off” convection over the Guinea Coast during the monsoon transitional stage (Janicot et al. 2009; Flaounas et al. 2012b; Mohino et al. 2012). We suggest that the MJO may act as a “gatekeeper” akin to the findings of Flaounas et al. (2012b), with high coastal convection limiting the conditions suitable for precipitation across the Sahel. There is evidence that the MJO state can prime the regional shift in the ITCZ during the transitional stage; although the MJO is not considered the sole cause of regional onset.

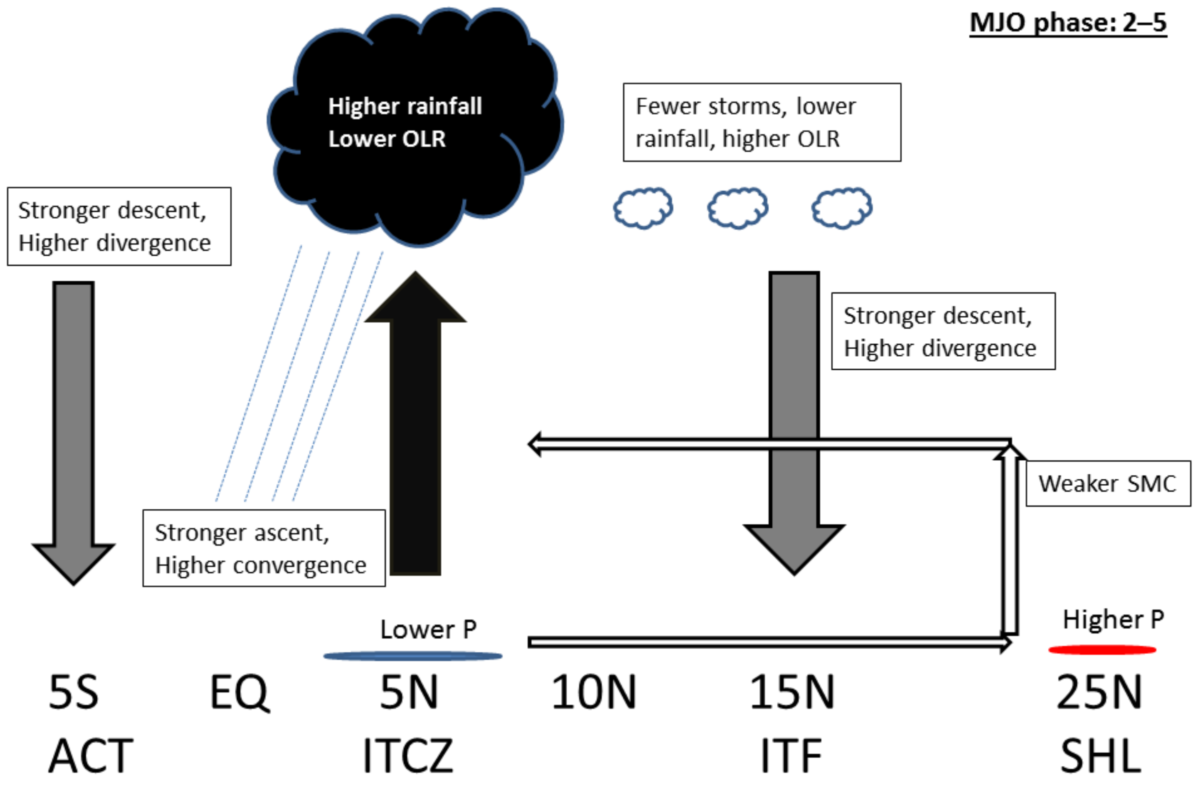

Figure 4.11 – Schematic of the relative impact (to climatology) of the MJO on West Africa when the MJO favours deep convection over the Guinea Coast (i.e. phases 2–5). ACT is the Atlantic Cold Tongue, ITCZ is the Inter-Tropical Convergence Zone, ITF is the Inter-Tropical Front, SHL is the Saharan Heat Low, OLR is Outgoing Longwave Radiation, SMC is the Shallow Meridional Circulation and P is surface pressure. Arrows denote regions of ascent (or descent) and the northerly flow. Shadings are indicative of the strength of the monsoon flow relative to climatology with white denoting weaker flow than climatology, and black denoting much stronger than climatology.

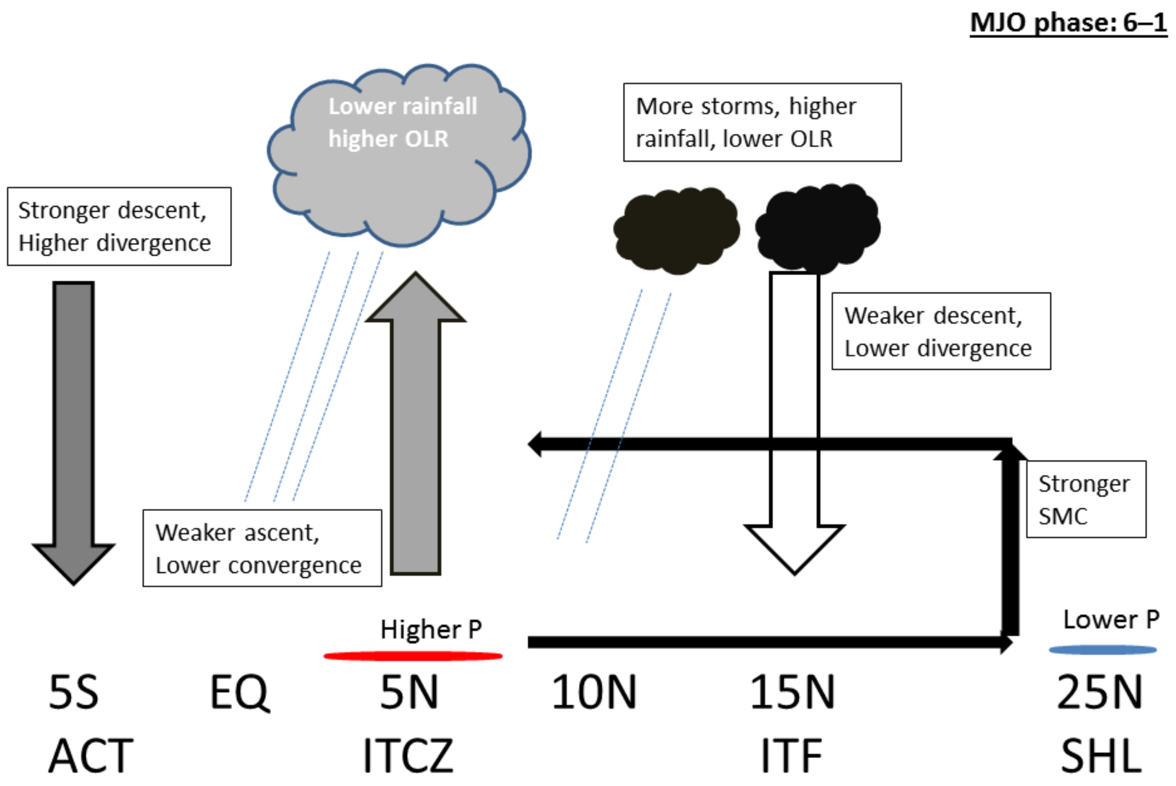

Figure 4.12 – As for Fig. 4.14, for MJO phases 6–1 (i.e. coastal convection over West Africa is inhibited).

Figures 4.11 and 4.12 coupled with the findings of this chapter suggest the existence of an apparent dipole like structure to the West African climates response to different MJO conditions with a rough demarcation point around the latitude of the ITF (although further south for precipitation). The reason for this dipole-like structure in precipitation, OLR, TCW and surface pressure fields is not fully understood. It is probable that the maintenance of the maximum rain belt near 5°N during the coastal monsoon phase is controlled by many factors occurring at multiple scales including the MJO (Birch et al. 2014b). Finally, for vertical velocity anomalies, there is a distinction between the MJO's effect on coastal convection and continental convection south of the ITF. Whilst the results presented above state the argument that the MJO is a key driver of WAM variability, the exact method by which different controls interact to modulate the WAM requires deeper consideration.

5. Analysis of MJO influence across LORs

Section 4 provided a regional view of the MJO's influence across West Africa. Here, the analysis is extended to focus on how the MJO can modulate more localised processes, particularly across LORs.

5.1 Comparison between MJO phase and local onset dates

We can subjectively analyse the likelihood that an early or late local onset date occurs during favourable or unfavourable MJO years. Table 4.2 lists the earliest and latest local onset years found for the five LORs in Fig. 4.1. In addition to the favourable and inhibiting MJO years previously listed (which are highlighted in bold green or red respectively in Table 4.2) the years 2011 and 2012 are considered conditionally inhibiting MJO years (as they only just miss the threshold set). Likewise, 2000 and 2007 are adjudged to be conditionally favourable years. These conditional years are highlighted with red and green font respectively. From Table 4.2, we can make some preliminary observations of the potential link between the MJO and local onset dates.

Table 4.2 – Early and Late onset dates in the five LOR regions and their comparison to MJO activity. Green and red filled dates are years that have been highlighted as favourable or inhibiting respectively in Fig. 4.2. Green and

red text dates can similarly be considered favourable or inhibiting MJO years, despite not meeting the specific threshold set from Fig. 4.2.

Region	Early onset years	Late onset years
Coastal	2001,2005,2008,2010	1998,2007,2009
Mali/Burkina Faso	2008,2012,2014	1998,1999,2000,2002,2009,2013
Benin/Nigeria	1998,2003,2010,2012	1999,2011,2013,2014
Niger/Nigeria	2003,2004,2010,2012	2002,2007,2014
Cameroon Highlands	2004,2006,2012	1998,2002,2008,2009

Of the 17 years of onset observed in the TRMM v7 dataset no early onset in the CT LOR occurs during a favourable MJO year. Likewise, no late CT onset occurs in an inhibiting year. Over the MBF LOR it is also true that no early onset dates occur during favourable MJO years. Likewise, no late onsets occur when the MJO inhibits deep convection over the Guinea Coast. However, a more mixed pattern is seen for the BN, NN and CH regions where early (or late) onsets occur during different MJO conditions. Monte Carlo simulations suggest that the link between late onset years and favourable MJO conditions is significant to the 95% confidence interval over the CT region and to the 80% confidence interval over the MBF region. Similarly there is a significant link (95% confidence interval) between late onset and inhibiting MJO conditions across the BN region. Finally, the link between early onset years and inhibiting MJO conditions is also significant to the 95% confidence interval over the MBF region. From Table 4.2, it is possible to hypothesise that there may be a link between the MJO and suitable conditions for early or late agronomic onsets across certain regions of West Africa.

The years 2011 and 2012 are in contrast with one another. For both years, there is a preference for the MJO to inhibit convection over the Guinea Coast. In 2011 there are average or late onsets in the MBF, BN and NN regions whereas in 2012 each of these regions has an earlier than average onset. The reason for this difference deserves special interrogation and will be the focus of future work. This result does however allow us to conclude that there is no guarantee of early or late onset dates across LORs given knowledge of the MJO state. A combination of factors are expected to control local onset variability across West Africa (such as sea surface temperatures, localized variability, African Easterly Waves etc.) and thus it is to be expected that the link between the MJO and local onset dates is not simple.

From the above findings we summarize that the MJO may have some effect on agronomic onset dates, however the link is not sufficient to state the MJO is a predictor of local onset dates. Precipitation is dependent on a combination of atmospheric conditions and it is not surprising that there is no explicit link between a large scale convective signal and localized precipitation even using non-arbitrary boundaries such as LORs. It is therefore useful to analyse how the MJO may impact the conditions that favour local onset across West Africa to gain a more holistic appreciation of any potential link.

5.2 Impact of the MJO on vertical motion profile across LORs

Section 4 highlighted the impact of different MJO conditions on the vertical velocity profile across the *monsoon region* longitudinal band. In a similar manner, the vertical velocity profiles across the MBF and NN LORs are considered.

5.2.1 Vertical velocity profile across the MBF LOR

Figure 4.13 shows the same four results as Fig. 4.10 with zonal-averaging performed across the longitudinal bounds of the MBF region. Figure 4.13a shows a similar result to Figs. 4.10a. There is descent over the region around 5°S with ascent over the expected latitude of the maximum convergence zone (5°N) and the ITF (15°N). There is also evidence of the descending Hadley Cell circulation in a similar location to that found in Fig. 4.10a. As for Fig. 4.10, we consider ERA-Interim a suitable representation of vertical velocity for comparative purposes.

Anomaly plots for the MBF region are similar to those for the monsoon region (compare Figs. 4.10b-c with Figs. 4.13b-c) with favourable years indicative of increased ascent over the equator and decreased ascent (or increased subsidence) around the ITF. Likewise during inhibiting MJO years, there is increased upwards motion across the latitude band 5-15°N for the MBF region.

The differences between inhibiting and favourable years (Fig. 4.13b) reinforce the findings of Figs. 4.13b and c with increased convection over the equator in favourable MJO years, increased convection between 5 and 15°N for inhibiting MJO years and decreased suppression over the SHL region in favourable years.

The impact of the MJO on vertical velocity across the MBF region appears similar to the findings presented for the monsoon region in Section 4. When the MJO enhances coastal convection, there is increased descent over the Sahel around the

MBF region. This lack of ascent means that the conditions suitable for large-scale, deep convection to occur are not present about the MBF LOR and thus later median onset occurs. The MJO may therefore provide insight into the relative timing of onsets over this region.

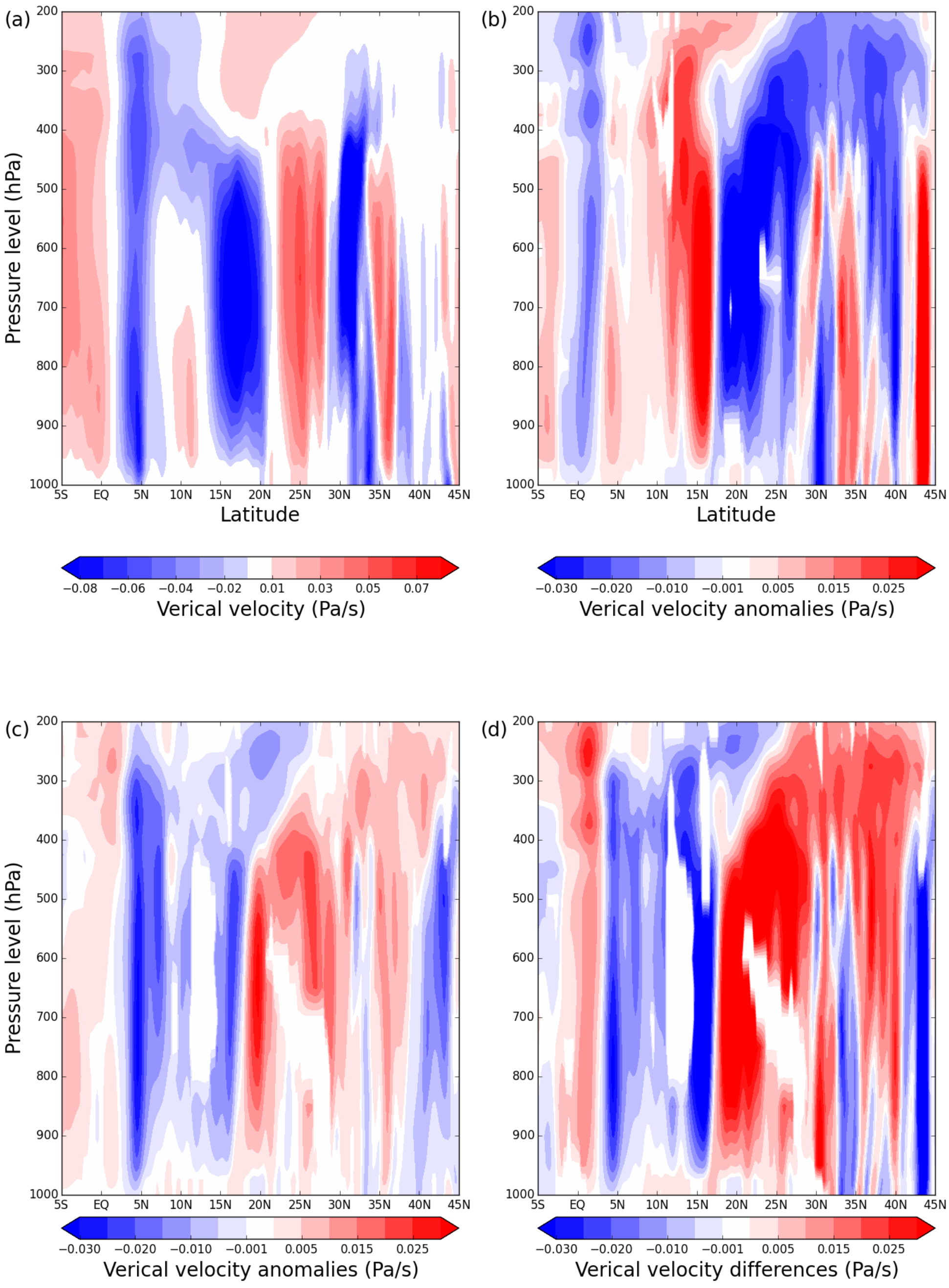

Figure 4.13 – As for Fig. 4.10, but with zonal averaging only done on the longitude bounds of the MBF LOR region (7.5–4°W).

