

# **Intraseasonal convective initiations – precursors and predictability**

विद्या वाचस्पति की

उपाधि की अपेक्षाओं की आंशिक पूर्ति में प्रस्तु शोध प्रबंध

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द्वारा / By

**डैनियल साइमन** / Daniel Simon

पंजीकरण सं. २०१८३६०६ / Registration No.: 20183606

शोध प्रबंध पर्यवेक्षक : **नीना जोसेफ मानी**

/ Thesis Supervisor: Neena Joseph Mani



भारतीय विज्ञान शिक्षा एवं अनुसंधान संस्थान पुणे

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# CERTIFICATE

Certified that the work incorporated in the thesis entitled “Intraseasonal convective initiations – precursors and predictability“ submitted by Daniel Simon was carried out by the candidate, under my supervision. The work presented here or any part of it has not been included in any other thesis submitted previously for the award of any degree or diploma from any other University or institution.



Signature of Thesis Supervisor

Dr. Neena J Mani

Associate Professor

Department of Earth and Climate Science

IISER Pune – 411008

Date: 19/11/2025



# Declaration by Student

Name of Student: Daniel Simon

Reg. No.: 20183606

Thesis Supervisor(s): Dr. Neena J Mani

Department: Earth and Climate Science

Date of joining program: 01 August 2018

Date of Pre-Synopsis Seminar : 21 May 2025

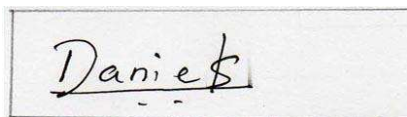
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Date: 19/11/2015

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Signature of the student

Mr. Daniel Simon

Department of Earth and Climate Science

ID no. – 20183606

IISER Pune – 411008

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# Contents

|                                                                                                                                                |           |
|------------------------------------------------------------------------------------------------------------------------------------------------|-----------|
| <b>Acknowledgements .....</b>                                                                                                                  | <b>4</b>  |
| <b>Abstract .....</b>                                                                                                                          | <b>8</b>  |
| <b>Chapter 1 .....</b>                                                                                                                         | <b>10</b> |
| <b>Introduction .....</b>                                                                                                                      | <b>10</b> |
| 1.1 The Madden–Julian Oscillation .....                                                                                                        | 10        |
| 1.2 Limitations in Predicting MJO Convective Initiation .....                                                                                  | 11        |
| 1.3 Proposed Mechanisms for MJO Convective Initiation .....                                                                                    | 12        |
| 1.4 Regional Heterogeneity in the Background State Over the Equatorial Indian Ocean:<br>Implications for MJO Convective Initiation .....       | 14        |
| 1.5 Aim and Scope of the Thesis.....                                                                                                           | 16        |
| <b>Chapter 2 .....</b>                                                                                                                         | <b>19</b> |
| <b>Regional and Seasonal Characteristics of Intraseasonal Oscillation Initiations in the Indian<br/>Ocean .....</b>                            | <b>19</b> |
| 2.1 Introduction .....                                                                                                                         | 19        |
| 2.2 Data and Methods .....                                                                                                                     | 20        |
| 2.2.1 Datasets and Preprocessing .....                                                                                                         | 21        |
| 2.2.2 Identification of MJO Convective Initiations.....                                                                                        | 22        |
| 2.3 Results and Discussion .....                                                                                                               | 24        |
| 2.3.1 Preferred locations of Indian Ocean MJO Initiations .....                                                                                | 24        |
| 2.3.2 SST control on the preferred locations of MJO Initiations .....                                                                          | 28        |
| 2.3.3 Instability build-up over the initiation domains.....                                                                                    | 32        |
| 2.3.4 Cloud Evolution over the initiation domains .....                                                                                        | 35        |
| 2.4 Summary and Conclusions .....                                                                                                              | 36        |
| <b>Chapter 3 .....</b>                                                                                                                         | <b>39</b> |
| <b>Preconditioning of Instability and Moistening Prior to Indian Ocean MJO Initiation: Role<br/>of Large-Scale Circulation Responses .....</b> | <b>39</b> |
| 3.1 Introduction .....                                                                                                                         | 39        |
| 3.2 Data and Methods .....                                                                                                                     | 41        |
| 3.3 Results and discussion .....                                                                                                               | 42        |

|                                                                                                    |           |
|----------------------------------------------------------------------------------------------------|-----------|
| 3.3.1 Instability Buildup Prior to Convection Initiation.....                                      | 42        |
| 3.3.2 Planetary boundary layer moisture budget analysis .....                                      | 44        |
| 3.3.3 Planetary boundary layer circulation responses and horizontal moisture advection...          | 48        |
| 3.4 Summary and Conclusions .....                                                                  | 52        |
| <b>Chapter 4 .....</b>                                                                             | <b>54</b> |
| <b>Role of MRG in Indian Ocean MJO Convective Initiation and Predictability .....</b>              | <b>54</b> |
| 4.1 Introduction .....                                                                             | 54        |
| 4.2 Data and Methods .....                                                                         | 55        |
| 4.2.1 Identification of MJO Initiation Events .....                                                | 55        |
| 4.2.2 Detection of MRG Activity Using EMD.....                                                     | 56        |
| 4.2.3 Diagnostics of MRG Structure and Energetics.....                                             | 56        |
| 4.2.4 S2S model reforecasts .....                                                                  | 57        |
| 4.2.5 Synoptic and MJO Signal Extraction in S2S models.....                                        | 57        |
| 4.2.6 ROMI Calculation in Models.....                                                              | 57        |
| 4.2.7 Model MJO Skill Metric .....                                                                 | 58        |
| 4.2.8 Observational Datasets .....                                                                 | 58        |
| 4.3 Results and discussion .....                                                                   | 59        |
| 4.3.1 MRG activity preceding MJO Onset: .....                                                      | 59        |
| 4.3.2 Case Study Evidence: Upper and Lower Tropospheric MRG Activity and EKE<br>Accumulation ..... | 63        |
| 4.3.3 Role of MRG Waves in MJO initiation Predictability in S2S Model reforecasts.....             | 68        |
| 4.3.4 MRG–Convection Coupling in CMA & NCEP Model reforecasts .....                                | 70        |
| 4.4 Summary and Conclusions .....                                                                  | 72        |
| <b>Chapter 5 .....</b>                                                                             | <b>74</b> |
| <b>Summary and Conclusions .....</b>                                                               | <b>74</b> |
| <b>References .....</b>                                                                            | <b>78</b> |
| <b>Manuscript submitted.....</b>                                                                   | <b>88</b> |

# Abstract

The equatorial Indian Ocean is widely recognized as a key region for Madden–Julian Oscillation (MJO) convective initiation, but it does not behave as a single, uniform initiation basin. Instead, strong zonal and seasonal contrasts in sea surface temperature, moisture, and circulation create distinct environments in the western (WEIO) and eastern (EEIO) equatorial Indian Ocean. This thesis identifies the locations where MJO convective initiations occur within the basin and examines the physical processes that lead to intraseasonal convective initiations in these subregions, with a particular focus on their thermodynamic and dynamical precursors, as well as the implications for subseasonal prediction.

Using the OLR MJO Index (OMI) over the period 1979–2021, 83 MJO convective initiation events are identified, with 41 occurring during boreal winter and 42 during summer. Two preferred initiation regions are identified: one over the WEIO, where initiations are more frequent and displaced off the equator—to the south in winter and north in summer—and the other over EEIO, where initiations are less frequent but remain near the equator and are associated with relatively strong convection. Winter initiations are preceded by a quiescent MJO convective state, while summer initiations follow vigorous earlier MJO activity. During boreal summer, the Indian Ocean Dipole (IOD) modulates where initiation occurs, with positive (negative) IOD phases favoring WEIO (EEIO) initiations. In winter, initiations do not exhibit any such preference, suggesting a minimal role of IOD influence, indicating a significant role by local intraseasonal processes.

Examining the thermodynamic features, with a focus on winter initiations, reveals two distinct initiation regimes. Over the EEIO, column instability increases rapidly (within  $\sim 9$  days) before initiation, whereas it is gradual over WEIO (within  $\sim 2$  weeks). Column instability buildup in both regions is driven by moistening in the planetary boundary layer (PBL) and deep cooling above with both factors having a relatively large magnitude over EEIO. Because PBL moistening is a key contributor to the buildup of tropospheric instability in both regions, with a more rapid increase over the EEIO than the WEIO, we examine the processes responsible for this moistening using a moisture budget analysis. This analysis shows that the strong PBL moistening over EEIO

is primarily driven by horizontal moisture advection associated with strong intraseasonal easterlies, which arise as an anticyclonic Rossby response to suppressed convection over the Maritime Continent acting on a strong background zonal moisture gradient. In contrast, WEIO moistening is controlled primarily by the evaporation of shallow clouds and precipitation in a subsiding pre-initiation environment, with a secondary contribution from horizontal moisture advection by weaker intraseasonal easterlies acting on a weaker background moisture gradient; together, these processes lead to a relatively gradual moistening.

This thesis also examines the role of precursor Mixed Rossby–Gravity (MRG) waves in MJO convective initiations and their predictability. During boreal winter, about 40% of WEIO and 35% of EEIO initiations are preceded by low-level MRG activity, compared with only around 10–12% in summer. Further focusing on winter WEIO initiations, it is found that most MRG-preceded cases exhibit a clear top–down eddy kinetic energy dispersion pathway proposed by Takasuka et al., 2021, in which upper-tropospheric MRG amplification during the suppressed phase is followed by the development of lower-tropospheric MRG wave packets leading to MJO convective initiation and following eastward propagation. Reforecasts from two S2S models (NCEP and CMA) show that the impact of MRG precursors on initiation skill depends strongly on how the MRG-convection coupling is in each model.