<u>5.2.2 Vertical velocity profile across the NN LOR</u>

Figure 4.14 provides the same assessment as Figs. 4.10 and 4.13 across the longitudinal bounds of the NN LOR. The results of Fig. 4.14 contrast with those of Figs. 4.10 and 4.13 in several ways.

Climatological averages show a wide band of ascent from the equator into continental West Africa as well as evidence of the descending Hadley cell branch and a region of deep suppression in the north of Africa. The northwards extent of negative vertical velocity values (synonymous with convection) stretches further north in Fig. 4.14a than in either 4.10a or 4.13a (approximately 25°N). There is also no evidence of a region of descent around 5°S which was seen in Figs. 4.10a and 4.13a. This is to be expected given that there is no oceanic body of water present around 5°S for the NN longitudinal band.

In favourable years (Fig. 4.14b) there is a decrease in the ascent seen from the equator to 25°N in Fig. 4.14a coupled with increased suppression north of 25°N. The conditions indicated in Fig. 4.14b suggest that there is less convection (both shallow and deep) across all latitudes in favourable MJO years. For inhibiting MJO years (Fig. 4.14c), the situation is less clear. There is general evidence that convection may be enhanced in the region from the equator to 20°N, however there are also latitudes where convection may be inhibited compared to climatology. The difference between inhibiting and favourable MJO years (Fig. 4.14d) shows that there is increased vertical motion for almost all latitudes south of 25°N and decreased subsidence north of this latitude when the MJO inhibits convection over the GoG compared to favourable years.

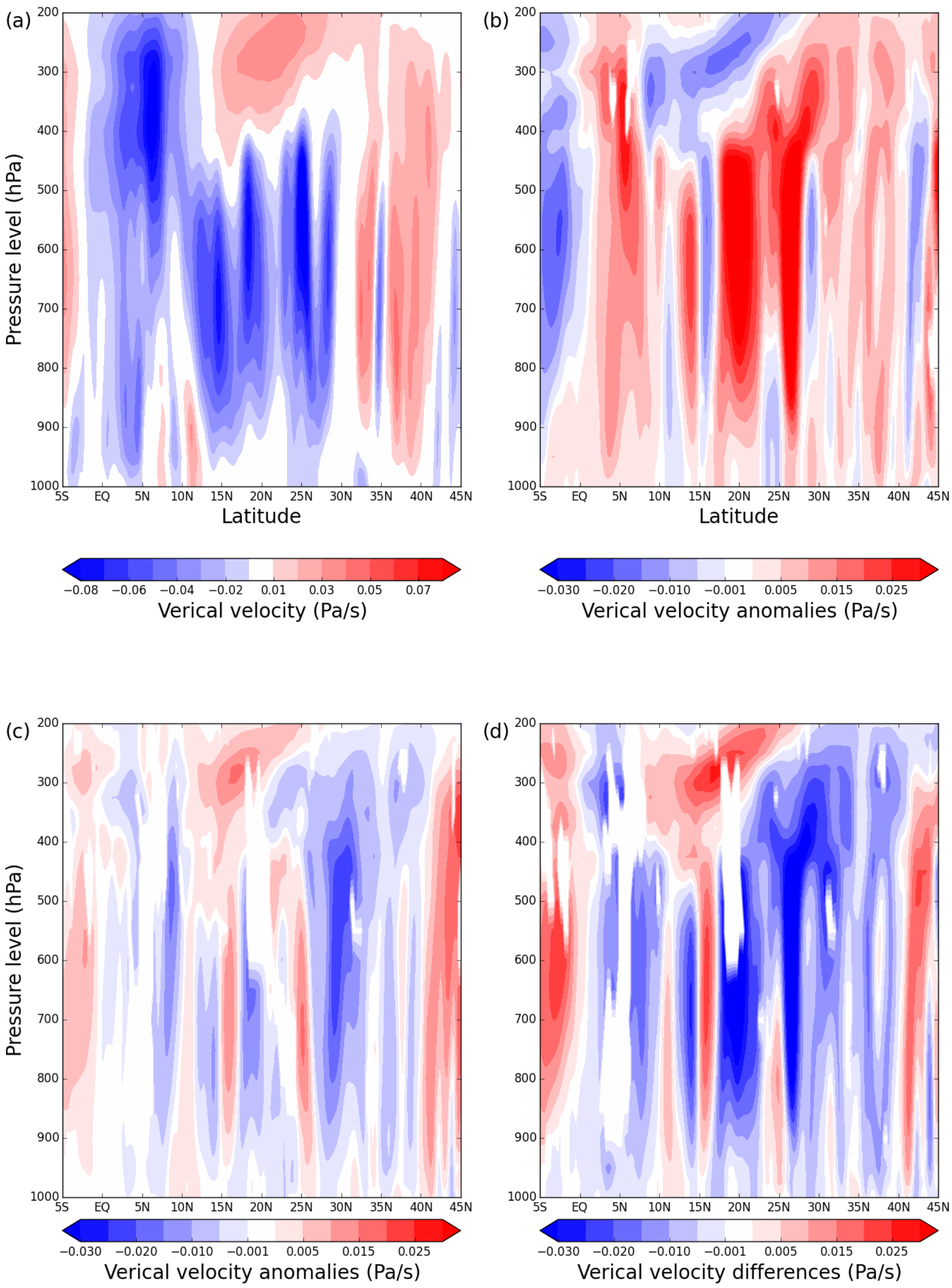

Figure 4.14 – As for Fig. 4.10 with zonal boundaries of the NN LOR region (7.25–10.5°E).

When considering the potential impact on localised precipitation and local onsets, we posit that favourable MJO years over the NN region are potentially more conducive to earlier than average onsets given the reduced inhibition over the Sahel (which is also suggested by Table 4.2). Given the findings of Figs. 4.3 and 4.14, it is possible that more frequent precipitation events occur in the NN region during favourable MJO years despite the fact that total precipitation is greater during inhibiting MJO years (as seen in Fig. 4.3). This is in contrast to the MBF region, where inhibiting MJO conditions are favourable for Sahelian ascent and convection.

6. Conclusions

The impact of the Madden-Julian Oscillation (MJO) on the West African Monsoon (WAM) has been the subject of considerable study. Here the impact of the MJO on the WAM and associated climatological metrics is assessed during late May and early June. Specific focus is given to the impact of the MJO across local onset regions (LORs; Fitzpatrick et al. 2016).

From a regional perspective, the MJO appears to have significant impact on several monsoon related metrics. Between the Gulf of Guinea and the approximate position of the Inter-Tropical Front (5–15°N), precipitation is decreased when the MJO favours convection over the Gulf of Guinea (south of 5°N). In addition there are higher OLR values (indicative of less deep convection) over this region and a weaker pressure gradient between the Gulf of Guinea and the Sahara. The opposite effect is seen when the MJO inhibits convection over the Gulf of Guinea. Despite the increase in precipitation over continental West Africa when the MJO inhibits convection over the Gulf of Guinea, zonal averages of convergence and vertical velocity suggest that rainfall during this period may be violent and intermittent owing to the high CIN environment. This result implies that an increase in early season precipitation may not always be coupled with early local onset dates and persistent rainfall necessary for crops.

Finally, a subjective link between the MJO phase and the relative timing of local onsets across LORs is presented. In general, late local onsets over the Sahel occur when the MJO predominantly favours convection over the Gulf of Guinea and vice versa. Although given the briefness of available high resolution precipitation data it is difficult to assess the long term trend of this relationship, the MJO phase in late May and early June may help highlight whether local onsets will be earlier or later than average.

Seasonal forecast products often struggle to capture the phase and intensity of the MJO. Given the results of this paper, we posit that this failure will inherently mean that prediction of local onset dates across West Africa will be limited. The accurate representation of the MJO within seasonal forecasting models should be considered a priority when attempting to improve onset forecasts across West Africa and would provide immediate benefit to West African forecast users.

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Chapter 5

Conclusions

Conclusions

The West African Monsoon (WAM) is a very complex system which is controlled by a variety of meteorological drivers occurring over various spatial and temporal scales. The WAM onset, a man made concept, is of substantial importance to forecast users across West Africa. As such, understanding and predicting the WAM onset is a key problem requiring immediate attention across the region. It is important that any work on the WAM onset provides clarity in its aims and offers measurable benefits to recognized forecast users within the region. The work presented here offers substantial new information on the variety of onset definitions in existence as well as how local onset definitions can be applied and potentially predicted. The work can therefore be considered of use for individuals and institutions interested in local farming.

Motivation within this work was given to improving forecast value with regards to the WAM onset. Whilst the consistency and quality of a forecast are regularly assessed, forecast value is a more complex topic which is rarely considered by forecasters. A full evaluation of forecast value requires in-depth studies in conjunction with *in situ* forecast users; however it is possible to subjectively determine how a forecast's value can be improved. This subjective assessment was made here and provided the motivation for the three articles presented in Chapters 2–4.

1. Key questions about the West African Monsoon

a. What is the WAM onset?

One of the largest sources of uncertainty in onset forecasts is the wide range of onset definitions available. In order for onset forecasts to be valuable there needs to be clarity provided by forecasters to forecast users. Furthermore, relevant to the work presented here, research needs to provide a consensus as to what exactly the WAM onset is in order to assist forecasters to evaluate model skill in predicting onset date. There is therefore a feedback required between forecast users, forecasters and researchers in order to best marry the needs of all three groups. Valuable progress in understanding the WAM onset requires consensus on the onset definition (or definitions) which are of high value to identified groups of forecast users. The first aim of this work was therefore to provide clarity into the variability of onset definitions.

In this work, we have presented one of the most comprehensive comparisons of published onset dates available for West Africa. There is a high level of subjectivity in certain onset definitions, a high level of inconsistency found for some onset definitions when calculated with multiple datasets, and a lack of agreement between local and regional onset dates. There are at least seventeen unique WAM onset definitions of which the regional onset definition presented by Sultan and Janicot (2003) appears to be the closest to a consensus (see Appendix A). However this definition may not be of use to certain forecast users. The main conclusions found in Chapter 2 have not previously been expressed in the literature and provide important insight for forecasters and forecast users.

The quality of a given onset forecast can be adjudged to be partially dependant on the observational dataset the forecast is measured against. This is particularly true for threshold based local onset definitions. It is necessary for the research and forecasting community to agree about the most representative observational dataset(s) for calculating monsoon onset(s). High-resolution datasets appear to give more realistic onset patterns (particularly for local onsets), however these datasets have relatively short histories. Given the lack of a spatially dense *in situ* observation network, it is difficult to calibrate satellite-based onset dates with rain-gauge data across large parts of West Africa leaving all work open to potential biases. In this work, the Tropical Rainfall Measurement Mission (Huffman et al. 2007) dataset is suggested as the most suitable precipitation dataset for future study.

Local and regional onsets have different mean timings and inter-annual variability. This is a key issue. Many sensitivity studies on the WAM onset reference the needs of farmers and other local forecast users within their core motivations, however then analyse the variability of the regional monsoon shift. This is contradictory as local farmers require knowledge at a specific and rather small-scale location. Regional onset knowledge is likely of little value to small scale farmers given the different timings and variability of local and regional onsets. Future work, influenced by this study, needs to focus on more localised onset metrics in order to provide valuable insight for the identified parties.

b. <u>Are local onset dates usable?</u>

A valuable onset needs to be usable (or practical). For local onsets this means that a semi-regional level over which onset variability can be studied is required as understanding, predicting and communicating local onset variability at the grid-cell level is not pragmatic. In this work, we derive and present a new approach to defining the level of spatial agreement of local onset dates using non-arbitrary boundaries.

Local Onset Regions (LORs, presented in Chapter 3) provide a different approach to determining spatial homogeneity of a given metric for a region. The spatial variability of local onsets has been assessed before (Marteau et al. 2009); although prior works typically give a general overview of onset agreement over national boundaries. Prior work therefore did not focus on maximizing spatial homogeneity.

Instead, LORs are focussed on the needs of the forecast users. Farmers require knowledge of the onset timing at their given location. This can either be an absolute onset date (e.g. onset will occur on the 8^{th} June), or an indicator of how early or late an onset will occur relative to local climatology (e.g. this year, onset will be later than average). LORs measure the maximum level of spatial consistency over which onset dates, or onset inter-annual variability are consistent. By utilizing these strategies two key results have been found.

Firstly, there is a usable level of spatial agreement in onset across large regions of West Africa. This is in direct contrast to prior work (particularly that of Marteau et al. 2009) who state that local onsets are too spatially noisy to be predictable. By highlighting LORs where a representative time series of onset dates can be used in sensitivity studies, more impactful future work can be produced of direct value to local forecast users.

Secondly, LORs are in the most basic form a visualization of the “signal to noise” over West Africa. A large region with similar inter-annual variability suggests that local noise in precipitation is not dominant in controlling the onset date; instead a more large-scale (and potentially identifiable and predictable) driver of onset exists. Similarly, regions where no LOR exists suggests that local precipitation noise dominates all regional signals; The size and coverage of LORs give a limit to predictability of local onsets. In some regions of West Africa, the local noise dominates local onset inter-annual variability thus no clear signal can be used as a predictor of onset.

The underlying methodology of LORs is important for future studies. By aiming methodology towards the needs of the intended forecast user, a modifiable method that can and should be employed on other meteorological issueshighly variable information is provided. LORs increase the forecast value of local onsets, as they are seen to be more usable than previously considered.

c. Are local onset dates predictable?

The level of onset predictability is an important measure on onset value. Unpredictable onsets are of little value to forecast users as minimal trust can be assigned to a given forecast. A predictable onset either occurs around the same time every year (in which case climatological onset dates are suitable for use) or is linked to a predictable (or observed) onset driver. Local onset dates tend to have high inter-annual variability; therefore the identification of local onset drivers was sought in this work using LORs.

Two such drivers have been identified. The northwards advancement of the Inter-Tropical Front (ITF) past an LOR occurs roughly 14-28 days prior to median onset within the LOR for many parts of West Africa. The ITF, measured at both the regional and LOR-based longitudinal length scale is linked to local onset variability. This result has not been presented in this manner before, however a link between the ITF and societally-useful rainfall was previously described in Lélé and Lamb (2010). Furthermore, influenced by Flaounas et al. (2012a, b), a link between the phase of the Madden-Julian Oscillation (MJO) and local precipitation (and onset dates) was found. High early season precipitation, and by extension early onset dates, are linked to MJO-related suppression over the Guinea Coast. Again, an explicit link between the MJO and local onsets has not been presented in prior work.

Future work can expand on the findings presented in Chapters 3 and 4 to identify further local onset predictors in order to aid understanding of the WAM system around the time of local onset. These influences include (but are not limited to): sea surface temperatures, the West-African westerly jet, the African Easterly Jet, and dry-air intrusions from mid-latitudes (an extension on the MJO work presented here).

The identification of controls over the local WAM onset occurring at pragmatic lead times increases the value of local onsets. The improved predictability of agronomic onset dates provided by this work should lead to an increased focus in early season localised rainfall directly relevant to forecast users.

d. Why is the skill of onset forecasts limited?

Ultimately, the quality of local onset forecasts is poor meaning that they are of little value to forecast users. Increased model forecast resolution and an improvement of model physics did not change the quality of forecasts.

Mean local and regional onset dates found for three generations of the UK Met Office Global Seasonal forecasting system (GloSea) match observations. However, inter-annual variability and correlation between model forecasts and hindcasts are poor.

The work presented highlights an issue with the GloSea model forecasts. We posit that, amongst other factors, inaccurate representation of the MJO leads to a lack of appreciation of the variability of precipitation and precipitation related metrics over West Africa around the time of local onsets. This problem needs to be resolved in order to improve the quality of local onset forecasts. Improvement of onset forecasts at the seasonal time scale is an ongoing problem. In part, the reason why model improvement is incremental is that the cause of local onset variability is not well understood. Future work including the work of the African Monsoon Multidisciplinary Analysis (AMMA-2050, http://futureclimateafrica.org/project/amma-2050) and the Improving Model Processes for African cLimAte (IMPALA, http://futureclimateafrica.org/project/impala) projects will allow for interrogation of local onset at very high resolution (4 km grid cell size) and potentially lead to important improvements in seasonal monsoon forecasts through increased comprehension of the WAM onset.

e. Summary of key findings

The value of local onset definitions has been increased through the findings of this work. Through the results of Chapters 3 and 4, it is apparent that local agronomic onsets are driven to some meaningful extent by large-scale and well-researched dynamical phenomena. In the course of this work, local onsets have been shown to be applicable across our study region and predictable to a greater extent than previously expected. Local onsets are therefore subjectively valuable and it should be considered necessary for forecasters and researchers to increase focus on local onsets, particularly agronomic local onsets. This marks a change in the view of local onset variability and allows for meaningful research based on the findings of this work to be conducted in the future.

Currently, seasonal model forecasts of local onset have little value. There is a need to balance priority as a forecasting community between what would be useful to predict and what is possible to predict. These two groups are not mutually exclusive however there are factors that only exist in one group. Local onsets are useful for a given subset of forecast users and potentially predictable. It should now be a priority of the forecasting community to improve prediction of agronomic onsets and their associated drivers at a seasonal scale by first improving the quality of onset drivers highlighted within this work.

2. Potential impact of the work

The work presented has sought valuable results that improve information provided to local farmers. As such, the greatest impact from this work will hopefully be felt by this group, although there are wider implications both for West Africa and other monsoon regions.

By providing new knowledge on local WAM onsets, particularly the agronomic onset from Marteau et al. (2009), there are potential impactful results for local and more regional decision makers. Local onsets can be predicted across non-arbitrary boundaries and relative onset timings can be given at a pragmatic lead-time with some level of confidence given knowledge of observable planetary metrics. LORs are unique within the WAM literature as all prior work has suggested that local onset dates are too noisy to deserve consideration; instead prior articles have focussed on regional precipitation metrics and assumed these to be of use for local forecast users (Maloney and Shaman 2008; Marteau et al. 2009; Nguyen et al. 2014). The research performed within this work therefore extends the current collective scientific knowledge.

It is hoped that the work presented will have further reaching and more fundamental impact within the science community. It is of great importance that West African researchers are aware of the fluidity in defining the WAM onset. This issue is not specific to West Africa. Other monsoon regions experience a similar problem; for example over the Indian subcontinent there is disconnect between local and regional onset dates (compare Ananthakrishnan et al. 1967 and Moron and Robertson 2014).

Given that different onset definitions are designed for different purposes, there is no single “right” onset definition. Similarly, no onset definition is unquestionably “wrong” or without any value. However, disparate focus with respect to onset definitions by different research communities provides an inefficient method to improve understanding of onset variability. Likewise, use of an onset definition without appreciation of the scope or limitation of the definition and its associated implications can give less impactful findings than otherwise possible. Whilst the monsoon “jump” (or abrupt northwards progression) is a common theme in studies, little work has previously been done on agronomic onset or societally-useful rainfall (Lélé and Lamb 2010). Improving the prediction of societally-useful rainfall will have implications for forecast users and is encompassed in the standard Hovmöller evaluation of rainfall provided in most model studies as the 4 mm/day isohyet (see for example Vellinga et al. 2012). It is hoped that future work will focus on both the local and regional onset metrics highlighted in this work to provide more holistic assessment.

From a wider perspective, the invention of the LOR technique for measuring local onset homogeneity has multiple potential uses. Over West Africa, it is possible to determine the spatial homogeneity of different high-impact metrics such as: dry-spell occurrence or duration, seasonal forecast totals or likelihood of intense flooding events. Over other monsoon regions, LORs can be used to determine the spatial coherence of onset in a similar method to that applied here for West Africa. In addition to utilizing the LOR method, researchers should be motivated to be more creative with their application of statistical techniques when attempting to find high-impact results. Tried and trusted statistical methods (such as degree of freedom analysis, cluster analysis or empirical orthogonal functions) have allowed the scientific community to discover many highly important results (not least the MJO). However, more bespoke, user-focused methods should sometimes be considered by researchers as they can provide different and potentially more relevant findings for decision makers.

3. Limitations of the work

a. Observational limitations

Any work conducted over West Africa will naturally be limited by a lack of observations. As mentioned in Chapter 1, there are more synoptic weather stations providing data for re-analysis models in Scotland than in Nigeria despite the fact that Nigeria is almost 12 times larger than Scotland. This issue becomes worse further north towards the Sahara. The lack of reliable *in situ* measurements with a long time series of data limits the scope of work that can be done over West Africa. A reliance on satellite data is the natural resolution to this issue but in itself is fraught with risk. Satellite data often have a short history of observations over West Africa (with the notable exception of the Global Precipitation Climatology Project dataset). High-resolution data, necessary for local onset analysis, has only been widely available since 1998. Whilst it is possible to adapt rain gauge data or more coarse resolution data to a high-resolution grid through interpolation this can produce potential biases depending on the methods employed and the spatial coverage of the rain gauge network. Furthermore, for threshold based onset definitions, pentad precipitation data (such as from the CPC Merged Analysis Product) is not useful without temporal interpolation.

Satellite data are not without their biases. A satellite product can only interpret the rainfall at a given location over a given time period. Certain products (such as TRMM) will bias correct results using rain gauge data, however as previously mentioned these data are spatially sparse over West Africa. In-depth projects such as the AMMA project from 2006 give a large amount of high quality information and can really further the scientific community's understanding of the monsoon onset (Janicot et al. 2008; Lebel et al. 2009; Lebel et al. 2011). Unfortunately, financial constraints mean that even the most detailed project is unlikely to capture the full spatial, seasonal or inter-annual scope of information needed to conclusively improve understanding of the monsoon in all conditions. In an idealised world, a spatially dense network of reliable *in situ* weather stations, coupled with high-resolution (both spatially and temporally) satellite information would be readily available for West Africa. These data would be easy to interpret at an institutional level and a network which disseminates this information to local farmers would be set up. The data required and associated connections required for data transfer is currently a long way from reality. By increasing collaboration between the science community, national institutions and local farmers, an inclusive system to provide a dense network of *in situ* rain gauges for measurements and increased collaboration between all interested parties will provide large-scale benefits at all levels of the West African community.

b. Definition and methodology limitations

There is no universal “right” onset definition; therefore any choice of definition for analysis will contain some level of subjectivity or personal preference despite a commitment to objectivity. In this work, the agronomic onset definition presented by Marteau et al. (2009) was selected due to the thresholds in their definition being relevant to agricultural management. However, this choice of definition was based on a subjective interpretation of the results presented in Chapter 2; thus this choice of local onset definition is not necessarily “right”. The work presented here relies on the local onset definition selected being relevant to forecast users. Without universal agreement on the most user-relevant onset definitions, this work is therefore limited by this subjective judgement.

For synergy of onset research and in order to provide the most meaningful benefits to decision makers, a dedicated study of relative crop yield improvement provided using different onset dates in several different types of monsoon years (particularly wet, consistently dry, intermittent dry spells in the early season) would be required. This study was beyond the scope of the work presented here but should be undertaken as suggested in the next section.

Evaluation of a forecast’s value, or the value added by a forecast, from the viewpoint of a decision maker is too infrequently discussed. From a critical evaluation perspective of current model studies this appears to be the most glaring current omission. By directing our methodologies towards improving value of information provided to decision makers this work has aimed to redirect the focus of future studies. However, more in depth financial, social and agricultural input is required for a comprehensive evaluation.

c. Limitation of current knowledge

Finally, not all potential triggers of local onset have been explored within this work. In particular, local dynamical interactions that could be influential around the time of onset (such as water recycling from isolated storm events conditioning the local environment for future convective events) have not been interrogated. In addition, the dynamical impact of the monsoon transitional period could provide further information on local onset variability. Given that local onset variability had barely been considered before this work, it was expected that some questions would be left unanswered. Priority was given to proving that local onsets are of value and can be predicted and some large-scale, well-known phenomena influence local onset. Ultimately, whilst accurate and reliable prediction of local onset is still some way from being a reality, substantial progress has been made towards a solution. Several avenues for future work have been identified and are listed below as suggestions.

4. Potential extensions to the work presented

The work presented in Chapters 2, 3 and 4 has opened up new topics for future research. Here, three extensions to this work are suggested that would have substantial impact on the West African research community and the general appreciation of the WAM onset.

a. The value of WAM onset definitions for forecast users

First, a dedicated forecast value assessment is required in order to evaluate the cost/benefit of using different onset dates and the associated trust that can be attributed to different observational datasets, definitions and forecast models.

Naturally, given the risks undertaken by farmers in West Africa, particularly those with low food security, trust in forecasts can be built gradually but broken very quickly, hence the need for a comprehensive self-evaluation of current state-of-the-art knowledge. Local farmers over West Africa are subject to huge risk when planting seasonal sustenance and cash crops. The selection of crops to plant for the season is a decision based on personal knowledge, seasonal forecasting speculations and the cost or availability of different crops. More collaboration between meteorological and agricultural researchers can provide a summary assessment of best practice when it comes to crop selection and how resistive crops are to the risk of false onset which exists in all onset definitions (particularly threshold based onsets). This may allow for the creation of specialised “agricultural onset dates” such as the societally-useful rainfall threshold or the definition presented in Marteau et al. (2009). Given knowledge of seasonal rainfall total, a particular range of crops could be recommended to farmers as ideal crops to plant in the upcoming season. Then a planting date, based on the thresholds required by each crop for successful germination and development can be presented and forecasted. Using precipitation observations from prior years a relative “yield uplift” by planting certain crops over other crops could be established. This work would not only provide a method of best practice for bespoke onset forecasting, but increase the collaboration between forecasters, researchers (both meteorological and agricultural) and agricultural decision makers.

b. Improved understanding of local onset variability

Secondly, an intensive study into whether AEWs drive local onset dates across the northernmost LORs found in Chapter 3 should be performed. The work presented here has highlighted some of the predictors of local monsoon onset, however it only provides an initial study. This work in isolation has a purpose for all levels of forecast users and decision makers, but further information is required to give a full picture of local monsoon onset dynamics akin to the work already created for regional monsoon dynamics. As an initial extension to this work, the interaction of AEWs and MCSs around the time of local onset across Mali-Burkina Faso and Niger/Nigeria provides a suitable middle ground between current regional studies and more localised work.

Current work has also shown that AEW activity and its coupling with high intensity rainfall from MCSs across West Africa is limited in seasonal forecasts (Bain et al. 2014). It is therefore suggested that a fuller understanding of the impact of AEWs on local onset would be a sensible first analysis to supplement the work presented here.

The impact of mid-latitude dynamics on local onset variability also deserves further consideration due to the potential superior predictability of mid-latitude weather than AEW activity. The works of Flaounas et al. (2012a, b) provide insight into the potential avenues for further assessment.

c. <u>Are current onset-forecast deficiencies model specific?</u>

Finally, a multi-model study of local onset variability could assist understanding of current predictive deficiencies in seasonal forecast models. Weather is by its nature highly non-linear; as such no single ensemble member of a single model can be expected to consistently accurately predict all facets of weather. It is therefore beneficial to critically assess a multi-model spread of predictive capabilities of local onsets. The work presented in Appendix B gives a condensed version of this potential study with three versions of the same model assessed. It would be of interest to the science community and forecast users to understand whether similar biases are found in different seasonal forecasting products and thus quantify the current limits of skill available in predicting local onsets. In addition to seasonal forecast products, the advent of very high resolution, convective permitting models allows for further analysis of the causes of local variability of local onset on a scale not previously possible. These models would be particularly useful when interrogating the potential reason why some local onsets exist outside of any LOR and how localised processes control onset in these regions.

5. Summary

Overall, this work has furthered understanding of the variability of monsoon onset across West Africa and by extension potentially improved forecast value. By critically assessing the current literature on the WAM onset, several areas of subjectivity and ambiguity have been found. Clarification of these areas has been provided by this work.

It is important that future works appreciate the full range of potential information available for forecast users across West Africa and tailor their results to best suit their target audience. This target audience should be specified in all works as it has here. Whilst the vast majority of studies on West Africa mention food security and the need for accurate agronomic information, few then focus on relevant metrics across the most important timescales. This leads to an over-appreciation of the scope of many works. Whilst the work provided here does not offer a finite conclusion as to what the WAM onset is and how it can be predicted with complete success, the appreciation of those limitations has allowed for the value of the work to be fully appreciated.

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Appendix A

The use of West African Monsoon Onset definitions in recent literature

Appendix A – West African Monsoon onset definitions used in recent research

A representative table of recent (primarily post 2000) literature that considers the West African Monsoon onset is presented below. The table is not comprehensive but does contain enough references to provide a suitable overview of the use of onset definitions in literature. Common references are abbreviated. The table presented highlights the amount of available onset definitions and lack of common consensus with onset definition in sensitivity studies. Papers are listed alphabetically.

Common abbreviations

- SJ03 – Sultan and Janicot 2003 - The West African Monsoon Dynamics. Part II: The "Preonset" and "Onset" of the Summer Monsoon
- M09 – Marteau et al. 2009 - Spatial Coherence of Monsoon Onset over Western and Central Sahel (1950–2000)

Table A.1 – West African Monsoon publications (listed alphabetically) and onset definition used.

Paper (author, year, title)	**Onset definition(s) used/presented**
Amekudzi et al. 2015 – Variabilities in Rainfall Onset, Cessation and Length of Rainy Season for the Various Agro-Ecological Zones of Ghana	New definition presented
Ati et al. 2002 – A comparison of methods to determine the onset of the growing season in northern Nigeria	Six localised onset definitions used: - Ramadan method - Walter 1967 - Olaniran 1983 - Kowal and Knabe 1972 - Sivakumar 1988

	- Benoit 1977
Bain et al. 2011 – Anatomy of an observed African Easterly Wave in July 2006	SJ03
Bell and Lamb 2006 – Integration of Weather System Variability to Multidecadal Regional Climate Change: The West African Sudan-Sahel Zone, 1951-98	No specific onset definition cited (onset occurs in late June)
Berhane et al. 2015 – The Madden-Julian Oscillation's Influence on Spring Rainy Season Precipitation over Equatorial West Africa	Local planting date: - Odekunle et al. 2005
Birch et al. 2014 – A seamless assessment of the role of convection in the water cycle of the West African Monsoon	Study uses data specifically designed to occur after monsoon onset (taken from SJ03 and Janicot et al. 2008)
Brandt et al. 2011 – Equatorial upper-ocean dynamics and their interaction with the West African Monsoon	Fontaine and Louvet 2006
Camberlin et al. 2010 – Climate Adjustments over Africa Accompanying the Indian Monsoon Onset	SJ03
Caniaux et al. 2011 – Coupling between the Atlantic cold tongue and the West African monsoon in boreal spring and summer	SJ03
Cavazos-Guerra and Todd 2012 – Model Simulations of Complex Dust Emissions over the Sahara during the West African Monsoon Onset	No specific onset definition cited, but onset phase is taken from AMMA special observation period. Onset phase listed as 7th – 12th June 2006
Chao and Chen 2001 – The Origin of Monsoons	Chao (2000) – Measurement of ITCZ displacement
Couvreux et al. 2010 – Synoptic variability of the monsoon flux over West Africa prior to the onset	Pre-onset date from SJ03 used
Dalu et al. 2015 – The Hydrological onset and withdrawal index (HOWI) for the West African Monsoon	New regional method presented
Diaconescu et al. 2015 – Evaluation of daily precipitation	Regional:

statistics and monsoon onset/retreat over western Sahel in multiple data sets	- Sijikumar et al. (2006) - Vellinga et al. (2013) Local: - Adaptation of the method presented by Liebmann and Marengo (2001)
Diallo et al. 2014 – Simulation of the West African monsoon onset using the HadGEM3-RA regional climate model	SJ03
Douville et al. 2001 – Influence of Soil Moisture on the Asian and African Monsoons. Part I: Mean Monsoon and Daily Precipitation	No specific definition cited (suggests onset occurs June)
Douville 2002 – Influence of Soil Moisture on the Asian and African Monsoons. Part II: Interannual Variability	No specific definition cited (suggests onset occurs June)
Drobinski et al. 2009 – On the late northward propagation of the West African monsoon in summer 2006 in the region of Niger/Mali	SJ03
Drobinski et al. 2005 – Role of the Hoggar Massif on the West African Monsoon onset	SJ03
Flamant et al. 2009 – The impact of a mesoscale convective system cold pool on the northward propagation of the intertropical discontinuity over West Africa	No specific onset definition cited.
Flaounas et al. 2012 – The West African monsoon onset in 2006: sensitivity to surface albedo, orography, SST and synoptic scale dry-air intrusions using WRF	SJ03
Flaounas et al. 2012 – The role of the Indian monsoon onset in the West African monsoon onset: observations and AGCM nudged simulations	SJ03
Fontaine and Louvet 2006 – Sudan-Sahel rainfall onset: Definition of an objective index, types of years, and experimental hindcasts	New regional definition presented
Fontaine et al. 2008 – Definition and predictability of an	New regional definition