Overall, this work shows that MJO convective initiation over the Indian Ocean is characterized by regionally varying regimes, majorly controlled by background moisture gradients, intraseasonal Rossby responses to suppressed convection, and MRG waves dynamics. The results highlight how diverse the initiation processes are within the basin and checking whether forecast models can reproduce this diversity is a useful way to test how realistically they represent MJO dynamics.

# Chapter 1

## Introduction

### 1.1 The Madden–Julian Oscillation

The Madden-Julian Oscillations (MJO) is the dominant mode of tropical intraseasonal variability characterized by the eastward movement of a large-scale convective envelope coupled with the circulation anomalies along the equator with a typical periodicity of 30-90 days and an average phase speed of around 5 m/s (Madden and Julian, 1971, 1972). The structure of this planetary-scale system, typically initiated over the Indian Ocean, consists of large-scale convection active regions and low-level convergence flanked to the east by suppressed convection and low-level divergence, dynamically linked by the easterlies in the low level and westerlies aloft. As this convection-circulation coupled system propagates eastward across the Maritime continent into the Pacific, it tends to weaken and decouples beyond the dateline where the cooler sea surface temperatures(SSTs) inhibit deep convection. However, the associated circulation anomalies, especially those in the upper troposphere, can continue propagating eastward, leading to or aiding another MJO event upon arrival over the Indian Ocean(Knutson & Weickmann, 1987; Zhang, 2005). During boreal summer, apart from the eastward-moving convective component, MJO exhibits an additional northward propagating component from the equatorial Indian Ocean into the South Asian monsoon region often called as Monsoon Intraseasonal Oscillations(MISO; Sikka & Gadgil, 1980; Krishnamurti & Subrahmanyam, 1982; Lorenc, 1984; Cadet, 1986; Wang & Rui, 1990).

Together the boreal winter and summer manifestations of this tropical, planetary-scale convectively coupled system, exerts a significant influence on a wide range of weather and climate phenomena over both tropical and extratropical regions(Webster et al., 1999; Lau & Waliser, 2005; Zhang, 2005, 2013) modulating monsoons (Krishnamurty & Bhalme, 1976; Yasunari, 1979; Gadgil & Asha, 1992; Goswami & Mohan, 2001; Hoyos & Webster, 2007), tropical cyclogenesis (Maloney & Hartmann, 2000; Schreck & Molinari, 2011; Klotzbach, 2010), and interacting with



interannual variability modes including El Niño–Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) (Lau & Chan, 1988; McPhaden, 1999; Rao & Yamagata, 2004; Han et al., 2007; Zhang et al., 2021).

## **1.2 Limitations in Predicting MJO Convective Initiation**

Despite decades of research, predicting the initiation of MJO convection remains a significant challenge for forecasting models (Kim et al., 2014; Kim et al., 2018; Lim et al., 2018; Wang et al., 2019; X. Fu et al., 2013; Wei et al., 2023). Eventhough, Many current-generation dynamical models can predict the MJO evolution 3–4 weeks in advance(Kim et al., 2014; Lim et al., 2018; Wang et al., 2019), skill for initiation remains significantly lower(Neena et al., 2014; Kim et al., 2018; X. Fu et al., 2013; Wei et al., 2023).

The primary initiation of MJO convection involves the onset of organized large-scale convection from a quiescent MJO state, and secondary or successive initiations follow a prior MJO event (Straub, 2013). Fu et al., 2013 using model simulations of the DYNAMO MJO events, demonstrated that initiation could be predicted with a lead time of up to two weeks. More recent studies based on the Subseasonal to Seasonal Prediction Project (S2S) reforecasts indicate typical initiation predictability near 18 days(Wei et al., 2023). For the primary initiations, the predictability extends to about 24 days when westward propagation of intraseasonal convective precursors near the dateline precedes initiation, decreasing to about 16 days without such precursors (Wei et al., 2023).

In summary the initiation is systematically less predictable than its subsequent evolution. It is also evident that initiation skill depends on the presence and representation of precursor signals. Thus suggest the necessity for improved understanding of the physical processes and precursors associated with MJO convective initiation, in particular over Indian Ocean, where many events originate.

## 1.3 Proposed Mechanisms for MJO Convective Initiation

Various mechanisms have been proposed to explain MJO initiation, spanning a range of spatial and temporal scales. Some mechanisms are linked to prior MJO activity ('internal' processes), while others are largely independent of preceding MJO convection ('external' processes). All these mechanisms ultimately converge on the buildup of tropospheric column moisture and instability, which are essential for the onset of MJO convective onset.

A notable mechanism that operates independently of prior MJO convection is the gradual local column moistening and instability buildup-referred to as the recharge phase- with clouds progressively deepening and moistening the troposphere from the surface upward leading to deep convection and precipitation(discharge phase), which ultimately stabilizes the column (Bladé and Hartmann 1993; Benedict & Randall, 2007): a process taking about 10-20 days. However, the MJO initiations during the intensive observation period (October 1, 2011, to January 15, 2012) of the DYNAMO field campaign witnessed rapid tropospheric moistening on a time scale of about 3–7 days(Powell & Houze, 2014; Johnson & Ciesielski, 2013). Based on the TRMM data, Xu and Rutledge (2016) found that roughly half of the MJO events over the Indian Ocean exhibit gradual buildup(~10-20 days). However, a significant portion-around 25%, demonstrates rapid buildup, with timescales shorter than 7 days(Xu & Rutledge, 2016). This suggests that MJO initiation can often occur on much quicker timescales than previously thought, thus indicating that multiple processes, leading to both fast and slow instability buildup, can sometimes operate together to lead to the MJO convective initiations.

Another pathway emphasizes on the role of large-scale Rossby response to preceding suppressed convection. Suppressed anomalies over the Indian Ocean, whether locally generated (Matthews, 2008; Ling et al., 2013) or as part of a prior MJO event (Zhao et al., 2013; Mei et al., 2015; Li et al., 2015; Maloney & Wolding, 2015; Takasuka & Satoh, 2020), can generate anticyclonic Rossby gyres straddling the equator to the West and the associated intraseasonal easterlies transport moisture from the EEIO and Maritime continent region into the WEIO, creating favorable conditions for convective onset over WEIO. This downstream forcing has been recognized as a key factor leading to MJO initiations in the Indian Ocean basin, both based on reanalysis-based composite studies(Matthews, 2000; Zhao et al., 2013; Takasuka & Satoh, 2020;

Wang & Li, 2022), case studies(Li et al., 2015), and based on model studies(Maloney & Wolding, 2015; Takasuka et al., 2018).

Equatorial Kelvin waves triggered by preceding MJO convection over the western Pacific can lead to MJO convective initiation. These waves propagating eastward along the equator, on reaching the Indian Ocean(in  $\sim 2$ -3 weeks) induce boundary layer convergence, upward motions and increased moistening, aiding the convective initiation (Matthews, 2000; Kikuchi & Takayabu, 2003; Powell & Houze, 2015; Snide et al., 2022). However, the role of Kelvin waves remains debated: some reanalysis and modeling studies argue that Kelvin waves are not critical for Indian Ocean MJO onset (Zhao et al., 2013) though they may influence the convective intensity once initiated (Maloney & Wolding, 2015; Takasuka & Satoh, 2020). They likely contribute to enhancing convection, particularly over moisture-rich EEIO regions.

Recent studies have highlighted the importance of high-frequency disturbances, particularly Mixed Rossby–Gravity (MRG) waves, in triggering MJO initiations over the southwestern equatorial Indian Ocean (Takasuka et al., 2018; Takasuka et al., 2019; Takasuka & Satoh, 2020; Takasuka et al., 2021). These disturbances, typically present in the mid to upper troposphere during the suppressed MJO phase, amplify under the influence of background circulation and disperse energy downward and eastward, leading to the formation of lower-tropospheric MRG wave packets and off-equatorial convergence, thus leading to MJO convective initiations and aiding the subsequent propagation(Takasuka et al., 2018; 2019; 2020; 2021). Apart from the dynamic role, the shallow circulations associated with these waves efficiently transport moisture over the Indian Ocean on a basin scale, especially in the mid troposphere, thus preconditioning the column for a rapid convective outbreak. These processes have been confirmed through field campaigns, reanalysis composites, and modeling studies(Takasuka et al., 2018; 2019; 2020; 2021).

In addition, processes originating outside the tropics('external processes'), such as extratropical Rossby waves, are suggested to lead to triggering MJO convective initiations. Rossby waves can penetrate into the tropics when upper-level flow is westerly—a condition that prevails over the Indian Ocean during boreal winter—allowing wave activity from the African–Asian Jet or the southern Indian Ocean to influence initiation (Hsu et al., 1990; Zhao et al., 2013; Mei et al., 2015). Matthews (2008) observed that high-frequency Rossby waves from the extratropics

influence secondary ISO events, while primary ISO events remain unrelated to extratropical wave influences.

All of these atmospheric processes discussed- from local moisture buildup to remote largescale wave influences- act on a background that exhibits pronounced regional and seasonal contrasts in the Indian Ocean basin where MJO initiations occur most frequently (Zhao et al., 2013; Zhang and Ling, 2017). In the next section the role of regional contrasts in the background state over the Indian Ocean and its implications for MJO convection is elaborated.

## **1.4 Regional Heterogeneity in the Background State Over the Equatorial Indian Ocean: Implications for MJO Convective Initiation**

The eastward propagation of MJO convection is restricted to west of the dateline over the Pacific, mainly due to the fact that the conditions over the eastern Pacific are not conducive for deep convection. The warm sea surface temperature (SST) over the Indian Ocean, meanwhile, ensures a strong eastward propagating convective MJO signal over the Indian Ocean, whose propagation to the Western Pacific is sometimes impacted by the Maritime continent (Hendon and Salby 1994; Kim et al. 2014). Nevertheless, the MJO is considered as an oscillating dipole between the Indian Ocean and the western Pacific, while the MJO circulation anomalies circumnavigate the globe (Knutson & Weickmann, 1987; Zhang, 2005).

Although the zonal asymmetry in the climatological mean SST distribution over the Indian Ocean is not as pronounced as that over the Pacific, significant SST anomalies develop over the eastern and western parts of the basin on both seasonal and interannual timescales. The smaller spatial scale, together with the landlocked nature of the basin, makes it a domain of interesting atmosphere-ocean dynamics. Heating of the Asian landmass to the north leads to the northward migration of the ITCZ in summer. As the MJO propagation is strongly tied to the ITCZ dynamics, the MJO exhibits northward propagation characteristics over the region (Sikka & Gadgil, 1980; Cadet, 1986; Lau & Chan, 1986).

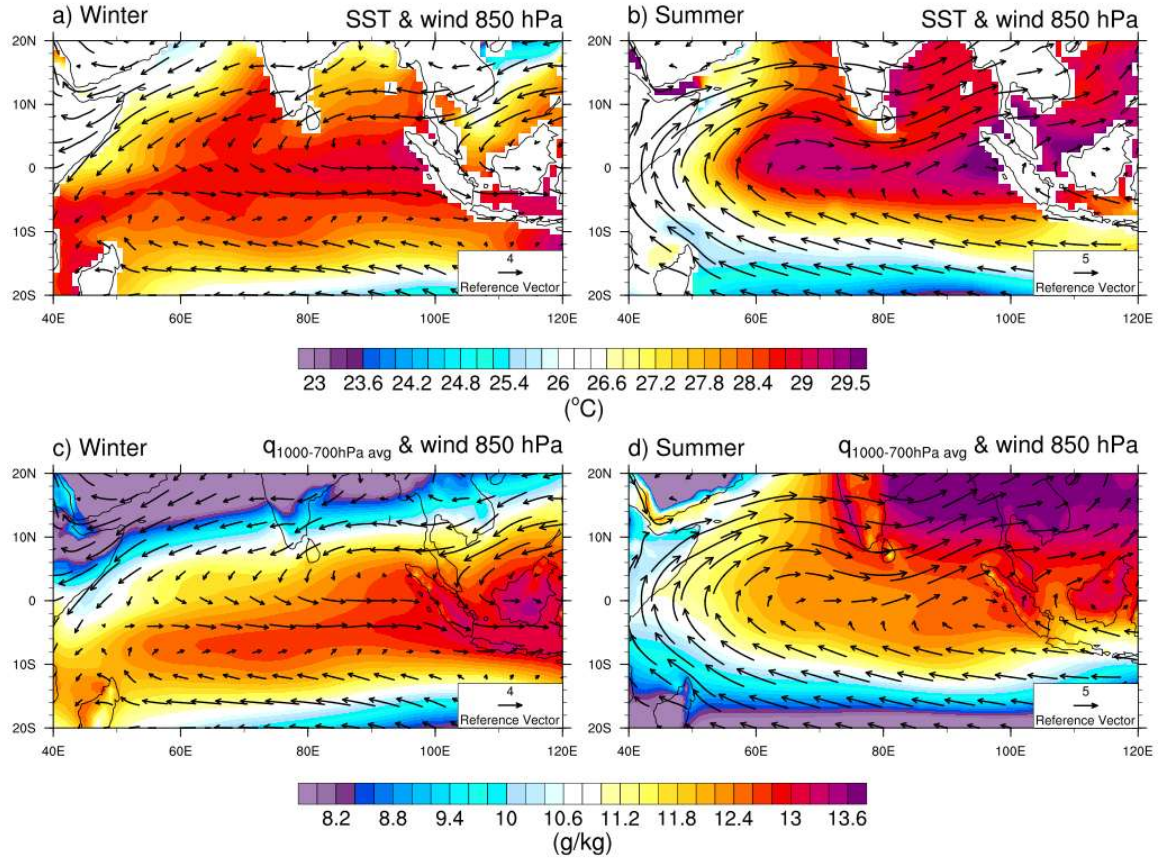


Figure 1.1 Boreal winter (November–March) and summer (May–September) mean (a & b) SST (shading; K) and 850-hPa horizontal winds (vectors;  $\text{m s}^{-1}$ ) (c & d) 1000–700 hPa average specific humidity ( $\text{g kg}^{-1}$ ) and 850 hPa winds over the Indian Ocean.

Westerly winds are mostly prevalent over the equatorial Indian Ocean and they contribute to the accumulation of warm waters over the eastern part of the basin. The warmest SSTs are observed over the region with the SST decreasing westward (Figure 1.1 a & b). Consistent with the SST the specific humidity distribution also exhibits a strong zonal gradient with relatively high moisture levels over the Maritime Continent (MC) and EEIO and decreasing drastically westward (Figure 1.1 c & d). As the thermodynamic conditions are more favorable for deep convection over the EEIO, the Indian Ocean Walker circulation ascends over the EEIO and descends over the WEIO. Over the EEIO, the SSTs are maintained at relatively high values throughout the year, while over the western Indian Ocean, the SSTs undergoes pronounced seasonal variations under the influence of the change in wind fields associated with the summer monsoon (Figure 1.1 a & b). During summer, in addition to the zonal gradient in humidity distribution, a very strong meridional gradient is also observed over the domain, as a resultant of the humidity accumulation

over the Asian monsoon region (Figure 1.1 c & d). During boreal winter, the warmest SSTs over the WIO are observed to the south of the equator, while during summer, the southwesterly monsoon winds induce upwelling and cooling over the region, and the warmest SSTs are observed to the north of the equator. The upper oceanic structure over the western equatorial Indian Ocean is marked by a shallow mixed layer and raised thermocline, which makes it susceptible to even small changes in the wind field (Xie et al., 2002, Schott et al., 2009). Studies indicate that intraseasonal fluctuations in SST driven by atmospheric forcing and oceanic dynamical processes involving oceanic Rossby waves, reduced upwelling, and weaker entrainment of cooler subsurface water can generate warm SST anomalies over the region which can trigger deep convection in the intraseasonal time scale (Vialard et al., 2008; Yokoi et al., 2008, West et al., 2018, 2020), Hence despite being climatologically less conducive for deep convection, the WEIO has been long been identified as the region of MJO convective onset over the Indian Ocean. However, very little attention has been given to the question of whether MJO initiations can occur over any other region in the Indian Ocean. Using a diagnostic approach for identifying MJO initiations, West et al. (2020) showed that the initiation domain is not confined to the western basin but can also extend into the eastern Indian Ocean. Although the EEIO, characterized by relatively warmer SST and higher abundance of humidity, is known to be more conducive for deep convection, it has not received as much attention as the WEIO in being a preferred location for MJO initiation. The impact of the seasonal shift in SST patterns on the preferred locations of MJO initiations and the seasonal differences in MJO convective initiations are other relevant aspects that deserves more attention.

Thus the MJO initiation depends not only on precursor disturbances but also on regional background state contrasts in SST, Moisture, and circulation and how it varies in seasonal and interannual time scales. In particular, understanding why and when initiations occur over different subregions of the Indian Ocean and how it varies between boreal winter and summer remains an open question.

## **1.5 Aim and Scope of the Thesis**

In light of the fact that MJO convective initiations over the Indian Ocean occur in distinct subregions with diverse oceanic and atmospheric background states, this thesis aims to identify and understand the key processes leading to MJO convective initiation in this basin.

In the second chapter, the MJO initiations over the Indian Ocean are objectively identified using the OMI index and further classified into subregions based on the regions of MJO convective initiation. Further, the potential role of the Indian Ocean interannual variability in the background state, specifically the Indian Ocean Dipole(IOD), is examined to understand if large-scale slowly varying modes influence the preferred regions of MJO convective initiations. Further, the precursor signals in convection, instability buildup, clouds, and circulations are examined in detail for the Boreal winter MJO initiations over the Indian Ocean sub-regions. subsequently based on the MJO initiation identified, the similarities and differences among the subregions are examined. Through this analysis, the chapter establishes the fundamental spatiotemporal characteristics of Indian Ocean MJO initiations and provides the baseline for the process-level investigations in the subsequent chapters.

In the third chapter, the factors leading to the lower tropospheric instability buildup over the MJO initiation subregions of the Indian Ocean are examined in detail, focusing on the boreal winter season. Particularly, the role of large-scale circulation responses associated with equatorial Rossby and Kelvin waves linked to precursor convective signals in leading to moistening and instability buildup during preinitiation is examined in detail. By contrasting the structure and magnitude of these processes across different initiation subregions, this analysis will provide evidence of regional similarities and differences that may be crucial for the initiation.