OLR-based West African monsoon onset	presented
Gazeaux et al. 2011 – Inferring change points and nonlinear trends in multivariate time series: Application to West African monsoon onset timings estimation	New regional onset definition presented
Genesio et al. 2011 – Early warning systems for food security in West Africa: evolution, achievements and challenges	Local onsets: - M09 - Sivakumar (1988) Regional onset: - SJ03
Gu and Adler 2004 – Seasonal Evolution and Variability Associated with the West African Monsoon System	No specific definition cited (can be inferred that onset is SJ03)
Guenang and Kamga 2012 – Onset, retreat and length of the rainy season over Cameroon	Odekunle et al. 2005
Hagos and Cook 2007 – Dynamics of the West African Monsoon Jump	Local - Agronomic onset presented but not used Regional – SJ03
Hagos and Cook 2009 – Development of a Coupled Regional Model and Its Application to the Study of Interactions between the West African Monsoon and the Eastern Tropical Atlantic Ocean	No specific onset definition cited (regionally averaged precipitation between 10°W–10°E used)
Im et al. 2014 – Improving the Simulation of the West African Monsoon Using the MIT Regional Climate Model	Sultan and Janicot 2000
Ingram et al. 2002 – Opportunities and constraints for farmers of west Africa to use seasonal precipitation forecasts with Burkina Faso as a case study	No specific definition cited (suggested that onset occurs around late June or July).
Issa Lélé and Lamb 2010 – Variability of the Intertropical Front (ITF) and Rainfall over the West African Sudan-Sahel Zone	Presentation of the term "societally-useful rainfall"
Issa Lélé et al. 2015 – Analysis of Low-Level Atmospheric Moisture Transport Associated with the West African Monsoon	Thorncroft et al. (2011)
Janicot et al. 2008 – Large-scale overview of the summer	SJ03

monsoon over West Africa during the AMMA field experiment in 2006	
Janicot et al. 2011 – Intraseasonal variability of the West African monsoon	SJ03
Jenkins 1997 – The 1988 and 1990 Summer Season Simulations for West Africa Using a Regional Climate Model	No specific definition cited (suggests that the onset is associated with south-westerly monsoon flow)
Kalapureddy et al. 2010 – Wind profiler analysis of the African Easterly Jet in relation with the boundary layer and the Saharan heat-low	No specific definition cited (onset occurs from May to mid-June)
Lafore et al. 2011 – Progress in understanding of weather systems in West Africa	No onset definition cited (text suggests regional onset date)
Lavaysse et al. 2009 – Seasonal evolution of the West African heat low: a climatological perspective	SJ03
Le Barbé et al. 2002 – Rainfall Variability in West Africa during the Years 1950-90	New semi-local definition presented
Lebel et al. 2010 – The AMMA field campaigns: Multiscale and multidisciplinary observations in the West African region	No specific onset definition cited (text suggests regional onset date)
Liu et al. 2012 – Observation of oceanic origin of Sahel precipitation from space	Sultan and Janicot 2000 – regional shift of precipitation
Lothon et al. 2008 – Observation of the Diurnal Cycle in the Low Troposphere of West Africa	SJ03 (and SJ00)
Lucio et al. 2012 – Dynamical Outlines of the Rainfall Variability and the ITCZ Role over the West Sahel	No specific definition cited (suggests the occurrence of a synchronous rain onset over Sahel using standard precipitation index)
Marteau et al. 2009 – Spatial Coherence of Monsoon Onset over Western and Central Sahel (1950–2000)	Agronomic definition presented
Marteau et al. 2011 – The onset of the rainy season and	Two meteorological climate

farmers' sowing strategy for pearly millet cultivation in Southwest Niger	onset definitions (Balme et al. 2005) and two agro-climate onset definitions (from Sivakumar 1998, M09 and Sultan et al. 2003) are used and analysed.
Martin and Thorncroft 2014a – The impact of the AMO on the West African monsoon annual cycle	Thorncroft et al. (2011)
McCrary et al. 2014 – Simulations of the West African Monsoon with a Superparameterized Climate Model. Part I: The Seasonal Cycle	SJ03
Mera et al. 2014 – Moisture variability and multiscale interactions during spring in West Africa	Onset of moisture (mentions pre-onset of SJ03 and Lélé and Lamb 2009)
Messager et al. 2010 – Structure and dynamics of the Saharan atmospheric boundary layer during the West African monsoon onset: Observations and analyses from the research flights of 14 and 17 July 2006	SJ03
Mohino et al. 2012 – Impact of the Indian part of the summer MJO on West Africa using nudged climate simulations	SJ03
Nguyen et al. 2011 – Guinean coastal rainfall of the West African Monsoon	Coastal onset from Thorncroft et al. (2011)
Nguyen et al. 2014 – Variations of monsoon rainfall: A simple unified index	New regional definition presented
Nicholson 2013 – The West African Sahel: A Review of Recent Studies on the Rainfall Regime and Its Interannual Variability	Local – M09 Regional - SJ03
Okumura and Xie 2004 – Interaction of the Atlantic Equatorial Cold Tongue and the African Monsoon	"Monsoon onset is loosely referred to as the rapid intensification of the southerlies in the Gulf of Guinea". Occurs during May/June

Omotosho 1990 – Onset of Thunderstorms and precipitation over northern Nigeria	New local definition presented
Omotosho et al. 2000 – Predicting monthly and seasonal rainfall, onset and cessation of the rainy season in West Africa using only surface data	New local definition presented (also available in Omotosho et al. 1990)
Omotosho 2008 – Pre-rainy season moisture build-up and storm precipitation delivery in the West African Sahel	No specific definition cited (possible to infer definition is Omotosho 1990)
Parker et al. 2005 – The diurnal cycle of the West African monsoon circulation	SJ03
Privé and Plumb 2005 – Monsoon Dynamics with Interactive Forcing. Part 1: Axisymmetric Studies	No specific definition cited (suggest monsoon is “abrupt”).
Prive and Plumb 2007 – Monsoon Dynamics with Interactive Forcing. Part II: Impact of Eddies and Asymmetric Geometries	Xie and Saiki (1999)
Roca et al. 2010 – Comparing Satellite and Surface Rainfall Products over West Africa at Meteorologically Relevant Scales during the AMMA Campaign Using Error Estimates	SJ03
Roehrig et al. 2011 – 10–25-Day Intraseasonal Variability of Convection over the Sahel: A Role of the Saharan Heat Low and Midlatitudes	SJ03
Salack et al. 2014 – Oceanic influence on the sub-seasonal to interannual timing and frequency of extreme dry spells over the West African Sahel	Local definitions mentioned: - Sivakumar 1988,1992 - Agrhymet 1996 - Marteau 2011
Sanogo et al. 2015 – Spatio-temporal characteristics of the recent rainfall recovery in West Africa	Regional onset - Wang and LinHo (2002) Local onset - AGRHYMET (1996)
Schwendike et al. 2010 – The impact of mesoscale convective systems on the surface and boundary-layer structure in West Africa: Case-studies from the AMMA	Misrepresented onset definition. Date references is regional monsoon of SJ03,

campaign 2006	but defined as the pre-onset date of SJ03
Sharma et al. 1998 – Interannual Variations of Summer Monsoons: Sensitivity to Cloud Radiative Forcing	No specific definition cited (suggested onset is linked to cross-equatorial low level flow)
Sijikumar et al. 2006 – Monsoon onset over Sudan-Sahel: Simulations by the regional scale model MM5	New regional definition presented
Sultan and Janicot 2000 – Abrupt shift of the ITCZ over West Africa and intra-seasonal variability	Regional onset definition presented (same as SJ03)
Sultan et al. 2003 – The West African Monsoon Dynamics. Part I: Documentation of Intraseasonal Variability	SJ03
Sultan and Janicot 2003 – The West African Monsoon Dynamics. Part II: The “Preonset” and “Onset” of the Summer Monsoon	New regional definition presented (SJ03)
Sultan et al. 2005 – Agricultural impacts of large-scale variability of the West African monsoon	SJ03
Sultan et al. 2007 – Characterization of the Diurnal Cycle of the West African Monsoon around the Monsoon Onset	SJ03
Taylor 2008 – Intraseasonal Land-Atmosphere Coupling in the West African Monsoon	Regional - Sultan and Janicot 2000, Le Barbé et al. 2002.
Taylor et al. 2011 – New perspectives on land-atmosphere feedbacks from the African Monsoon Multidisciplinary Analysis	No specific onset definition cited (suggestion of regional onset)
Thorncroft et al. 2011 – Annual cycle of the West African monsoon: regional circulations and associated water vapour transport	Sahelian onset phase defined
Tompkins and Adebiyi 2012 – Using *CloudSat* Cloud Retrievals to Differentiate Satellite-Derived Rainfall Products over West Africa	SJ03, Marteau et al. (2009)
Vellinga et al. 2012 – Seasonal forecasts for regional onset of the West African monsoon	Regional: Local:

Waongo et al. 2015 – Adaptation to climate change: The impacts of optimized planting dates on attainable maize yields under rain fed conditions in Burkina Faso	Overview of multiple agronomic planting dates (e.g. Stern 1981)
Webster et al. 1998 – Monsoons: Processes, predictability, and the prospects for prediction	Ramage 1971
Yamada et al. 2012 – The onset of the West African monsoon simulated in a high-resolution atmospheric general circulation model with reanalysed soil moisture fields	SJ03
Yamada et al. 2013 – Seasonal variation of land-atmosphere coupling strength over the West African monsoon region in an atmospheric general circulation model	New onset definition presented
Zeng and Lu 2004 – Globally Unified Monsoon Onset and Retreat Indexes	New onset definition presented (no scale set).

Appendix B

An assessment of the skill of the Met Office seasonal forecast model in predicting the West African Monsoon Onset

An Assessment of the skill of the Met Office seasonal forecasting model in predicting the West African Monsoon onset

Internal Met Office report

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Abstract

The skill of the Met Office Global Seasonal forecasting model (GloSea) in predicting the West African Monsoon Onset is assessed across three recent generations of the model. For completeness, a regional onset definition, a local onset definition and an established precursor to local onset are evaluated.

It is found that all three GloSea models are able to capture the mean precipitation fields and regional onset patterns. Regional onset date uncertainty in observations matches forecast variability with useful agreement between observations and forecasts.

By contrast, more localised processes over West Africa are not well captured by GloSea. The models over-predict average onset conditions and do not capture the correct level of inter-annual variability compared with observations. Understanding why local onset dates are not well predicted by GloSea should be a priority area of future research.

1. Introduction

Accurate forecasting of high-impact weather events on the seasonal timescale is one of the fundamental issues concerning forecasters. The ability to provide reliable and pragmatic information about events with high risk profiles to dependent users across the world at a relevant time scale is one of the underlying goals of forecast development. Here the skill of the Met Office Unified Model (Met_UM) to predict the onset of the West African Monsoon (WAM) on a seasonal timescale is assessed across three versions of the Met_UM Global Seasonal forecast system (GloSea).

The seasonal evolution of the WAM has been well documented in previous studies. Hamilton and Archbold (1945) provide one of the first documentations of the annual shift in high intensity precipitation from near the Gulf of Guinea (around 5°N) towards continental West Africa about the latitude of 10°N around late June/ early July. More recently, Thorncroft *et al*. (2011) gave four distinct phases to the WAM. These phases are denoted as the oceanic phase (where maximum precipitation and convection is located in the southern Atlantic Ocean), the coastal phase (maximum precipitation and convection is centred at around 5°N), the transitional phase (a period when convection “switches off” over the Gulf of Guinea prior to the abrupt monsoon shift northwards), and the Sahelian phase (when the maximum precipitation and convective band is located at a quasi-stationary latitude of 10-11°N).

The WAM is rather unique compared to other monsoon regions across the world. Typically in other regions, the migration of the maximum zonal rain belt or zone of convergence (sometimes referred to as the Inter-Tropical Convergence Zone or ITCZ), is a steady process. By contrast, the transition of the maximum rain belt over

West Africa is more abrupt (Sultan and Janicot 2003; Fontaine and Louvet, 2006; Hagos and Cook 2007; Gazeaux et al. 2011; Janicot et al. 2011). The abrupt northwards shift of the maximum zonal rain belt between the quasi-stationary locations is often referred to as the monsoon “jump” (Sultan and Janicot 2000; Sultan and Janicot 2003).The accurate representation of the monsoon jump is a common criterion by which forecasts over West Africa are assessed (Vellinga et al. 2012). Indeed the majority of research on the WAM onset has focussed on the cause of the monsoon “jump” and associated dynamics (e.g. Mathews 2004; Hagos and Cook 2007; Lavender and Matthews 2009; Lavaysse et al. 2009; Flaounas et al. 2012a,b; Cook 2015).

The cause of seasonal and inter-annual variability of the latitudinal shift in monsoon precipitation has been attributed to multiple large scale processes. Sea surface temperature (SST) variations over the Gulf of Guinea, the eastern Atlantic Ocean, the Mediterranean and the Indian Ocean have all been shown to have an impact on either the monsoon jump or seasonal rainfall variability (Flaounas et al. 2012a; Rowell 2013; Brandt et al. 2011; Caniaux et al. 2011; Liu et al. 2012). The Saharan Heat Low (SHL) intensifies shortly before the regional monsoon shift in late June, which favours northwards progression of convection and precipitation (Lavaysse et al. 2009). It is also suggested by Flaounas et al. (2012a) that the primary modulator of the monsoon shift is the effect of moisture fluxes at the boundaries of the West African domain, emanating from the onset of the Indian Monsoon. There is also an apparent link between the northwards progression of the Inter-Tropical Front (ITF) and local precipitation totals (Ilesanmi 1971; Lélé and Lamb 2010); however there appears to be little connection between the ITF and the regional shift of precipitation (Sultan and Janicot 2003). The ability of seasonal forecasts to accurately capture acknowledged monsoon triggers will naturally affect the skill of monsoon forecasts. Although the study of associated monsoon metrics within the seasonal forecast models is beyond the scope of this work (with one exception), it is important to appreciate that superior realisation of monsoon drivers should lead to improved monsoon onset forecasts.

Three aspects of the seasonal monsoon system are often evaluated: the monsoon onset (for example Vellinga et al. 2012; Diallo et al. 2014), the occurrence and duration of monsoon “breaks” or dry-spells, and the total accumulated rainfall across the season (McCrary et al. 2014). Ingram et al. (2002) found that users in West Africa view the timing of monsoon onset as the most important piece of information affecting their decision making. In this work focus is specifically given to the monsoon onset and one associated monsoon driver.

The WAM onset has multiple definitions that occur over different length scales, over different time periods and are observed using different metrics (see Tables 1 and 2 of Fitzpatrick et al. 2015). The various onset definitions can be broadly categorised into “regional” (onset measured on the supra-national scale) or “local” (onset calculated at the grid-cell or rain gauge scale). The relevance or value of an onset definition is related to its applicability and the needs of forecast users; as such a given monsoon definition may be more valuable for one set of forecast users than for others. For example, a local farmer is naturally more interested in the timing of sufficient rainfall at their position than in the meridional movement of the maximum zone of convection (Marteau et al. 2009). By contrast, information on the likelihood of tropical cyclogenesis off the West African coast is best captured by observing the shift in large-scale systems and processes such as the African Easterly Jet and associated African Easterly Waves (Berry and Thorncroft 2005; Fink and Reiner

2003). A complete onset forecast should encompass information relevant to all intended users. It is therefore important when analysing forecast skill to use multiple onset definitions that use different observational metrics (Vellinga et al. 2012). Here we consider the skill of the GloSea seasonal forecast at predicting regional WAM onset (from Sultan and Janicot 2003), local onset (Marteau et al. 2009) and seasonal progression of the ITF (termed the “pre-onset” in Sultan and Janicot 2003; studied in detail in Lélé and Lamb 2010).

The issue of sub-seasonal-to-seasonal forecasting has grown in interest over recent years. Improvement in computer processing power has allowed forecasters to begin to approach the problem of forecasting important meteorological processes at pragmatic lead times. Here we assess what improvements, if any, have been made to seasonal prediction of the WAM onset through recent developments of the GloSea forecasting system. The differences between the GloSea systems used in this study are described in detail in Section 2.2.

Section 2 outlines the models studied and the observational datasets used for comparison. Section 3 gives the three onset definitions studied as well as findings on their inter-annual variability from prior work. Section 4 evaluates the three models and offers key results of forecast skill. Section 5 provides a discussion of results and recommendations for future work.

2. Model and observational dataset choice

2.1 Overview of Met Office seasonal forecasting products

The Met Office seamless forecasting system allows simultaneous development of forecast products over multiple forecast time periods, resolutions and areas (http://www.metoffice.gov.uk/research/modelling-systems/unified-model). Met Office forecast models are run at different resolutions using the same base infrastructure and physical parameterisations (unless there is a clear reason for a difference) in order to allow for differences between forecasts to be traceable (Arribas et al. 2011). In practice, seamless forecasting greatly improves efficiency of model development.

Seasonal forecasts can provide directly relevant information for local and institutional decision makers on a relevant timescale. For this reason, GloSea is chosen here as the most relevant model to use for our study.

The use of ensembles in forecast verification allows for a more holistic appreciation of the level of uncertainty captured by the models. All three GloSea models used provide an ensemble of at most nine members per start time for three start times of practical use to forecast users (24 April, 1 May and 9 May). This gives a maximum ensemble size of 27 members for each model each year. An ensemble of this size has the potential to capture observed variability of the WAM onset; however given the highly chaotic nature of weather there is no guarantee that an ensemble will fully capture all possibilities.

2.2 The Met Office Global Seasonal Forecasting system (GloSea)

Three different versions of the GloSea model have been evaluated over West Africa in this study. The three models are denoted here as GloSea4 (GS4; Arribas et al. 2011), GloSea5 (GS5; MacLachlan et al. 2015) and GloSea5_GC2.0 (GC2.0; Williams et al. 2015). All three models have coupled land, sea and atmosphere components and are allowed to run freely during the forecast time period. A full specification for each system can be seen in the three articles referenced above; a summary of important model differences is provided in Table B.1.

Table B.1 - Comparison of the three GloSea model set ups used in this study.

	GloSea4 (GS4)	GloSea5 (GS5)	GloSea5_GC2.0 (GC2.0)
Horizontal Resolution (land/atmosphere)	N96	N216	N216
Horizontal Resolution (Ocean)	1° x 1°	0.25° x 0.25°	0.25° x 0.25°
Vertical levels (atmosphere)	85	85	85
Vertical levels (soil)	4	4	4
Vertical levels (ocean)	75	75	75
Dynamical Core	NewDynamics	NewDynamics	EndGame

The comparison between GS4 and GS5 allows for an evaluation of the improvement in forecast skill associated with increased spatial model resolution. GS4 is relatively coarse in both the atmosphere and ocean in comparison with both GS5 and GC2.0. The same physical parameterisation scheme is used in both the GS4 and GS5 models, meaning increased resolution is likely to be the principal cause of differences seen. Although it has previously been suggested that regional WAM onset is resilient to dataset resolution, the increase in precision may be of particular interest when evaluating local onset across West Africa (Fitzpatrick et al. 2015).