In the fourth chapter, the role of the high-frequency equatorial disturbances, particularly the MRG waves on MJO initiations over the Indian Ocean, is systematically explored. Specifically, by diagnosing the lower tropospheric MRG activity, the Indian Ocean MJO initiations over the subregions are categorized into those preceded by and those without such precursors. Particular emphasis is given to WEIO, where off-equatorial warm anomalies and background circulation patterns during both seasons create an environment favorable for MRG-induced low-level convergence and convective triggering (Takasuka et al., 2021). Further, the WEIO provides a dynamically favorable environment for upper tropospheric MRG waves to disperse downward, forming lower tropospheric MRG wave packets, triggering MJO convective initiations (as per the case study by Takasuka et al., 2021). Hence, the WEIO initiation is focused on seeing how many WEIO MJO initiations show evidence of the top-down energy dispersion mechanism as proposed by Takasuka et al. (2021). Finally, the analysis evaluates whether the MRG precursor enhances the

MJO convective initiation skill over the Indian Ocean, relying on the reforecasts available as part of the subseasonal to seasonal prediction project.

Chapter 5 summarizes the thesis work and discusses the future direction of work.



# **Chapter 2**

## **Regional and Seasonal Characteristics of Intraseasonal Oscillation Initiations in the Indian Ocean**

### **2.1 Introduction**

Convective initiation of the Madden-Julian Oscillation (MJO) remains one of the least understood processes in MJO dynamics and one of the main challenges in addressing this problem lies in the difficulty in objectively identifying MJO initiations. Primary initiation of MJO convection is identified as the development of shallow convection from a quiescent MJO state, followed by its organization into large-scale deep convection exhibiting MJO characteristics and eastward propagation along the equator. Secondary or successive MJO initiations are categorized as those which occur in succession to a preceding MJO event (Mathews 2008, Straub, 2013). The most common approach used for identifying MJO initiation is based on the day when the intraseasonally filtered OLR or precipitation anomalies over an arbitrarily or empirically chosen domain over the Indian Ocean transition from positive to negative values (Li et al., 2015, Ling et al., 2013, Zhao et al., 2013, Mei et al., 2015). Considering the ease of usage, popularity and forecast applicability, several studies (eg, Straub 2013, Ling et al., 2014, West et al., 2018, West et al., 2020) have also identified the MJO initiations using real-time monitoring MJO indices, such as the Real-time Multivariate MJO (RMM) index (Wheeler & Hendon, 2004) and the OLR MJO Index (OMI, Kiladis et al., 2014). Globally, Straub (2013) identified 28 primary and 376 secondary boreal winter MJO initiations during 1979–2010 using an RMM index based identification method. However, Li et al., (2015) pointed out that the RMM index having a higher contribution from MJO circulation, may not accurately capture the timing and location of MJO convective initiations, and a convection based metric will be more preferable for identifying the MJO convective initiations.

Several studies employing different approaches have consistently identified the western Indian Ocean as the preferred location for MJO convective initiation (Zhao et al., 2013; Mei et al.,

2015; Zhang & Ling, 2017; Wang and Li, 2022). Wang and Li (2022), using an objective cluster analysis of MJO convection, identified that nearly two-thirds (66%) of boreal winter MJO initiations occurred over the Indian Ocean, approximately twice the frequency compared to any other region. Takasuka and Satoh (2021), using an approach which combined precipitation and OLR tracking, similarly found that ~58% of all warm-pool initiations are observed over the Indian Ocean. Matthews (2008), using an OLR-based index, identified 1–2 primary and 2–3 successive MJO initiations per year over the Indian Ocean, with more frequent occurrences during boreal winter. The Indian Ocean initiations mostly outnumbered those in the Maritime Continent and western Pacific combined. Meanwhile, Ling et al. (2014), using some constraints on the rainfall anomalies and the RMM index evolution, found that 57% of the Indian Ocean MJO initiations during boreal winter were primary in nature. Furthermore, West et al. 2020, using the OMI, found that 71% of MJO initiations occurred over WEIO and 24% over the eastern equatorial Indian Ocean (EEIO), and a few over the northwestern equatorial Indian Ocean.

The Indian Ocean domain is very dynamic in the sense that the ocean-atmosphere coupled processes can together drive large scale variations in SST, humidity, convection and winds over the region, in the intraseasonal, seasonal, as well as in the interannual timescale (Waliser et al., 2003, Vialard et al., 2008). As discussed in Chapter 1 of the thesis, the background state over the equatorial Indian Ocean exhibits strong east-west asymmetry and the region is also impacted by largescale variations due to the wind reversal associated with the South Asian monsoon. The zonal and meridional diversity in the mean field over the region implies that, over different subdomains over the Indian Ocean, diverse mechanisms might be operational in driving the destabilization processes responsible for triggering convection in the intraseasonal scale. Nevertheless, studies investigating the preconditioning processes behind Indian Ocean MJO convective initiations have mostly overlooked the variability of MJO initiations within the basin. In this Chapter, the diversity of Indian Ocean MJO convective initiations is addressed in the context of: frequency of occurrence and its sensitivity to the background state, local instability buildup and convection strength.

## **2.2 Data and Methods**

For addressing the thesis objectives outlined in Chapter 1, it is necessary to objectively identify the MJO initiations, using a metric that can be easily adapted in predictability studies. In this chapter, MJO convective initiations over the Indian Ocean are objectively identified and the

thermodynamic characteristics and cloud evolution associated with the convective initiations are investigated. The methods are described in detail below.

## 2.2.1 Datasets and Preprocessing

To characterize the large-scale thermodynamic and dynamic features associated with MJO initiation, a range of satellite and reanalysis datasets for the period 1979-2021 were used:

- Daily Outgoing Longwave Radiation (OLR) data with a spatial resolution of  $2.5^\circ \times 2.5^\circ$  from NOAA (Liebmann & Smith, 1996), were used to extract convective features associated with the MJO events.
- Daily-averaged temperature, specific humidity, and vertical velocity data, at pressure levels from 1000 hPa to 200 hPa, with a spatial resolution of  $1^\circ \times 1^\circ$ , obtained from ECMWF Reanalysis (ERA5) (Hersbach et al., 2018, 2020), were used to compute the vertical profiles of moist static energy (MSE) and other thermodynamic parameters.
- Daily Optimum Interpolation Sea Surface Temperature (SST) data with a spatial resolution of  $1^\circ \times 1^\circ$  was obtained from NOAA (OISST Version 2.1, Reynolds et al., 2007; Banzon et al., 2016; Huang et al., 2021), The product combines satellite observations (AVHRR and VIIRS) and in-situ measurements and is accessible at : <https://psl.noaa.gov/data/gridded/data.noaa.oisst.v2.highres.html>.
- The cloud top pressure (CTP)– cloud optical thickness ( $\tau$ ) joint histograms constructed following the International Satellite Cloud Climatology Project (ISCCP) cloud classification criteria (Rossow & Schiffer, 1991) available from MOD08\_D3 product, part of MODIS Collection 6.1, based on the MODIS sensor aboard the Terra satellite (equatorial overpass time: 10:30 local time), offers daily global measurements at a  $1^\circ \times 1^\circ$  spatial resolution (King et al., 2013) for the period 2000-2021. These histograms providing counts of valid/nonmissing pixels in each CTP- $\tau$  bin range (Hubanks et al., 2008) is used in this study to understand the cloud evolution features associated with MJO convective initiations. This publicly available dataset used can be found at the following link: [https://ladsweb.modaps.eosdis.nasa.gov/archive/allData/61/MOD08\\_D3/](https://ladsweb.modaps.eosdis.nasa.gov/archive/allData/61/MOD08_D3/).
- Monthly values of the Dipole Mode Index (DMI) derived from the HadISST were downloaded from (<https://psl.noaa.gov/gcos wgsp/Timeseries/Data/dmi.had.long.data>). The

DMI is calculated as the difference between SST anomalies averaged over the western equatorial Indian Ocean (50°E–70°E, 10°S–10°N) and the southeastern equatorial Indian Ocean (90°E–110°E, 10°S–0°).

Intraseasonal variability was extracted by applying 20–90-day bandpass filter(Duchon, 1979) after removing the climatology from the data sets. Interannual variability was obtained using a low-pass filter with a cutoff period of greater than 90 days, allowing for the examination of the background state during MJO initiation.

## 2.2.2 Identification of MJO Convective Initiations

MJO convective initiations over the Indian Ocean were identified using the OLR MJO Index (OMI; Kiladis et al., 2014), which is based on intraseasonal filtered OLR anomalies and is well-suited for detecting MJO convective features. Compared to the other MJO indices, the OMI is known to capture the spatial structure, propagation, and seasonality of MJO convection more accurately (Wang et al., 2018). The MJO convective initiations over the Indian Ocean were identified based on the following set of objective criteria:

- 1) The OMI amplitude is less than 0.8 (within the unit circle - weak MJO) for at least four days preceding the initiation day.
- 2) Initiation day is defined as when the OMI amplitude comes out of the unit circle in phases 1-3, indicating intensification of convective activity over the Indian Ocean. A threshold range of 0.8 - 1.2 is used to select the initiation day.
- 3) For days following the initiation day, an anticlockwise rotation of at least 45 degrees is observed in the OMI phase space, while maintaining an amplitude above 0.8. This criterion ensures the eastward propagation of MJO signals following initiation.

These criteria ensure the selection of robust and spatially coherent convective initiations associated with the MJO. Furthermore, the initiations were verified by examining the MJO eastward propagation in the equatorially averaged intraseasonal OLR anomalies. Based on the OMI index from 1979 to 2021, a total of 83 initiation events were identified, 41 during the boreal winter season (November to March) and 42 during the boreal summer season (May to September). Table 2.1 gives the list of the WEIO and EEIO MJO initiation dates identified using the OMI based

| Total of Indian Ocean MJO initiations (1979-2021 ) = 83 |            |             |            |
|---------------------------------------------------------|------------|-------------|------------|
| Winter (41)                                             |            | Summer (42) |            |
| WEIO (27)                                               | EEIO (14)  | WEIO (25)   | EEIO (17)  |
| 1980-12-26                                              | 1979-02-21 | 1980-05-20  | 1980-07-21 |
| 1986-03-05                                              | 1982-12-20 | 1981-07-14  | 1982-09-15 |
| 1987-03-01                                              | 1983-02-09 | 1982-07-27  | 1983-09-03 |
| 1987-11-30                                              | 1983-11-02 | 1983-06-07  | 1984-09-23 |
| 1988-01-14                                              | 1988-11-04 | 1984-07-04  | 1986-06-03 |
| 1989-01-04                                              | 1997-01-25 | 1987-07-19  | 1990-07-29 |
| 1991-12-16                                              | 2002-11-05 | 1989-06-27  | 1990-09-16 |
| 1994-01-31                                              | 2003-12-02 | 1994-05-20  | 1991-06-26 |
| 1994-11-08                                              | 2006-03-20 | 1994-08-03  | 1992-05-03 |
| 1996-01-06                                              | 2011-03-18 | 1996-05-27  | 1992-06-03 |
| 1998-02-01                                              | 2012-12-23 | 1998-05-01  | 1992-09-24 |
| 1999-01-05                                              | 2015-02-11 | 2001-07-11  | 2000-06-26 |
| 1999-03-08                                              | 2017-12-31 | 2002-07-18  | 2002-06-04 |
| 1999-11-18                                              | 2018-11-04 | 2003-08-05  | 2003-09-28 |
| 2002-01-09                                              |            | 2006-08-18  | 2005-08-18 |
| 2006-01-03                                              |            | 2007-06-01  | 2008-08-21 |
| 2006-12-17                                              |            | 2008-07-08  | 2016-06-17 |
| 2009-12-21                                              |            | 2009-06-22  |            |
| 2010-11-11                                              |            | 2010-09-19  |            |
| 2014-02-04                                              |            | 2011-08-05  |            |
| 2014-11-13                                              |            | 2012-08-07  |            |
| 2014-12-15                                              |            | 2014-05-28  |            |
| 2016-11-08                                              |            | 2015-05-29  |            |
| 2017-01-19                                              |            | 2018-09-27  |            |
| 2020-02-25                                              |            | 2019-07-12  |            |
| 2020-11-08                                              |            |             |            |
| 2021-01-03                                              |            |             |            |

*Table 2.1: List of dates of MJO convective initiations identified using the OMI-based initiation criteria, over the Western and Eastern Indian Ocean domains, during boreal winter and summer seasons from 1979-2021.*

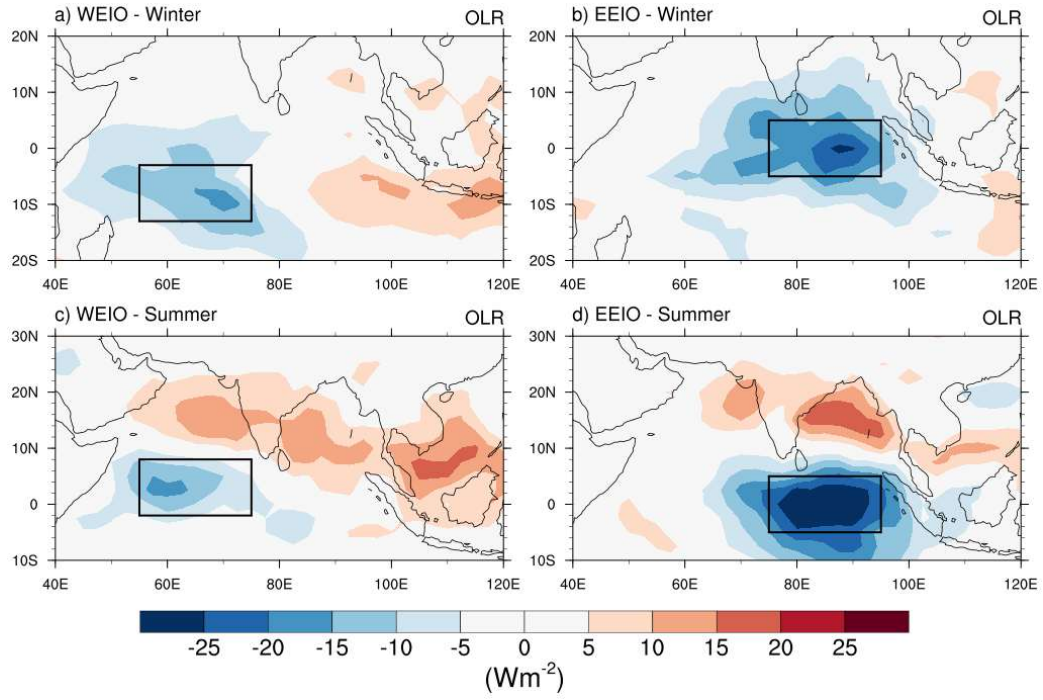
identification method, in the winter (November to March) and summer (May to September) seasons from 1979 to 2021. WEIO initiations are more frequent during both seasons, accounting

for 66% of winter cases (27 out of 41) and 60% of summer cases (25 out of 42). Thus, while both regions support MJO convective initiation, the WEIO consistently emerges as the primary initiation region, particularly in winter.

## **2.3 Results and Discussion**

### **2.3.1 Preferred locations of Indian Ocean MJO Initiations**

The location of MJO convection initiation over the Indian Ocean domain exhibits clear regional preferences, which also vary between the boreal winter and summer seasons. Initiation events identified for OMI phases 1-3 were categorized based on the spatial location of development of intraseasonal convective anomalies. During boreal winter (November–March), for the MJO initiations in phases 1 and 2 the convective anomalies were observed to develop over the western Indian Ocean and were classified as Western Equatorial Indian Ocean (WEIO) initiations, while for phase 3 MJO initiations the convective anomalies developed in the eastern part of the basin and were categorized as Eastern Equatorial Indian Ocean (EEIO) initiations. On the other hand, during summer (May–September), phase 1 MJO convective initiations were observed over the western Indian Ocean and were classified as WEIO initiations, and phases 2 and 3 initiations were classified as EEIO initiations. The regional distinctions among these initiation categories are visually depicted in Figure 2.1, which shows the composite maps of intraseasonal OLR anomalies averaged over all the initiation days over the WEIO and EEIO domains. WEIO initiations tend to occur off the equator—in the southwestern Indian Ocean in winter and in the northwestern Indian Ocean in summer. In contrast, EEIO initiations are generally equatorially centered and exhibit a stronger convective signal as compared to the WEIO initiations. Based on the composite maps, the WEIO initiation location is identified as 13°S–3°S & 55°–75°E during boreal winter, and 2°S–8°N & 55°–75°E during boreal summer. EEIO initiation location is identified as 5°S–5°N & 75°–95°E during the both seasons. While the EEIO initiations are sometimes considered as an extension of the WEIO initiations, the composite analysis indicates that they are mostly independent of each other.



*Figure 2.1: Composites of 20-90 day filtered OLR anomalies for the Western (left panel) and Eastern (right panel) Indian Ocean initiation days, during boreal winter and summer seasons. Black boxes denote the initiation regions identified for the respective categories.*

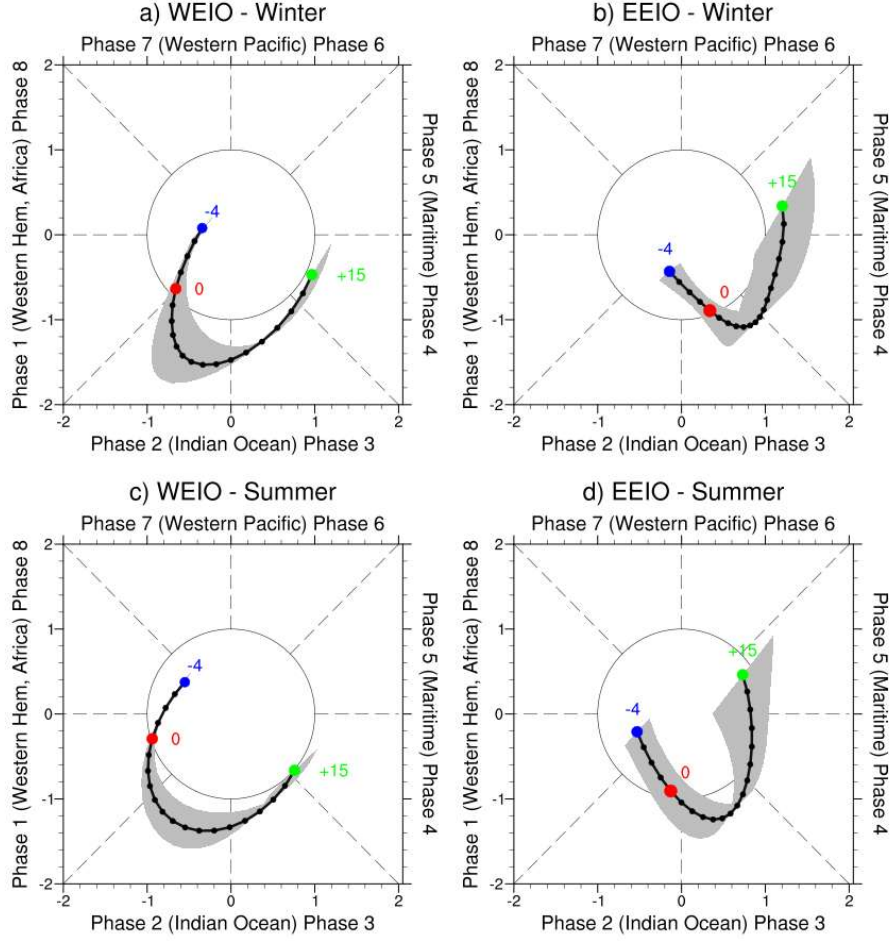


Figure 2.2: Composite phase space evolution of the OMI Index (thick black trajectory) from day  $-4$  to day  $+15$  relative to the MJO initiation days over the WEIO (a & c) and EEIO (b & d) during boreal winter (top panel) and summer (bottom panel) seasons. The red-filled circle indicates the initiation day (Day 0), and the blue (green) filled circles denote day  $-4$  (day  $+15$ ), respectively. The grey shaded region indicate the 95% confidence interval.