The recent development of the EndGame dynamical core for Met Office forecast models provides tighter coupling between land and atmosphere as well as ocean and atmosphere, and a better representation of the diurnal cycle (due to 3-hourly coupling as opposed to 24-hourly coupling in previous models). A detailed list of the technical improvements of EndGame dynamics over NewDynamics as well as example results can be found at http://www.metoffice.gov.uk/media/pdf/s/h/ENDGameGOVSci_v2.0.pdf. Whilst the GC2.0 model still parameterises convection, it is hoped that a better diurnal cycle will improve the representation of precipitation within the model and give more realistic onset dates compared to prior generations of the model.

All three models studied have a hindcast spanning 1996-2009. In order to compare high-resolution observations with the model hindcasts, the period 1998-2009 is used for both the regional and local onset dates. For dew-point temperature profiles, the full hindcast length is used. It is found that the regional and local onset results presented in this work are not changed substantially with the inclusion of 1996 and 1997; thus the exclusion of these years does not majorly change findings.

2.3 Observational data

Precipitation observations have been taken from the Tropical Rainfall Measurement Mission 3B42 v7 daily dataset for the period 1998-2009 (TRMM v7; Huffman et al. 2007). The native resolution of the dataset (0.25° x 0.25°) has been interpolated to match the resolution of the GloSea hindcasts (i.e. N96 and N216). In an evaluation of onset date representation in different operational datasets, it was found that regional onset dates in TRMM v7 closely matched those found in other observational datasets as well as the ERA-Interim re-analysis dataset and previous studies (Fitzpatrick et al. 2015). For local onset dates it was found that TRMM v7 gave a more realistic representation of the seasonal pattern of onset dates than in coarser datasets (such as the Global Precipitation Climatology Project 1-degree daily rainfall data; Adler et al. 2003) and so is chosen to represent “reality” here. The authors do however concede that no satellite-based precipitation dataset can be considered truly reliable and there are biases within the TRMM v7 data (Roca et al. 2010; Seto et al. 2011). Unfortunately however, given the sparsity of reliable, *in-situ* measurements over West Africa, it is somewhat necessary to use such data.

In order to track the ITF, 2-metre dew-point temperature is taken from the ERA-Interim re-analysis dataset from the years 1996-2009 (ERA-I, Dee et al. 2011). Daily dew-point data is taken for 1200 UTC as this is the time when the vertical structure of the monsoon layer is the most consistent giving the most reliable location of the ITF (Flamant et al. 2007, Bou Karam et al. 2008). Overnight, due to the increase in surface cooling and the potential impact of cold pool outflows the ITF has a shear closer to the surface (Garcia-Carreras et al. 2013, Provod et al. 2015). During the day, as the sun heats the surface, vertical mixing makes the humidity profile of the ITF and associated dew-point temperature profile more vertically consistent. For this reason we use dew-point temperature values at 1200 UTC. In order to directly compare re-analysis data with the model data, 925 hPa dew-point temperature values are calculated from ERA-Interim. The ITF can be tracked using other metrics at other times in the day (for example, surface wind convergence overnight and at 0600 UTC; Roberts et al. 2015).

It is important to stress that ERA-Interim data are not observational data; however, it is considered a bench mark analysis dataset to compare model hindcasts against. In lieu of consistent, spatially dense, and reliable observations of dew-point temperature across West Africa, the decision to use re-analysis data was taken.

Roberts et al. (2015) show that there can be a discrepancy in the representation of the ITF in different re-analysis products. However, it is found that the majority of disagreement occurs during the ITF retreat and the seasonal advancement of the ITF is reasonably consistent across products to provide a base for model assessment. The selection of ERA-Interim as a model comparison dataset is also justified by the findings of Roberts et al. (2015).

2.4 Onset Definitions

Three different monsoon onset metrics are analysed in the model hindcast and observations/re-analysis data. The assessed metrics mark the seasonal progression of cool, moist monsoon winds into the Sahel (the ITF onset), the commencement of local agronomic rainfall across West Africa (local onsets), and the timing of the abrupt shift of the maximum rain belt (regional onset). These three onset definitions capture distinct phases of the seasonal WAM progression and the correct forecasting of each is important for specific users.

The regional onset definition analysed is based on the work of Sultan and Janicot (2003); the most commonly used onset definition in WAM literature. The definition observes the seasonal northwards migration of the zonal maximum of precipitation from the Guinea Coast (5°N) towards the Sahel (10°N). The definition as provided in Sultan and Janicot (2003) has some subjectivity in its assessment. Here, an objectified version of the definition from Fitzpatrick et al. (2015) is used. The definition, denoted henceforth as SJ10, states:

- Monsoon onset, SJ10, occurs on the first date when the zonally-averaged (between 10°W and 10°E), ten-day time-smoothed precipitation total at 5°N is less than or equal to precipitation totals at 10°N for seven consecutive days.

This objective definition differs from that provided in Sultan and Janicot (2003) by providing an explicit minimum length of time for which precipitation at 10°N must be greater than, or equal to, precipitation at 5°N. It is found that the SJ10 onset dates are consistent under dataset choice and resolution used and hence our exclusive use of TRMM v7 data will not give biased results (Fitzpatrick et al. 2015). Interestingly, it has previously been shown that this regional onset date has minimal correlation with either the pre-onset date or local agronomic onset date across West Africa (Sultan and Janicot, 2003; Fitzpatrick et al. 2015). Therefore the regional onset date can be thought of as isolated from the other two onset dates analysed here, albeit a key date in the wider monsoon system.

The local, agronomic monsoon definition analysed originates from Marteau et al. (2009), and is also similar in construction to Stern et al. (1981). The agronomic onset date from Marteau et al. (2009) at a given grid cell (**x**); hereafter denoted as the local onset, is defined as:

- The first rainy day at grid cell **x** (with precipitation > 1 mm) of two consecutive rainy days (total precipitation > 20 mm) with no 7-day spell of precipitation less than 5 mm in the subsequent twenty days.

The local onset used here was originally produced for agronomic interests in Senegal, Mali and Burkina Faso. The use of an extended observation window in which persistent rainfall must occur (referred to here as the dry-test) reduces the risk of false onset observation. Marteau et al. (2009), find that the local onset denotes a point in the local climate when an increase in meso-scale convective activity occurs suggesting that the onset is not triggered by low intensity rainfall and indeed may be triggered by an important change in the localised climate.

One issue with all local onsets, particularly from a forecasting perspective, is the high level of spatial and temporal noise of local rainfall. However, recent work suggests that there is a level of spatial consistency of onset dates appreciable over sub-regions of West Africa (Fitzpatrick et al. 2016). Both the onset dates and their spatial coherence are compared between TRMM v7 and the three GloSea versions (see Section 3.1 for method used to calculate spatial coherence).

Finally, the seasonal progression of the ITF is assessed as well as the structure of dew-point temperature behind the ITF. The ITF advancement can be thought of as being analogous to the maximum extent of moisture into the continental monsoon region. The front, here represented using the daytime 15°C isodrosotherm (inspired by Lélé and Lamb 2010), marks the location where cool, moist southerly monsoon winds meet warmer, drier northerly Harmattan winds. Prior work has suggested a link between the ITF northwards progression and the presence of *societally-useful rainfall* (at least 4 mm/day, Lélé and Lamb 2010), and a link between ITF progression and local onset dates (Fitzpatrick et al. 2016). It can therefore be considered that ITFR15 provides a necessary condition for the ensuing precipitation based monsoon onsets.

3. Forecast analysis

Assessing what makes a “good” or “bad” forecast is not straightforward. Whilst fundamentally a “good” forecast will have greater skill at predicting a given metric or combination of metrics than a “bad” forecast, determining what defines forecast skill is an open question. Murphy (1993) offers three ways in which a forecast’s skill can be qualified. These three measures are: the forecast consistency (i.e. to what degree does the forecast agree with a forecaster’s educated judgements), the forecast quality (to what degree does a forecast agree with best observations) and the forecast value (using the forecast what societal or economic benefit would a user realise). These three methods of evaluation provide a clear structure for assessing a forecast’s skill and allow for ease of comparison as to which forecast is “better” or “best”.

In this work, priority is given to forecast consistency and quality (as a detailed assessment of forecast value requires intensive case studies). However, forecast value is increased with improved forecast quality (as the higher quality a forecast is, the more useful it is). Therefore improvement in quality through the three generations of GloSea studied here will lead to a more valuable and hence “better” forecast.

3.1 Forecast Consistency

The WAM system has been well researched in many previous studies. As a result, there are many large scale metrics which can be studied within a model in order to determine whether the model accurately captures the correct responses. Examples include the migration and deepening of the Saharan Heat Low prior to the regional monsoon onset (Lavaysse et al. 2009), the coupling of precipitation with African Easterly Waves (which has been studied within the Met_UM in Bain et al. 2014) and the Hovmöller of zonally-averaged precipitation and associated monsoon shift denoting the monsoon onset (Vellinga et al. 2012). It is important to understand whether a model accurately captures, or has improved realisation of key mean fields relevant to the forecasted event.

In this study, three consistency measures are assessed. Firstly, Hovmöllers of zonally-averaged precipitation across observations and the three GloSea models are compared. This comparison allows for analysis as to whether the models can capture the regional shift of precipitation across West Africa. Accurate representation of precipitation across the monsoon region (10°W-10°E) implies that the models have a reasonable representation of key drivers of monsoon rainfall including those that drive the northwards displacement of the maximum rain belt.

Local onsets have traditionally been under-studied in literature due to the belief that they are too noisy to warrant intensive investigation. A recent study has quantified the level of spatial homogeneity of onsets providing non-arbitrary regions where onsets can be considered consistent to a measurable degree (Fitzpatrick et al. 2016). These regions are termed Local Onset Regions or LORs; a full explanation of the method used to calculate LORs is presented in the above mentioned article. Five distinct areas where LORs are clustered have been found (Table B.2). These are: the coastal region, the Mali-Burkina Faso region, the Benin-Nigeria region, the Niger-Nigeria region and the Cameroon Highland region. The largest LOR within each region is presented in Fig. B.1. The three seasonal forecasting models studied here are analysed to determine whether they can accurately capture the level of spatial homogeneity found in observations. The size of LORs relates to a regional signal to local noise evaluation of local onsets. Larger LORs imply that regional signals dominate local variability in controlling local onsets. Thus, the size of LORs found in observations and forecast models gives insight into the level of regional control over localised precipitation.

The ITF has been shown to be linked to *societally-useful* precipitation (Lélé and Lamb 2010) and local onset dates (Fitzpatrick et al. 2016). Here the location of the ITF and the structure of low-level dew-point temperature ahead and behind the ITF are compared between observations and models.

Table B.2 - Location of the five LOR areas used in this study (from Fitzpatrick et al. 2016).

Region (abbreviation)	Spatial limit	Latitude and longitude of largest LOR within region	Area of largest LOR within region (‘000 km^2)
Coastal (CT)	20–10°W 8–16°N	20–13.25°W 8–13°N	337.5
Mali/Burkina Faso (MBF)	8–3°W 8–14°N	7.5–4°W 12.5–15.5°N	105
Benin/Nigeria (BN)	0–7°E 8–14°N	2–5°E 10–12.25°N	67.5
Niger/Nigeria (NN)	7–15°E 12–15°N	7.25–10.5°E 11–14°N	97.5
Cameroon Highlands (CH)	8–20°E 8–12°N	11.5–20°E 8–11.25°N	268.125

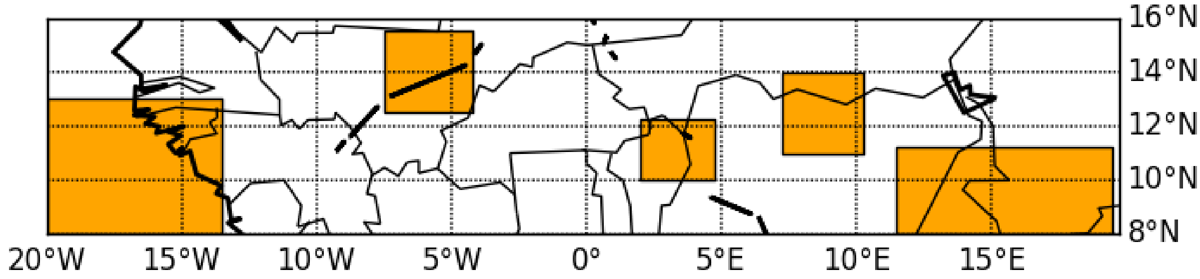

Figure B.1 – Location of the largest inter-annual LOR within each of the five LOR areas. For more details on inter-annual LORs, read Fitzpatrick et al. (2016).

3.2 Determining forecast quality

Forecast quality is perhaps the most commonly understood and assessed measure of forecast skill. It is important for all forecast verification to highlight how closely a forecast matches observed metrics over a long time period. Crucially, the method used to measure forecast quality is as important in some ways as correct selection of assessment metrics.

The quality assessment of an ensemble forecast can either be done from a probabilistic or non-probabilistic standpoint. A non-probabilistic assessment of onset may compare the onset date forecast by an ensemble for a given year or time period against observations. Correlation between forecast and observed dates may be considered and the inter-annual variability in the forecast can be compared to observations. These three results give insight into the quality of a forecast at reproducing expected climatology and variability metrics and all metrics are treated as continuous. By contrast, probabilistic assessments are produced on discrete partitions of data. A probabilistic assessment of onset date may assess the likelihood that onset occurs within a given date range, or given anomaly range, in both observations and forecasts. The use of both probabilistic and non-probabilistic quality methods can provide a holistic evaluation of forecast skill.

Prior work has suggested that the mean regional and local onset dates in GS4 match closely with observations, however the inter-annual variability of both is too low (Vellinga et al. 2012). A similar assessment for both regional and local onset dates using GS4, GS5 and GC2.0 highlights that the inter-annual variability in model data is lower for all three forecast models than observations (see Fig. B.2 for an illustrative example). It can be concluded that from a non-probabilistic view, variability in GloSea onset forecasts is too low in all three models. In addition, correlations between forecasts and observations for both local and regional onset dates are not significant at the 95% confidence interval (not shown). We suggest here that a more meaningful evaluation of GloSea forecast quality in the three models studied can be obtained by assessing the hindcast quality from a probabilistic perspective.

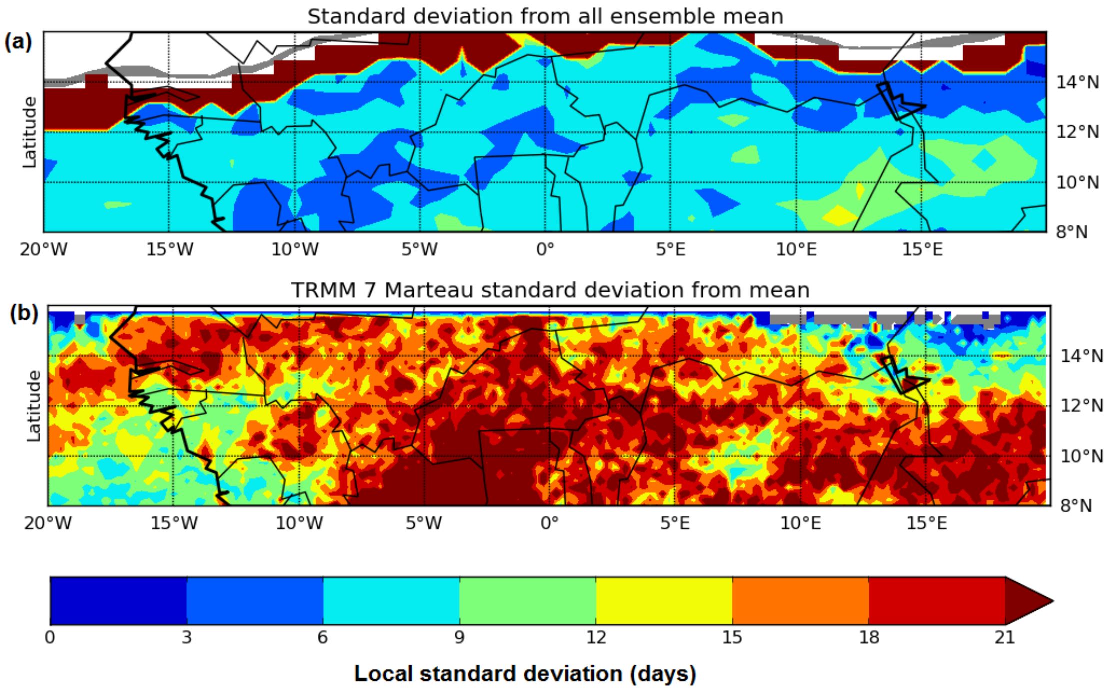

Figure B.2 Comparison of inter-annual variability of local onset dates. (a) Local standard deviation of local onset in the GS4 model hindcast (1998-2009). (b) As for (a) but for the TRMM v7 observational dataset for the same period. Both datasets are analysed at their native resolution.