The composite evolution of the MJO in the OMI phase space for the two initiation categories during the two seasons are shown in Figure 2.2. The composite OMI trajectory, along with the 95% confidence estimates, is shown from day  $-4$  to day  $+15$  with respect to the WEIO and EEIO initiation days during the winter and summer seasons. The OMI composite trajectories indicate that the identification method has correctly captured the low-amplitude quiescent state of the MJO prior to the initiation day and the coherent anticlockwise propagation across the phase space after the initiation. The MJO convective initiation identification method is further validated by examining the MJO eastward propagation in OLR anomalies.



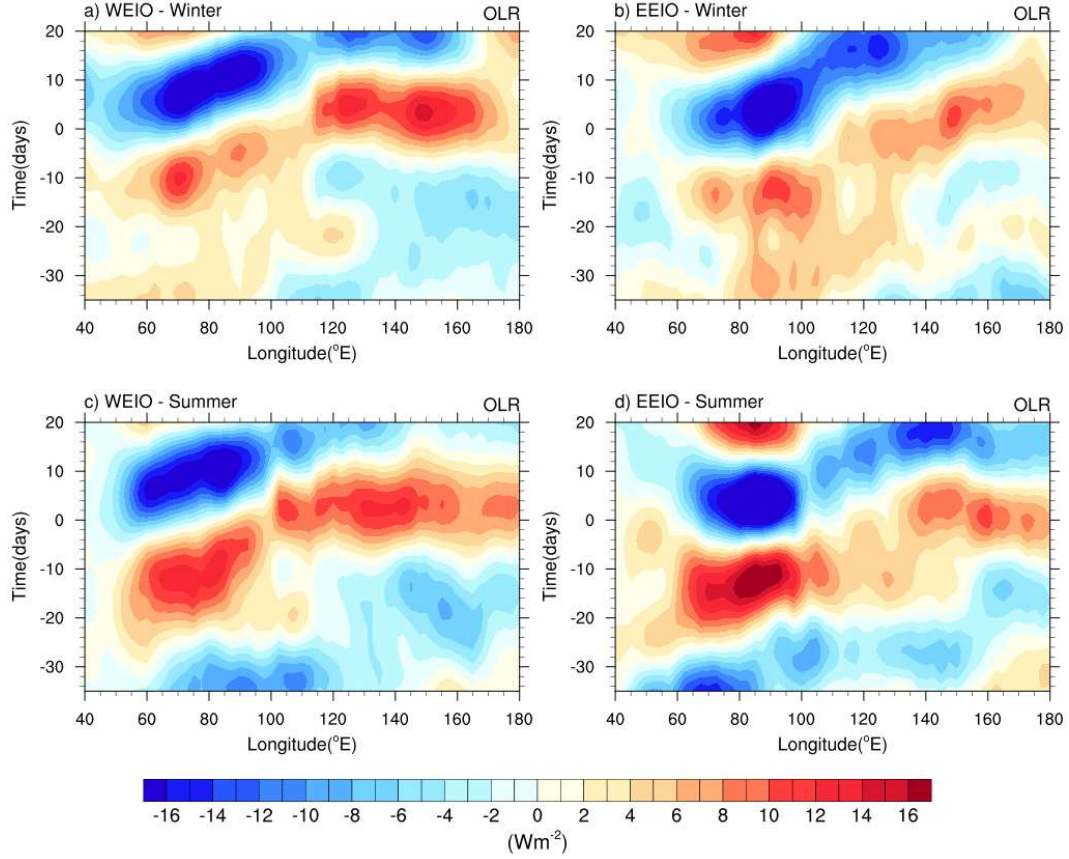


Figure 2.3: Lead-lag Composites of 20-90 day filtered OLR anomalies, relative to the MJO initiation days over the WEIO (a & c) and EEIO (b & d) during boreal winter (top panel) and summer (bottom panel) seasons, meridionally averaged between  $10^{\circ}\text{S}$  and  $10^{\circ}\text{N}$  latitudes.

Figure 2.3 presents the time–longitude Hovmöller diagrams relative to the MJO convective initiation day, in the two initiation categories. Intraseasonally filtered OLR anomalies were composited at different lag and lead days relative to the MJO initiation day, and the composite OLR anomalies were averaged between latitudes  $10^{\circ}\text{S}$ – $10^{\circ}\text{N}$ . Coherent eastward propagation of convective anomalies is evident over the Indian Ocean, following the MJO convective initiations in the two categories. The consistency of the eastward propagation pattern further affirms that the selected convective events are indeed the MJO and not just isolated or stationary convective systems. Some differences are observed in the phase speed of the MJO over the Indian Ocean and West Pacific domains for the two initiation categories. For WEIO initiations during both seasons, the MJO convective anomalies originate around  $55^{\circ}\text{E}$  longitude, propagate eastward over the

Indian Ocean, weaken over the Maritime Continent, and further strengthen over the Western Pacific, where they appear to propagate eastward at a slower phase speed. The weakening of phase speed over the West Pacific, as evident in the time-filtered OLR anomalies, is mainly observed during the winter season and is attributed to the presence of westward-propagating planetary-scale Equatorial Rossby wave activity over the West Pacific (Figure not shown). For the EEIO initiations in winter, the MJO convective anomalies, which originate around 70°E longitude, exhibit a coherent eastward propagation across the MC and slowly weaken in amplitude beyond 130°E. During summer, on the other hand, the MJO eastward propagation following EEIO initiations is strongly affected by the MC. Two to three weeks preceding the MJO initiation in both categories, suppressed convection (positive OLR anomalies) is observed to prevail over the Indian Ocean, and the positive OLR anomalies exhibit eastward propagation across the Indian Ocean and the Western Pacific. During boreal winter, both WEIO and EEIO initiations are preceded by relatively quiescent conditions, even at 5 weeks prior to the initiation day (Figure 2.3 a & b); hence, the initiations may be classified as primary initiations. (Some weak westward propagating convective signals are also observed upstream over the east Pacific between 110°E and 160°E, about three weeks preceding the initiation). On the other hand, for the summer initiations (Figure 2.3 c & d) coherent eastward propagation of negative OLR anomalies is evident over the Indian Ocean at five to six weeks preceding the initiation day, indicating the previous convective phase of MJO. Hence, the summer initiations may fall under the category of secondary or successive initiations.

### 2.3.2 SST control on the preferred locations of MJO Initiations

As noted in Chapter 1 of the thesis, there is a stark zonal asymmetry in the distribution of SST over the Indian Ocean (Figure 1.1) and it also undergoes significant variability in the seasonal and interannual timescales. Climatologically the EEIO (being part of the warm pool) tends to have high SSTs throughout the year and the warmer background SST would favor higher moisture availability over the region and promote the development of deep convection. The climatological mean state of the Indian Ocean Walker circulation, hence has its ascending branch over the EEIO and westerly surface winds prevail over the equatorial Indian ocean. The background state over the WEIO on the other hand, is characterized by cooler SSTs, a drier environment, and subsidence and the mean state exhibits a more pronounced seasonal variability as compared to the EEIO. The interannual variability of the climatological mean state over the Indian Ocean, known as the Indian

Ocean Dipole (IOD) (Saji et al., 1999), is associated with changes in Walker circulation and convective activity over the eastern and western Indian Ocean. A positive IOD phase is characterized by anomalous warming over the western Indian Ocean, cooling over the eastern Indian Ocean off the coast of Sumatra and Java, and low-level easterly wind anomalies. If the background SSTs were to exert a dominant influence on the preferred location of MJO initiations, the interannual variability in the mean state would also reflect in the frequency of occurrence of MJO initiations over the WEIO and EEIO domains. To investigate this, MJO initiations were further classified based on their association with the phases of the Indian Ocean Dipole (IOD). An MJO initiation was considered to occur in a positive (negative) IOD background state if the DMI value during the month of initiation was  $\geq 0.2$  K ( $\leq -0.2$  K) respectively. In the case of MJO initiations occurring in the beginning or end of a month, the DMI values from the two consecutive months were examined to ensure consistent phase classification. The frequency of occurrence of WEIO and EEIO initiations in the two IOD phases are indicated in Table 2.2.