Probabilistic outcome distributions of forecast onset are used for evaluation (Murphy and Winkler 1987). For each location **x** each year **t** and each ensemble member **e**, we assign a value to both the forecast ensemble member (f) and the observations (g) as follows:

$$F(x,e,t) = \begin{cases} 1 \; if \; f(x,e,t) > \overline{f(x)} + \sigma(x) \\ 0 \; if \; \overline{f(x)} - \sigma(x) \leq f(x,e,t) \leq \overline{f(x)} + \sigma(x) \\ -1 \; if \; \overline{f(x)} - \sigma(x) > f(x,e,t) \\ -2 \; if \; onset \; is \; not \; predicted \end{cases} \qquad (B.1)$$

$$G(x,t) = \begin{cases} 1 \; if \; g(x,t) > \overline{g(x)} + \sigma(x) \\ 0 \; if \; \overline{g(x)} - \sigma(x) \leq g(x,t) \leq \overline{g(x)} + \sigma(x) \\ -1 \; if \; \overline{g(x)} - \sigma(x) > g(x,t) \\ -2 \; if \; onset \; is \; not \; observed \end{cases} \qquad (B.2)$$

Where $\overline{g(x)}$ denotes the mean observational onset date at a given location, x, and $\sigma(x)$ denotes the local standard deviation in onset at the given location. In short, we assess whether the observed (forecasted) onset date for a given location lies within one standard deviation of the observed (forecasted) mean onset date for that location. Note that for regional onsets, due to the zonal averaging in the definition, there is only one location **x** for each year and ensemble member (observation). The series G(x,t) is based on one observation for each location and each year whereas the series F(x,e,t) is averaged across all ensemble members to give a relative probability of average onset date series F(x,t). For our regional onset assessment, onset is observed and predicted in all years. For local onsets it is possible for an onset to not be observed (forecasted).

There are two main types of forecast quality metrics that can be used: strictly proper scoring rules and joint distributions of forecast and observations (Murphy and Winkler, 1987; Murphy 1993). Strictly proper scoring rules, including mean absolute error, Brier skill scores and root mean square error provide a simple and clear identifier of the level of agreement between a forecast and a set of observations. However, the assessment of these scores can sometimes mask key information. For example, mean absolute error does not distinguish between levels of error occurring at different magnitudes. In addition, proper scoring rules tend not to distinguish whether a forecast overestimates or underestimates a metric relative to observations (due to the absolute part of the mean absolute error method for example). For local forecast users, this distinction may be of substantial importance. A predicted early onset in a year when observed onset was average or even later than average can lead to a higher risk of crop failure then if the predicted onset is later than observations. Joint distribution metrics can give a more expansive understanding of a forecast's quality. A variety of metrics are presented in Murphy and Winkler (1987), which are summarized here.

Given a probabilistic forecast result, *f*, and the coinciding observation of this parameter, *g*, the calibration-refinement factorization, *C(f,g)*, is given as:

$$C(f,g) = p(g|f)p(f) \quad \text{(B.3)}$$

The calibration-refinement factorization (or calibration-refinement method) can be thought of as the variability of observations given forecasts. The conditional distribution, *p(g|f)*, is indicative of how often different observations occur when a particular forecast is given. This distribution can be thought of as the model's calibration rank or its reliability. Ideally a dichotomous probabilistic forecast would have p(g=1|f) = f. Such a forecast would be perfectly calibrated. When more than two values of x exist, the conditional distribution is said to be perfectly calibrated if the expected probability, E(g|f), is equal to f for all outcomes (e.g. if observed average forecasts have a 60% probability of occurring, E(g = average onset | f = average onset) = 60%). The marginal distribution, *p(f)*, highlights how frequent different forecasts occur. The marginal distribution is considered the refinement or relative *sharpness* of the forecast. A forecast that consistently reports climatological forecast probabilities is considered not sharp as there is no variation in onset date year to year.

A similar joint distribution can be made by assessing the variability of forecasts given observations. This method is termed the likelihood-base rate factorization (or method), here denoted as L(f,g), and is calculated as:

$$L(f,g) = p(f|g)p(g) \quad \text{(B.4)}$$

As with the calibration-refinement method, the likelihood-base rate factorization consists of the conditional distribution of forecasts given observations and the observational uncertainty. The conditional distribution, p(f|g), gives the level of forecast discrimination. This can be thought of as how well the forecast ensemble captures the difference between early, average and late onsets for the purpose of the work presented here. A forecast that is perfectly discriminatory will have clearly different values for p(f=i|g) where *i* denotes the different possible onset classifications (early, average, late or no onset). The marginal distribution, p(g) highlights the observational uncertainty of the metric being assessed. Intuitively, the less uncertain the variable, the less critical it is to capture the variability of the metric as bias correction to a climatological value will often suffice for practical purposes.

Both the likelihood base-rate method and the calibration-refinement method are traditionally presented in tabular from. Tables B.3 and B.4 gives examples of the likelihood base-rate and calibration-refinement method respectively for the SJ10 regional onset using the GS5 model. From Table B.3 we can determine the forecast's discrimination by comparing the probabilities across any row of Table B.3 (bold values). The observational variability is measured along the bottom row of Table B.3 (italicised values). In a similar manner, the forecasts calibration can be assessed by reading across rows in Table B.4 (bold values) and forecast sharpness is given in the bottom row of Table B.4 (italicised values). It is worth noting that measures of model discrimination and model calibration (or reliability) are not the same. An onset can be perfectly discriminatory but also have no reliability as to whether or not an onset occurs for a given year. Similarly, the impact of a model having poor calibration is very different to the impact of a model not being discriminatory when considering decision makers. For instance, a model that consistently predicts late onsets when early onsets are observed and *vice versa* would be perfectly anti-calibrated with observations however the model could be seen as reliable given that reality is always the converse to what is predicted (for the sake of this example we presume that models and observations consistently predict the same years as average onsets). The use of the likelihood-base rate and calibration-refinement quality assessment can therefore give more in depth detail about model skill than a simple scoring method.

Table B.3 - Likelihood Base rate analysis for SJ10 in GS5

	Early observation		Average observation		Late observation	
Early forecast.	2		20		0	
	P(f=-1|x=-1)	**0.11**	**P(f=-1|x=0)**	**0.23**	**P(f=-1|x=1)**	**0**
Average forecast.	16		56		0	
	P(f=0|x=-1)	**0.89**	**P(f=0|x=0)**	**0.65**	**P(f=0|x=1)**	**0**
Late forecast	0		10		0	
	P(f=1|x=-1)	**0**	**P(f=1|x=0)**	**0.12**	**P(f=1|x=1)**	**0**
Base rate	*18*		*86*		*0*	

For this work, 30 tables would be required to complete the assessment for local onsets alone (2 methods for 5 regions across 3 models); for the ease of comparison, the methods are presented here instead in Figs. B.7 and B.8. For regional onsets a similar figurative representation is given in Fig. B.5.

Table B.4 - Calibration-refinement analysis for SJ10 in GS5

	Early forecast		Average forecast		Late forecast	
Early observation	2		16		0	
	P(f=-1|x=-1)	**0.09**	**P(f=-1|x=0)**	**0.22**	**P(f=-1|x=1)**	**0**
Average observation	20		56		10	
	P(f=0|x=-1)	**0.91**	**P(f=0|x=0)**	**0.78**	**P(f=0|x=1)**	**1.0**
Late observation	0		0		0	
	P(f=1|x=-1)	**0.0**	**P(f=1|x=0)**	**0**	**P(f=1|x=1)**	**0**
Model sharpness	*22*		*72*		*10*	

4. Results

4.1 Mean regional and local onset dates

4.1.1 Mean regional precipitation pattern and onset

Regional Hovmöllers of rainfall across the monsoon region show a clear contrast between GS4 and both GloSea5 products (GS5 and GC2.0). Figure B.3a shows the average observed regional progression of rainfall from the TRMM v7 dataset for the period 1998–2009. The maximum in rainfall is located near the Gulf of Guinea prior to late June (representative of the coastal onset phase). Around late June/early July, rainfall totals at 5°N rapidly decrease with a second maximum rainfall band occurring at around 10°N after this date denoting the regional onset date or the Sahelian phase of the monsoon. Figures B.3b–d show the ensemble mean hindcast precipitation over the same period for GS4, GS5 and GC2.0. The clear distinction between the coastal and Sahelian monsoon phases is more apparent in the two GloSea5 hindcasts than in the GloSea4 hindcast (compare Fig B.3b to Figs. B.3c and B.3d). Consistent with observations, the coastal monsoon phase has higher rainfall totals than the Sahelian phase. In GS4, there is a more transitional progression between the coastal and Sahelian monsoon phases with much more rainfall in the Sahelian phase than in either observations or the GloSea5 hindcasts where an abrupt monsoon shift is seen. Precipitation totals at 10°N are arguably closer to observations in GC2.0 than in the other two hindcasts. In all three hindcasts, *societally-useful rainfall* (4 mm/day) occurs at 10°N during the middle of May consistent with observations.

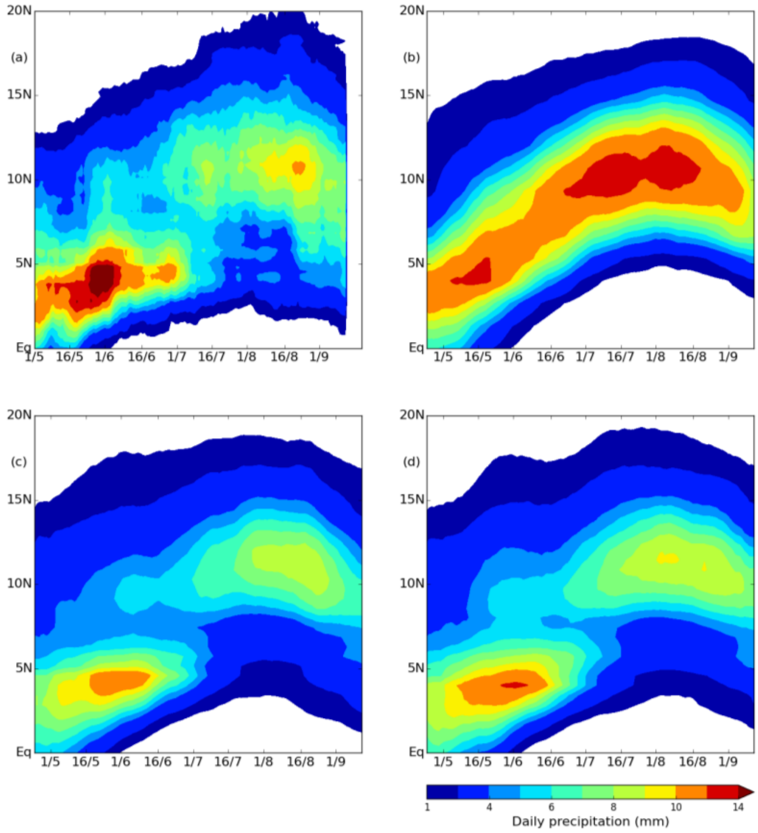

Figure B.3 – Average seasonal migration of the zonally-averaged precipitation total. Hovmollers of zonally-averaged (from 10W – 10E) precipitation from 1 May to 11 September for (a) TRMM v7, (b) GS4, (c) GS5 and (d) GC2.0.

The northernmost limit of the maximum rain belt is further north in GS5 and GC2.0 than in GS4, and is more in line with observations. This suggests that increased model resolution results in a more realistic representation of the maximum zonal rain belt. It is possible that this improvement is due to the better representation of sea surface temperatures and the associated low-level pressure difference across continental West Africa (Caniaux et al. 2009; Hagos and Zhang 2010; Nguyen et al. 2011) as the representation of key features such as ENSO events are improved in more recent generations of GloSea (MacLachlan et al. 2015). The accurate representation of sea surface temperatures improves the mean fields however may not lead to a more accurate timing of the regional onset as link between sea-surface temperatures and the timing of the regional onset is contentious (Flaounas et al. 2012b; Druyan and Fulakeza 2015) .

The timing of the regional monsoon onset, SJ10, has been shown in studies to be consistent across datasets and observation periods selected (see for example results in Sultan and Janicot, 2003; Fontaine et al. 2008; Janicot et al. 2011; Fitzpatrick et al. 2015). It is found here that the regional onset date is similarly consistent across hindcasts. Mean *SJ10* onset in the GS4 hindcast is 26 June with a standard deviation of 6 days. GS5 mean onset date is 22 June with standard deviation of 7.6 days. GC2.0 mean onset date is 25 June with standard deviation of 6.5 days. The mean onset date and variability found in the three models is similar to that found in observation and re-analysis datasets.

In conclusion, the increase in spatial resolution between GS4 and GS5 appears to improve the representation of the monsoon jump found in observations. Furthermore, there appears to be a more realistic level of rainfall precipitating over the Sahel during the monsoon season in GS5 compared with GS4. Whilst the differences between GS5 and GC2.0 are less striking than the differences between GS4 and GS5, it appears that the change in physical core further improves the average spatiotemporal variability of rainfall across West Africa through the monsoon season. We therefore conclude that GC2.0 does provide improvements in the representation of the mean climatology across West Africa.

4.1.2 Mean local onset dates

Fig. B.4 shows the average local onset date in TRMM v7 and the three model hindcasts studied. The general northwards progression of local onset dates is present in all three model hindcasts in agreement with observations. The northernmost limit of onset is similar in all three hindcasts as well as in the observations (white regions). In all three models, there are earlier than observed onset dates over the Cameroon Highlands. Similarly, in GS4 and GC2.0, earlier onset dates are observed over the northernmost limit than in TRMMv7 observations. The reason for these differences is not obvious from Fig. B.4 however they are potentially explained in later sections.

There exist differences between local onset dates across all three models over certain parts of West Africa. In general, local onset dates in GC2.0 and GS4 occur on average earlier than the onset dates found in the GS5 hindcast. This is particularly apparent over the Senegal coast and the border of Niger and Nigeria. There is increased spatial heterogeneity in the models with increased resolution when compared with GS4 as can be seen by the region of early onset dates around Cameroon and Nigeria (~10–20°E, 8–11°N). The differences highlight that there is some alteration in the forecasting of agronomic rainfall between the three models. However, comparison with TRMM observations suggests that none of the three hindcasts has an unequivocally “better” representation of average onset dates.

Broadly speaking, the general pattern of onset dates found is similar to observed onset dates suggesting that GloSea has a reasonable representation of mean local onset. The local onset dates found in hindcast models are better than those found in re-analysis products such as ERA-Interim (Fitzpatrick et al. 2015). Although for zonally-averaged rainfall there was an observed improvement in representation from GS4 to GS5 and between GS5 and GC2.0, for local onset date this pattern is not striking. Fig. B.4 and the associated analysis suggest that the increase in resolution from GS4 to GS5 did not greatly improve the representation of local onset across West Africa nor did the change to a new dynamical core.

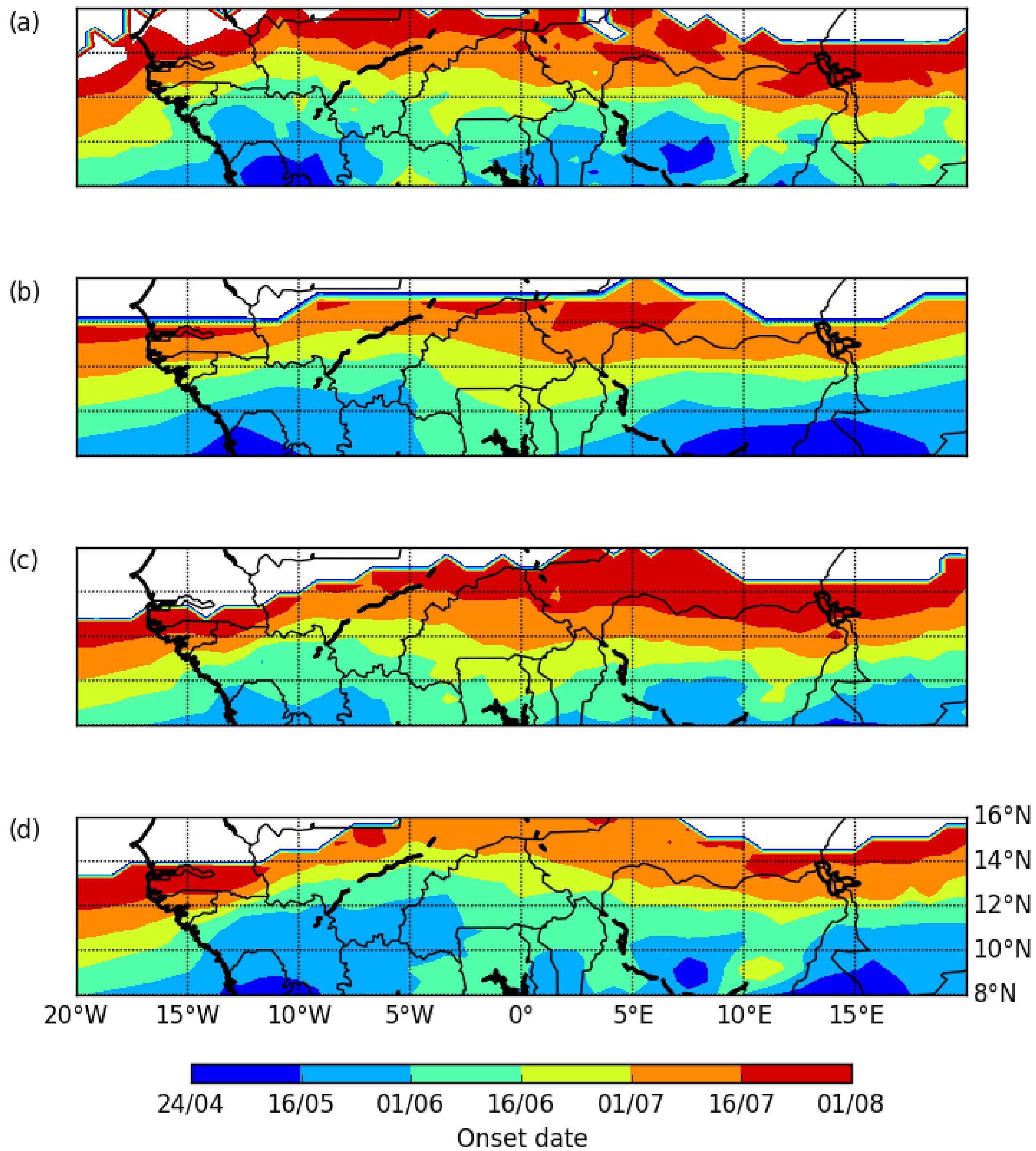

Figure B.4 – Average local onset dates for the period 1998-2009 for: (a) TRMM v7, (b) GS4, (c) GS5 and (d) GC2.0. White contours denote regions where average onset is later than 1 August or onset is not realised in 5 or more years.

Inter-annual variability of local onsets has also been calculated (GS4 in Fig. B.2a, GS5 and GC2.0 not shown). For all three models, there is much lower inter-annual variability at the local scale compared to observations (often a factor of three or more). This result is similar to the regional onset analysis where the mean onset field is comparable, but inter-annual variability is not well captured.

Overall, there is not a very large change between the average onsets found in all three hindcast models. We posit that the drivers of local onset variability may not be better captured in either of the two more recent models compared with GS4. It must however be stressed that the cause of local onset variability is not yet fully understood and hence this hypothesis cannot be explicitly proven.

4.2 Local Onset Regions in the GloSea models

Inter-annual LORs give a level of spatial homogeneity across West Africa and allow for sensitivity assessment of local onset variability across non-arbitrary regions. As such the accurate representation of LORs in GloSea forecast models would indicate that the causes of local onset variability are potentially constrained to the correct sub-regions of West Africa.

LORs have been calculated using ensemble means (not shown) and random selections of ensemble members. A Monte Carlo method was used to summarise the LORs found using 1,000 random combinations of ensemble members. For both ensemble means and ensemble members, all three forecasting models over-estimate the level of spatial homogeneity present over West Africa. There is also no distinction within model analyses between the five LOR areas highlighted in observations. This result is consistent when TRMM v7 data are smoothed to GloSea spatial resolutions.

It can be summarised that the models are not consistent with the observed level of spatial variability in local onset dates. This finding suggests that regional forcing dominates local variability over West Africa in the GloSea models to a much greater degree than in reality. This result is present for both GS4 and the high resolution GS5 and GC2.0 suggesting that the improvement in model resolution does not improve this result (although even higher resolution models may capture realistic LORs).

4.3 Summary

The analysis of mean fields allows for sweeping assessment of potential model improvement. It has been shown that there is an improvement in the representation of zonally-averaged precipitation as a result of increased model resolution and improved physics. For the local, precipitation based onset this improvement is not as apparent and it is arguable that no improvement exists. In order to calculate the specific improvement of onset date forecasts, the joint probability distribution analysis is performed on both the regional and local onsets.

5. Likelihood base-rate analysis and calibration-refinement analysis

5.1 Regional onsets

Table B.5 highlights the observational uncertainty and model sharpness for SJ10 across the period studied. There is an apparent increase in model sharpness from

GC4 to the more high resolution GS5 and GC2.0 model. This increase suggests that the model has improved ability to discern between “average” and “not-average” regional onset dates. In observations, there is an approximate 83% chance that onset will be deemed “average”. For GS4, this probability is 59%, GS5 has a probability of 69% and GC2.0 has a probability of 67%. There is an appreciable increase in the sharpness of the model toward a more realistic uncertainty of average or not-average SJ10 onset. Although model sharpness has increased with enhanced spatial resolution, there is still a propensity for models to predict non-average onset dates more frequently than they are observed.

Table B.5 – Comparison of observational uncertainty and model sharpness.

TRMM v7 SJ10 observational uncertainty		GS4 SJ10 sharpness		GS5 SJ10 sharpness		GC2.0 SJ10 sharpness	
Average onset	Early/late onset	Average onset	Early/late onset	Average onset	Early/late onset	Average onset	Early/late onset
10	2	64	44	72	32	116	56
Percentage average onset	83.3%	59.3%		69.2%		67.4%	

There is a limitation within the method of analysing onset dates that skews this analysis. The regional onset SJ10 is shown to have low observational uncertainty; however this could be a result of the threshold set for average and non-average onset dates. Within the 12 years of observed onset dates used in this study, two years (2002, 2006) have onset date on the upper limit of “average” onset as they occur exactly one standard deviation later than the mean onset date. If these two years were considered “late” onsets rather than “average” onsets, the sharpness of all three models studied would be consistent with observations (as observational uncertainty would be 66.6%). The discrete nature of onset forecasts (as an onset never occurs over half a day) leads to this error. In addition, the sample size of observational data is very low compared to the ensemble forecasts leading to less reliability in the observational uncertainty score than for the model’s sharpness. We therefore conclude that the three GloSea models studied here can capture the observed uncertainty in regional onsets.

In order to extend our analysis, the likelihood-base rate and calibration-refinement factorization methods are performed on observations and model data. Figure B.5 gives the likelihood-base rate assessment (Fig. B.5a) and calibration-refinement score (Fig. B.5b) for all three models (GS4, GS5 and GC2.0 are shown from left to right in each group of columns within each plot). All three models are poorly refined (i.e. $p(f=1|x=0) \geq p(f=1|x=1)$). In particular, early observed onsets are often predicted as average onsets in all three models (Fig. B.5a). This over-prediction of average onset dates increases in GS5 and GC2.0 compared with GS4 suggesting that the refinement of onsets is actually lower in more recent versions of the GloSea forecasting models.

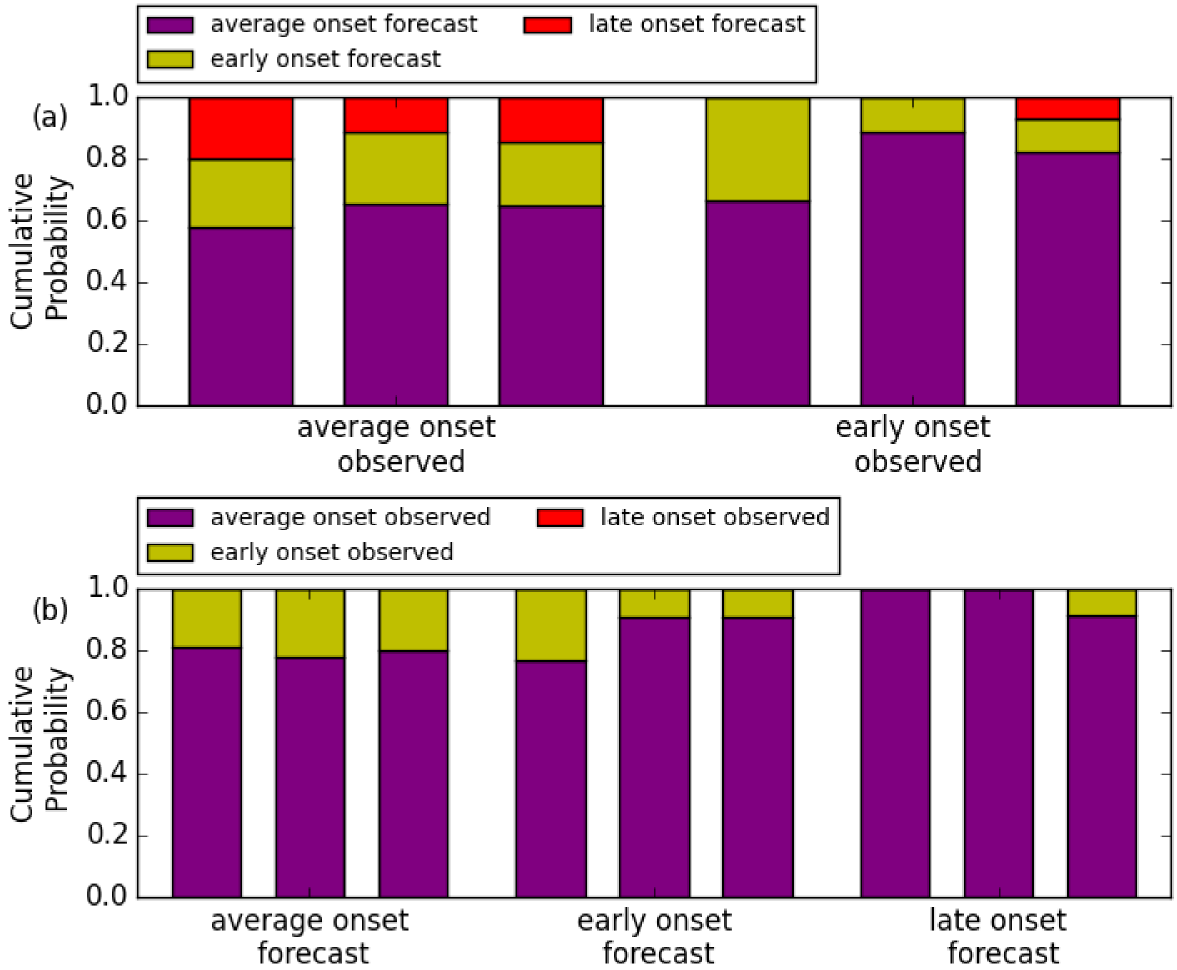

Figure B.5 – Joint-distribution assessments of SJ10 in GloSea hindcasts. Likelihood-base rate (a) and calibration-refinement (b) factorization assessments of the three GloSea models studied against observed SJ10 onset dates found using TRMM v7 for the period 1998-2009. For each onset classification (x-axis), left column represents GS4 quality, middle column represents GS5 and right column represents GC2.0.

The models are also not well calibrated with observations (Fig B.5b). When models forecast early or late onset dates, the observed onset is almost exclusively average. Again, this issue becomes more apparent in GS5 and GC2.0 compared to GS4 suggesting that there is no improvement in onset forecast quality. Forecasts appear to have little discrimination, poor calibration and poor reliability suggesting low quality forecasts. Furthermore, there appears to be no improvement, and in fact potentially a regression in quality between the coarser GS4 and the two higher-resolution forecasting models.

The quality of regional onset forecasts appears to be low in all three models studied. However, the importance of this result can be questioned given the very high proportion of observed onset dates occurring within one standard deviation of the long term mean. Given that the standard deviation of regional onset is approximately one week in observations, this suggests that the inter-annual variability of SJ10 is low enough to mitigate the associated risk caused by poor onset prediction (see the findings of Sultan et al. 2005). For practical purposes, although the three models fail to capture the inter-annual variability of regional onset, the variability is low enough that accurate mean onset date prediction may suffice for practical decision making.

5.2 Local onsets

A comparison of observational uncertainty and model sharpness for the five LORs considered is presented in Fig. B.6. For all five regions, average local onsets occur approximately 50-70% of the time. The most uncertain region is the NN LOR where average onset only occurs about 50% of the time. In the CT, MBF and CH regions, the amount of early and late onsets are approximately equal. Compared to observations, models tend to predict average onsets too much (with the notable exception of the BN region and to a lesser extent the CT region) and do not capture non-onset events as much as in observations. There is no substantial difference across the three model sharpness assessments across any of the LORs analysed. This is in contrast to the results found for the regional onset date SJ10. Furthermore, the bias in models is not consistent across regions suggesting that there is no simple statement which captures the whole error of models. Finally, there appears to be little improvement in model sharpness across the three generations of models considered. We therefore conclude that the increase in model resolution and improved dynamical core have not improved model sharpness. Overall however, model sharpness is not distinctly different from observations, confirming along with Fig. B.4 that the GloSea models can capture the mean local onset field reasonably well.

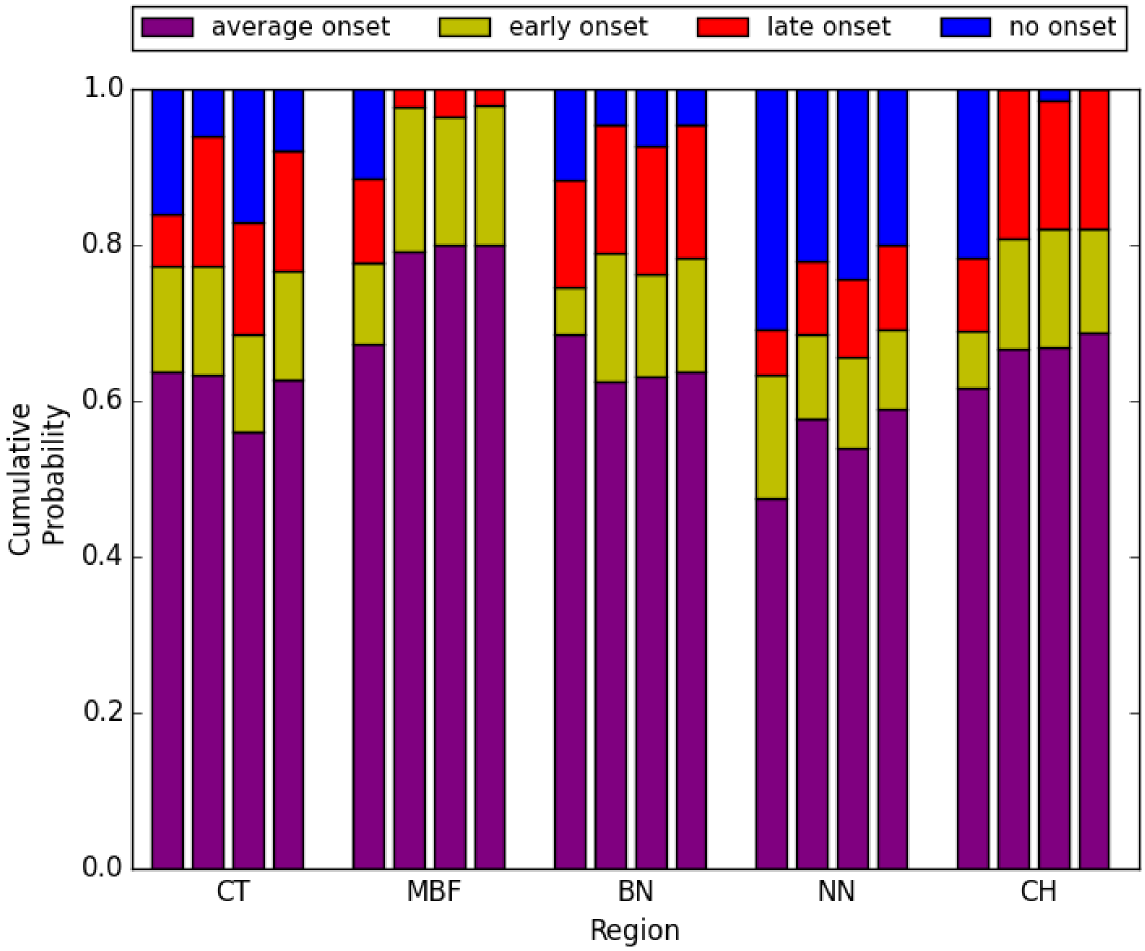

Figure B.6 - Comparison between observational uncertainty and model sharpness for local onset across the five LORs. For each of the five LOR regions presented in Table 2, the relative occurrence of average, early, late and no onset events are presented for (from left to right): TRMM v7 (at N96 resolution), GS4, GS5 and GC2.0.

Comparing observed local onset uncertainty with regional observed uncertainty suggests that the level of uncertainty in both local and regional onsets is similar. However, local, agronomic onsets have much higher inter-annual variability than regional onsets (Fitzpatrick et al. 2015). Therefore, it is possible to conclude that the value of accurate model forecasting for local onsets is of greater importance than accurate regional onset forecasting.

Figure B.7 shows the likelihood base-rate analysis for all five LORs across the three generations of GloSea studied. There is a propensity in all models to over-predict average local onset regardless of observed variability. This is highlighted by the large fraction of average onsets predicted (purple bars) in early and late onset years for all regions with one exception. Over the NN region, GS4 favours a prediction of “no onset” for late observed years. This is possibly caused by the relative lateness of onsets over the NN region in general (Fitzpatrick et al. 2015, their Fig. 8a). However, although GS5 and GC2.0 partially rectify this issue, there is still a tendency to over-predict average onsets.

In addition to the results of Fig. B.7, a single sided Brier Skill Score was performed for all three models on each of the five LORs separately. Results ranged from 0.4–0.5 suggesting little to no forecast skill was present. This result did not notably improve in more recent versions of the GloSea forecast nor were any regions notably better predicted.