| <b>Total of Indian Ocean MJO initiations (1979-2021 ) = 83</b> |                        |              |                        |              |
|----------------------------------------------------------------|------------------------|--------------|------------------------|--------------|
| <b>Winter (41)</b>                                             | <b>WEIO -27 (66%)</b>  |              | <b>EEIO - 14 (34%)</b> |              |
|                                                                | IOD +ve<br>3           | IOD -ve<br>5 | IOD +ve<br>5           | IOD -ve<br>4 |
| <b>Summer (42)</b>                                             | <b>WEIO - 25 (60%)</b> |              | <b>EEIO - 17 (40%)</b> |              |
|                                                                | IOD +ve<br>12          | IOD -ve<br>6 | IOD +ve<br>2           | IOD -ve<br>9 |

*Table 2.2: Number of MJO convective initiations over the Western and Eastern Indian Ocean, during boreal winter and summer seasons identified using OMI-based initiation criteria. Also indicated are the number of MJO initiations which occurred during positive phase and negative phases of IOD.*

During winter, the IOD is typically in a neutral or decaying phase, and only about 40% of the MJO initiations were observed to occur during positive or negative IOD states. Only 3(5) of the 27 WEIO MJO initiations were observed during positive (negative) IOD phase and 5(4) of the 14 EEIO MJO initiations were observed during positive (negative) IOD phase respectively. During summer, on the other hand, the IOD is mostly observed to be in a developing or mature phase and about 70% (29 out of 42) of the summer MJO initiations were observed during active positive or

negative phase of IOD. Further classification into the WEIO/EEIO initiation categories indicate that while nearly half (12 out of 25) of the WEIO initiations occurred during positive (negative) IOD background state, relatively a smaller fraction (24%; 6 out of 25) of WEIO initiations occurred during a negative IOD background state. And, out of the 17 EEIO initiations, nearly half (9) occurred during negative IOD background state and only 2 occurred during a positive IOD background state. This indicates that a positive IOD background state favors more MJO initiations over the WEIO and a negative IOD background state favors more MJO initiations over the EEIO. In order to further verify this finding, the thirty-day mean background state of SST and 850 hPa wind fields preceding the MJO initiations in the two initiation categories were examined during winter and summer seasons (Figure 2.4). In order to derive the low frequency background state, a low pass filter ( $> 90$  day) was applied to the SST and 850 hPa wind fields and the anomalies were used to compute the mean state, which was then composited for the two categories.

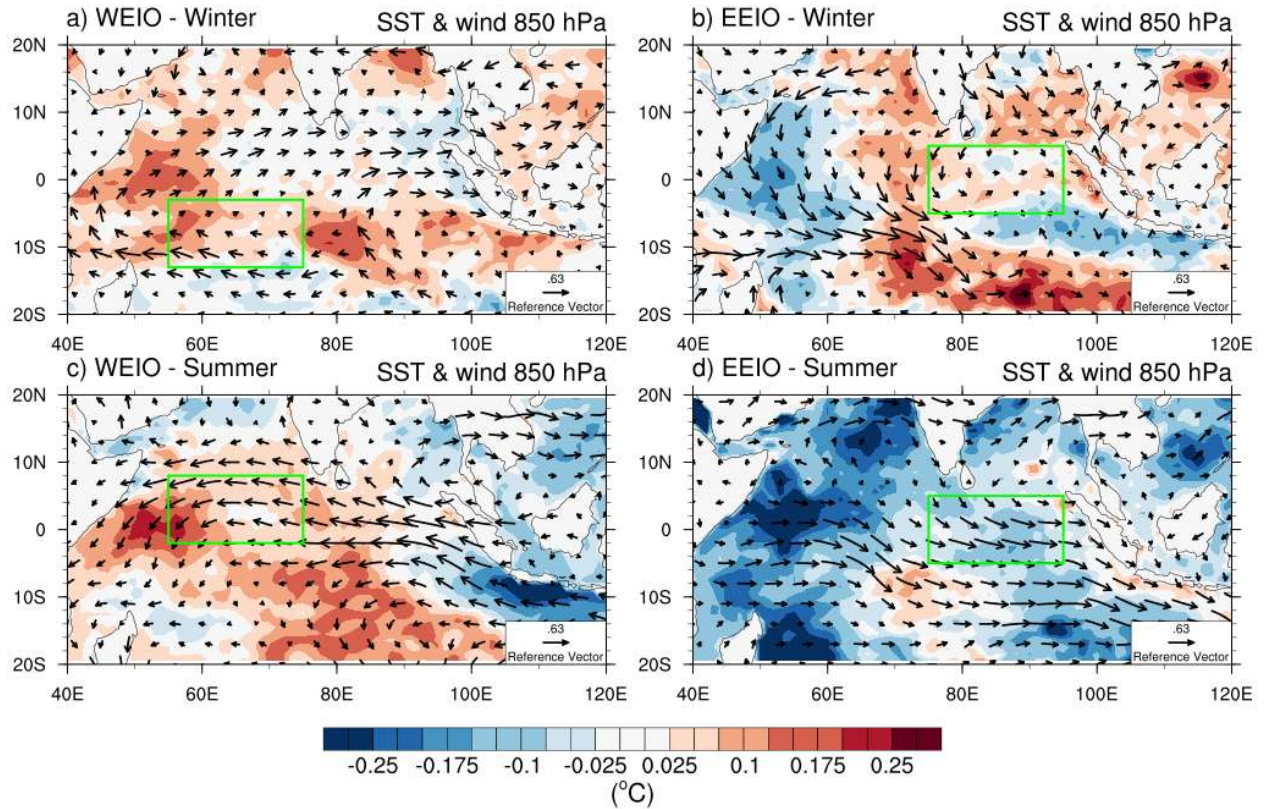


Figure 2.4: Composite maps of the 30 day average low-frequency ( $> 90$  day) background state of SST and 850 hPa winds, preceding the MJO initiations over the WEIO (a & c) and EEIO (b & d) domains. The top (bottom) panel represents the winter (summer) season respectively.

Consistent with the statistics presented in Table 2.2, the composite maps representing the low frequency background SST state preceding the WEIO & EEIO MJO initiations during winter (Figure 2.4 a & b) do not bring out a prominent east west dipole like pattern indicative of any IOD phase preference. While positive SST anomalies are observed over both the western equatorial Indian Ocean and the south eastern equatorial Indian Ocean domains in the WEIO initiation composite, negative SST anomalies are observed over both the regions in the EEIO initiation composite. The low-level winds also do not match with those associated with an active IOD phase. Meanwhile, consistent with the observation that a positive IOD background state favors more WEIO MJO initiations, composites of the low-frequency SST and 850 hPa wind anomalies during the 30-day period preceding the summer WEIO initiations (Figure 2.4c) exhibits a positive IOD-like SST and wind pattern, with positive SST anomalies over WEIO and negative SST anomalies over the eastern part of the basin, accompanied by easterly wind anomalies. Though such a pronounced distinction of the SST dipole pattern is not evident in the EEIO initiation based composites (Figure 2.4d), the strong westerly wind anomalies are indicative of a negative IOD state, implying that a negative IOD state in summer might favor more EEIO initiations.

In short, these results suggest that the SST background state over the Indian Ocean and its interannual variability might play a major role in determining the location of MJO initiations in summer. A positive IOD phase is found to favor more MJO initiations over the WEIO, while the frequency of occurrence of EEIO initiations may be more enhanced during a negative IOD background state. The regional preference of MJO initiations in winter, however, does not seem to be strongly affected by the SST background state. Possibly, the winter MJO initiations are majorly controlled by the intraseasonal wind anomalies and the associated destabilization processes. In the accompanying sections, the local destabilization and convective evolution over the WEIO and EEIO domains are contrasted.