As mentioned in Section 3.2, there is very little significant local correlation between observed onsets and the ensemble mean local onset dates from any of the three GloSea models. This lack of local correlation, coupled with the results of Fig. B.7 and the lack of inter-annual variability captured by the models suggests that the models cannot capture sufficient variability to accurately predict local onsets.

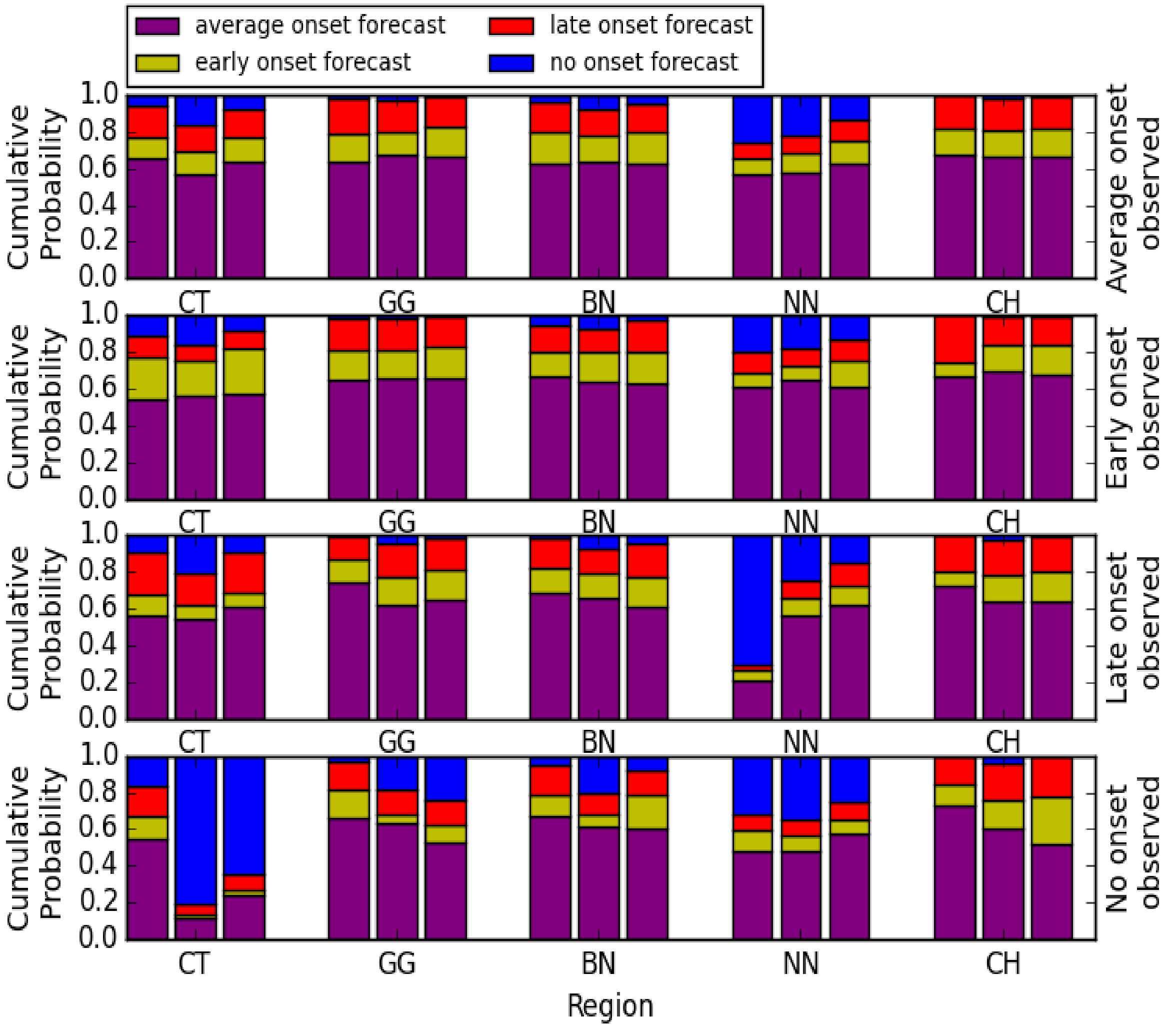

Figure B.7 - Likelihood base-rate assessment for the five LOR regions. For each of the five regions presented in Table 2, the model discrimination is presented for (from left to right): GS4, GS5 and GC2.0.

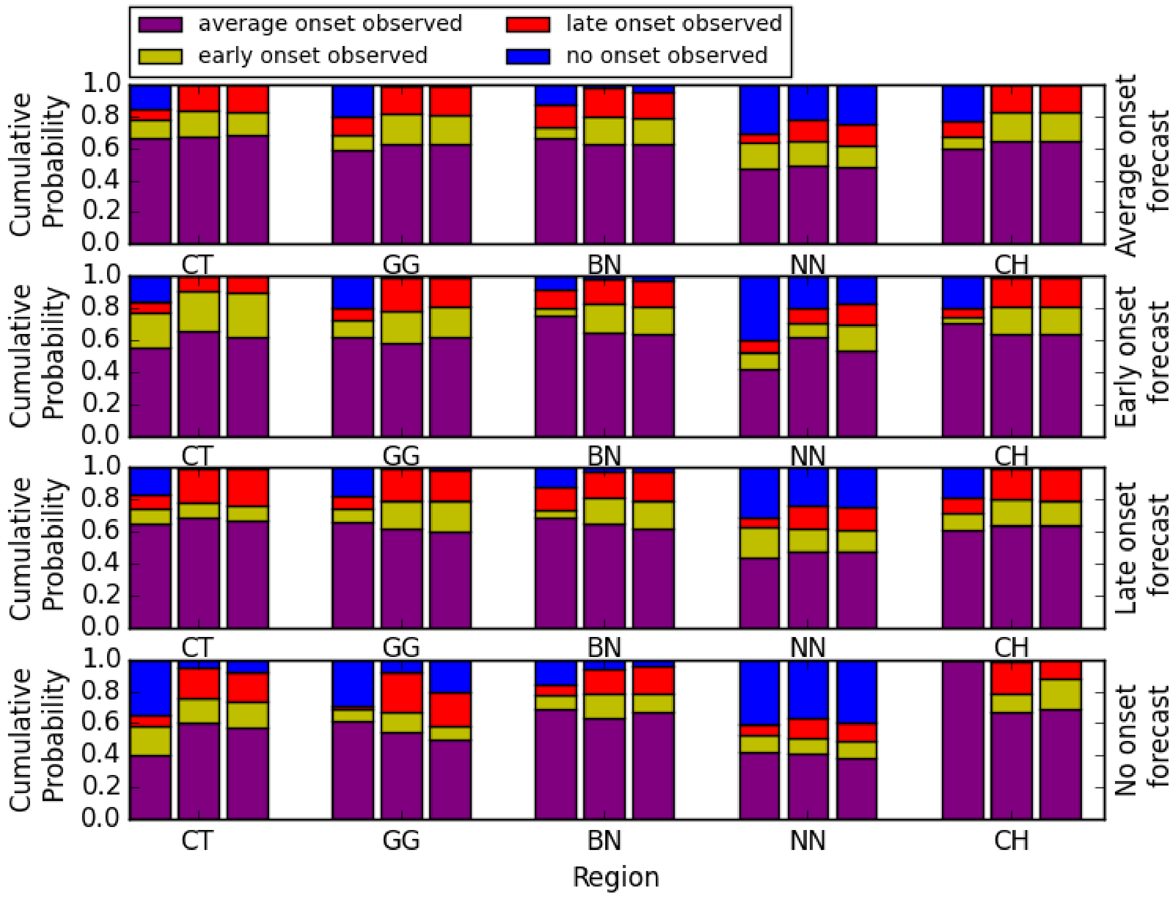

Figure B.8 - Calibration-refinement assessment for the five LOR regions. For each of the five regions presented in Table 2, the model discrimination is presented for (from left to right): GS4, GS5 and GC2.0.

Figure B.8 shows the calibration-refinement analysis for the three models and five LORs and is directly comparable to Fig. B.7. The results shown are broadly similar between the likelihood base-rate and calibration-refinement method. The GC2.0 and GS5 models cannot be said to be more calibrated than the GS4 model. In fact, for the CT region, the GS5 and GC2.0 hindcasts fail to capture "no onset" events as well as GS4. It appears that for local onsets, whilst the mean fields are reasonably well captured, the inter-annual variability is not well captured in any of the three models.

Through the three generations studied here, there is little improvement in the quality of onset forecasts. This suggests that the increase in resolution and the development of a new dynamical core has not improved onset forecasts. The cause of variability of local onsets has not yet been captured by improvements in the GloSea model.

6. Representation of the ITF

The northwards progression of the ITF can be thought of as a proxy for the seasonal advancement of moisture into West Africa. It follows that the further north the ITF is located, the higher the potential for rainfall in the northern parts of the Sahel. Figure B.9 compares the location of the ITF and associated dew-point temperature profile across West Africa preceding the regional monsoon shift in re-analysis data and the three hindcasts (note the different scales between Fig. B.9a and B.9b-d).

Overall, there exist widespread regions of high dew-point temperature behind the ITF in all three GloSea models that are not present in re-analysis (B.9a for ERA-Interim, B.9b-d for GS4, GS5 and GC2.0 respectively). Furthermore, the seasonal forecasts appear to have a more zonally consistent structure to dew-point values than seen in the ERA-I re-analysis. This suggests that there is potential for increased convection and precipitation in GloSea than seen in observations.

The inter-annual variability in dew-point temperature values is low in each of the three GloSea models. This is in contrast to observations which show more variability. Furthermore, there is no improvement in the representation of dew-point temperature in the higher-resolution models. Whether this lack of improvement is primarily due to the spatial resolution, convection scheme used or other factors is currently unknown.

The ITF advances further north in both GS5 hindcasts compared with GS4. In particular the ITF advance in GC2.0 is at least 2-3 degrees deeper into continental West Africa than that found in GS4. This suggests that there is potential for more frequent rainfall at higher latitudes in GS5 than in GS4. Interestingly, the pattern of dew-point temperature south of the ITF remains consistent between the three hindcasts. The dynamical, large-scale and local controls of the monsoon layer are not fully understood. However, it appears that the representation of the monsoon layer to the south of the ITF has not been better captured within more recent GloSea systems.

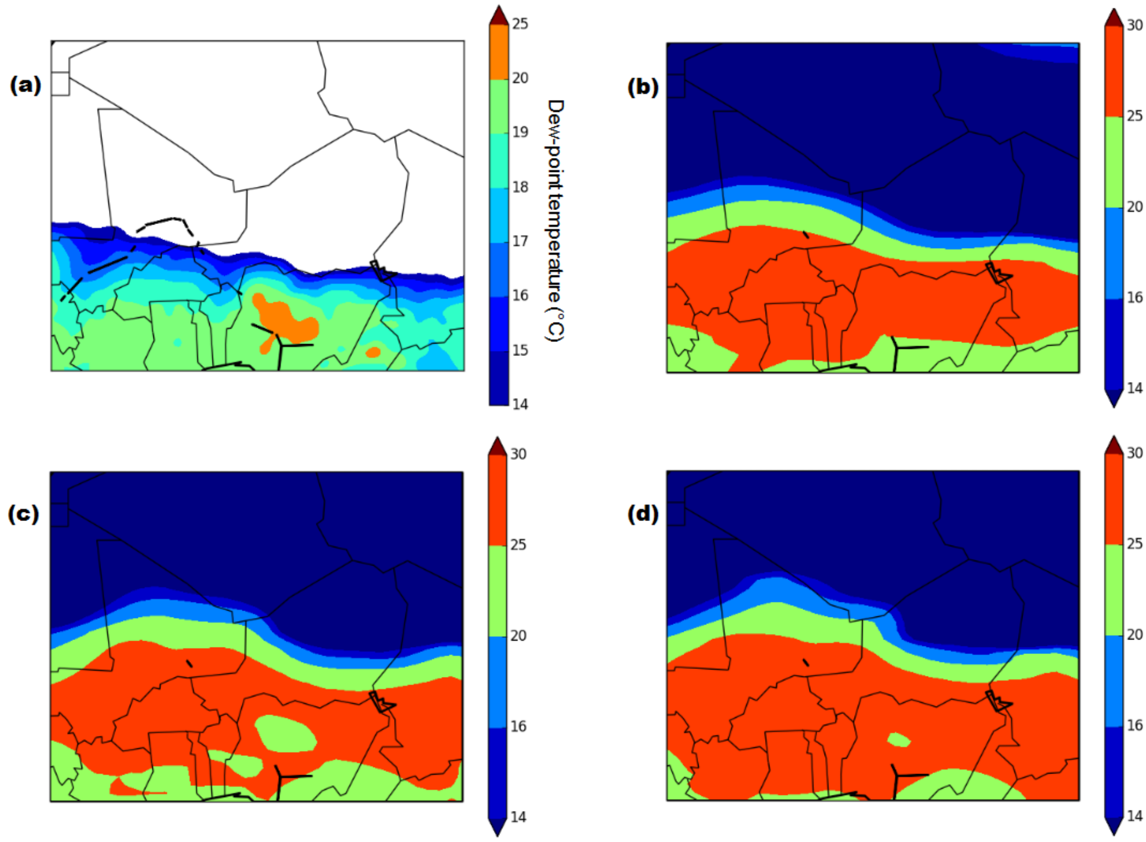

Figure B.9 – Comparison of ITF position and dew-point profiles over West Africa for re-analysis and model hindcasts. Average 925 hPa dew-point temperature profile for period 14 June – 24 June in (a) ERA-I, (b) GS4, (c) GS5 and (d) GC2.0. Location of the ITF is equal to the 14 degree isodrosotherm.

In conclusion, it appears that the impact of increased resolution within the GloSea forecasting systems is to shift the entire monsoon system further northwards. It is possible that superior representation of sea surface temperatures leads to a zonal shift of the monsoon regime to a more realistic latitude range. The dynamical structure of the monsoon regime is not improved however, suggesting that the dynamical controls over moisture across West Africa are not better captured in more recent iterations of GloSea. The findings presented here potentially explain why the zonally-averaged precipitation band is better captured in GC2.0 and GS5 than GS4 despite the lack of improvement in explicit onset date forecast.

7. Discussion and Conclusions

In order for meaningful and successful decisions to be made by forecast users over West Africa, skilful forecasts at a useful lead time are required. Here, the skill of three generations of the Met Office Unified Model, Global Seasonal forecast product (GloSea) have been evaluated. The consistency and quality of the models have been compared to give an indication of each model’s value.

Recent developments of GloSea have included an increase in resolution (from GloSea4 to GloSea5) and the integration of an improved dynamical core (from GloSea5 to GC2.0). Previous results have shown a better representation of the diurnal cycle and tropical storms in more recent generations of GloSea. However, these successes have not translated into an improvement of local onset forecast. It is possible that parameterisation of convection within seasonal forecasting impacts the quality of all three models. Very high resolution, convective permitting models have a superior representation of the diurnal cycle but may over-estimate precipitation leading to similar errors in forecasting of local onsets (Birch et al. 2014). How this issue can be rectified for threshold-based metrics is an ongoing problem deserving detailed exploration.

Regional onset definitions are commonly used over West Africa both for analysis and forecast verification. There is an apparent improvement in the representation of zonally-averaged precipitation across the monsoon region of West Africa through the three generations of GloSea. GC2.0 provides the most realistic representation of the seasonal progression of the maximum rain belt with the location of the zone of maximum precipitation closer to observations in the high resolution models. Higher-resolution models studied here are shown to better represent the abrupt shift (jump) of the maximum rain belt around late June which is observed in satellite data. When considering the explicit onset date however, none of the three models accurately predict the inter-annual variability of observed onset. Whilst the mean onset date and variability in each of the three models are similar to observations, there is little correlation or quality in each of the three models.

The quality of local onset dates forecast in all three models studied is poor. Models are shown to have little skill at discriminating between early, average and late onset dates and are poorly calibrated with observations. There is little reliability for any of the three models with only marginal improvements found from GS4 to the higher-resolution GS5 and GC2.0. Finally, there is little inter-annual variability forecast in local onset dates compared with observations. Given the high observed variability in the commencement of agronomic rainfall, coupled with the relevance of local onsets to farmers, the value of seasonal forecasts for local decision makers is limited.

Forecast value is a key aspect of forecast verification. An improvement in forecast value leads to a more valuable forecast and hence a “better” forecast. From the assessment presented here it is possible to argue that none of the three generations of the GloSea forecasting system analysed are unquestionably “better”. There is therefore no relative uplift to agronomic decision makers in using more recent iterations of the GloSea model for seasonal forecasts of onset dates (both local and regional).

The reason for the lack of quality increase across the three models is currently unknown. Whilst an increase in resolution (both over land and ocean) has led to a more realistic representation of the zonally averaged precipitation fields, it has not changed the accuracy of onset dates. From a local perspective, there seems to be a lack of appreciation of local dynamical triggers for agronomic onset dates across West Africa. Furthermore, regional forcing of local onset dates does not appear to have been accurately captured. It appears from the assessment presented here that spatial resolution and improved sea surface temperature representation are not providing immediate uplift in onset forecast quality. Identification of onset drivers substantially influence onset variability (both local and regional) should be of principle importance for the science community in order to better assess the deficiencies of seasonal forecasting models.

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