### 2.3.3 Instability build-up over the initiation domains

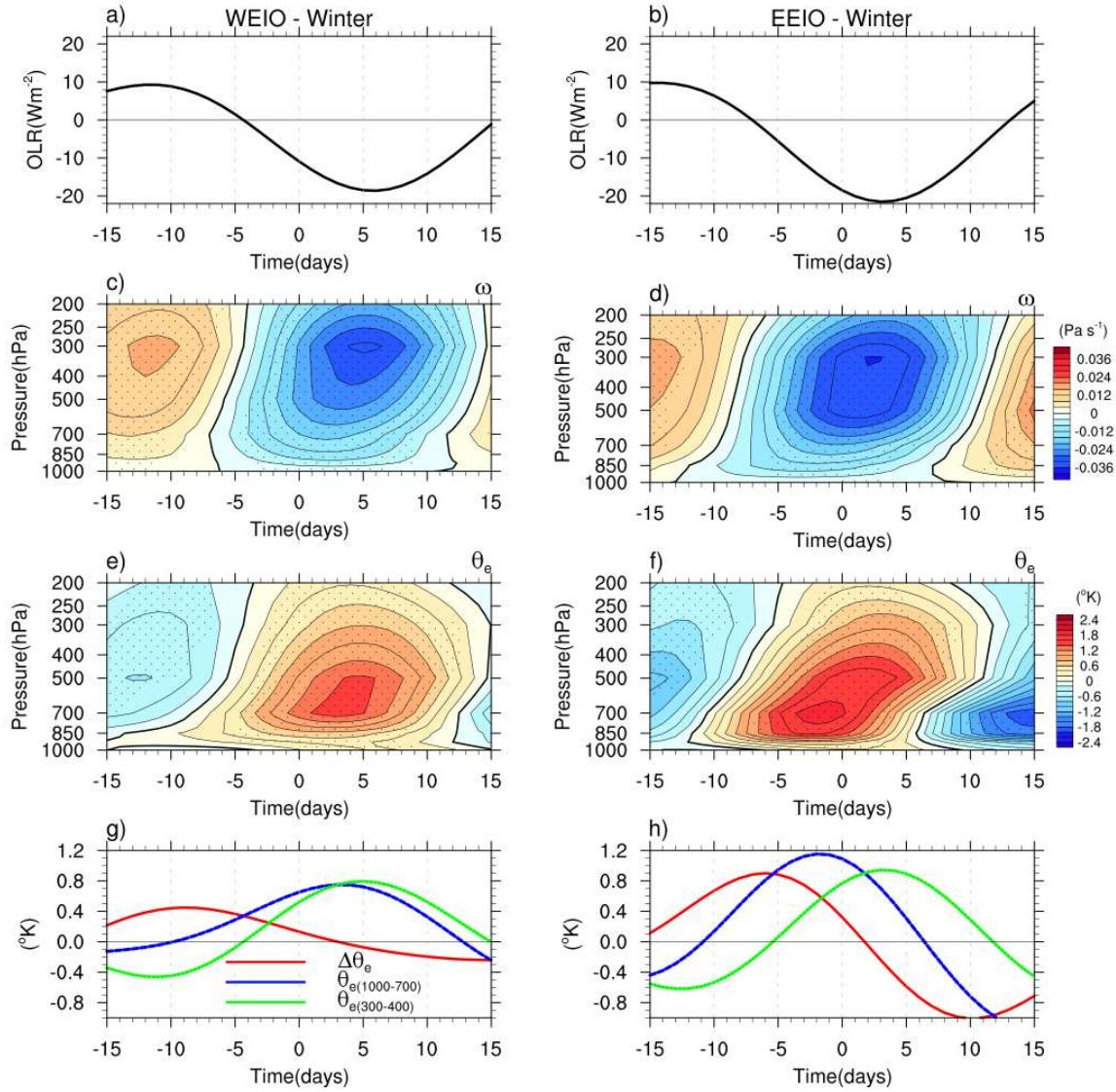


Figure 2.5: Lead-lag composite evolution of 20-90 day filtered OLR (a,b),  $\omega$  vertical velocity (c,d) ( $\text{Pa/Sec}$ ) and equivalent potential temperature  $\theta_e$  (e,f) anomalies relative to the winter time MJO initiations over the WEIO (left panel) and EEIO (right panel) domains. (g-h) shows the composite time evolution of lower (1000–700 hPa) and mid (300–400 hPa) troposphere average  $\theta_e$ , and their difference (red), which gives the instability parameter over the two initiation domains for the days preceding the OLR zero crossing day.

The boreal summer MJO convective initiations are often accompanied by off equatorial propagation of convection and are strongly influenced by the monsoon background state making its dynamics complex to understand. Also evident is the role of interannual variability modes which together can complicate the processes leading to the Summer MJO convective initiations. Therefore, the following analysis focuses on the boreal winter season during which the MJO convection is confined near the equator and the background is comparatively simpler without much influence from the interannual variability.

In order to capture and understand the local development of instability and convection over the WEIO and EEIO initiation domains, lead-lag composite fields of 20-90 day filtered OLR anomalies, omega vertical velocity anomalies, equivalent potential temperature and instability parameter were derived, relative to the initiation dates over the WEIO and EEIO domains during the winter season (Figures 2.5).

Time evolution of OLR anomalies with respect to the initiation day (Figure 2.5 a-b) indicates that a pronounced suppressed phase precedes the MJO convective initiation, characterized by positive OLR anomalies and tropospheric subsidence (positive  $\omega$ , indicating descent). The subsidence extends throughout the tropospheric column but it is the strongest in the mid-to-upper troposphere. Relatively stronger suppressed convection anomalies are observed over the EEIO initiation domain as compared to the WEIO domain. During winter, over the WEIO initiation domain, positive OLR anomalies ( $\sim +10 \text{ W m}^{-2}$ ) peak at around lag  $-12$ . Subsidence anomalies of a similar magnitude are observed over the EEIO domain near lag  $-15$  (Figure 2.5 a-b). The OLR anomalies transition from positive to negative at day  $-4$  over the WEIO and around day  $-7$  over the EEIO initiation domain, relative to the OMI based initiation dates (Figure 2.5 a-b). Consistent with the transition in OLR anomalies,  $\omega$  vertical velocity anomalies transition from positive to negative in the mid troposphere, from the planetary boundary layer (PBL) into the mid-troposphere, indicative of the development of deep convection. The apparent difference relative to the OMI based initiation dates is due to the fact that the OMI index captures the large-scale MJO convective signal, whereas convection over the domain typically develops much earlier than that. It is also noted that, stronger peak convection (maximum negative OLR anomaly) is observed over

the EEIO domain as compared to the WEIO domain. Convection peaks over the WEIO domain reaching values of about  $-18 \text{ W m}^{-2}$ , but the peak OLR anomalies are about  $-22 \text{ W m}^{-2}$  over the EEIO domain. Over the WEIO, large-scale convective organization associated with the MJO is established faster, with the OLR anomalies crossing zero on day -4 and growing to about  $-10$ - $-12 \text{ W m}^{-2}$  on the day of MJO initiation. Over the EEIO, large-scale convective organization takes slightly longer, with the OLR anomalies crossing zero on day -7 and growing to about  $-18$ - $-20 \text{ W m}^{-2}$  on the initiation day. The relatively short time interval between the development of convection and its large-scale organization as measured by the OMI based initiation day, over the WEIO domain, indicates that MJO convection is established faster over the region as compared to the EEIO initiation domain. But the stronger convective anomalies observed over the EEIO domain indicates that the thermodynamic conditions favor the growth of deep convection over the region in comparison to the WEIO region.

The  $\omega$  vertical velocity anomalies in the mid-troposphere occur in conjunction with the OLR anomalies, but the  $\omega$  negative vertical velocity anomalies in the PBL are found to precede the OLR zero crossing time over the two domains. During WEIO winter initiations (Figure 2.5c), vertical motion begins at the PBL around day -7, which then extends throughout the tropospheric column in a day or two. On the other hand, over the EEIO domain (Figure 2.5d), vertical motion begins at the PBL around day -13 and the omega vertical velocity anomalies turn negative in the mid-troposphere by day -8. The instability development prior to the breakout of convection (OLR zero crossing day) over the two initiation domains is further examined in the intraseasonally filtered equivalent potential temperature ( $\theta_e$ ) anomalies, Figure 2.5 (e-f) and also using an instability parameter defined as the difference between the lower (1000–700 hPa) and mid (300–400 hPa) tropospheric averaged  $\theta_e$  (Zhao et al., 2013) over the two regions (Figure 2.5 g-h). A vertical decrease of  $\theta_e$  with height indicates convective instability, while an increase indicates stability. Hence a positive value of the instability parameter is taken as indicative of convective instability. Figures 2.5 (e-f) presents the composite vertical profiles of intraseasonal  $\theta_e$  anomalies for WEIO and EEIO initiations for the winter season. Consistent with the stronger convective anomalies observed over the EEIO initiation domain and the relatively stronger suppressed convection state which were observed to precede the convection initiation, the positive and negative  $\theta_e$  anomalies display relatively higher amplitudes over the EEIO domain. Over the WEIO domain (Figure 2.5 e-f), positive  $\theta_e$  anomalies are observed in the PBL at day -15, about ten days



before the zero crossing day of OLR anomalies, which then gradually extends to the mid-troposphere by the initiation day (day -4). Over the EEIO domain, on the other hand, positive  $\theta_e$  anomalies develop in the PBL and rapidly extend to the upper levels in a shorter period of 5 days (day -12 to day -7). The time evolution of the lower and mid-tropospheric  $\theta_e$  and the instability parameter reveals a clearer picture of instability development over the two initiation domains. Prior to convection initiation, the lower-tropospheric  $\theta_e$  increases, followed by an increase in the mid-tropospheric  $\theta_e$ , and the increase in lower-tropospheric  $\theta_e$  is much more pronounced over the EEIO domain. Over the WEIO domain, the instability parameter becomes positive at day -18, about two weeks preceding the convection initiation day, while over the EEIO domain, the instability parameter turns positive at day -16, about 9 days prior to convection initiation. The peak magnitude of the instability parameter over the EEIO domain is almost double the value over the WEIO domain reflecting a stronger destabilization of the tropospheric column over the EEIO, which is mainly a result of the increase in lower tropospheric  $\theta_e$ . The analysis brings out a rapid and stronger destabilization of the tropospheric column prior to the EEIO initiations during winter season.

### 2.3.4 Cloud Evolution over the initiation domains

To further understand the differences in destabilization and the nature of convection over the two domains the evolution of the cloud regimes with respect to the convection initiations were analyzed over the two initiation domains during winter (Figure 2.6). The dominant cloud types observed over the initiation domains, during the period from about one week preceding the convection initiation day to ten days following the initiation day, were identified using the cloud-top pressure–optical thickness (CTP– $\tau$ ) joint histograms, following the ISCCP classification scheme (Rossow & Schiffer, 1991). The composite CTP– $\tau$  joint histogram at different lead-lag with respect to the initiation day was obtained by averaging the data over the respective initiation domains. In the composite histograms, the frequencies (corresponding to each CTP-  $\tau$  bin) are normalized by the total number of occurrences obtained by summing the occurrences across the individual CTP- $\tau$  bin to obtain the relative frequencies. The time evolution of the composite CTP- $\tau$  relative frequency joint histograms around the MJO initiation days over the two domains during the winter season are shown in Figure 2.6.

A shallow to deep convection transition is considered a hallmark of MJO convection initiation, which is evident in the composite CTP– $\tau$  joint histograms over the two domains, during

the winter season (Figure 2.6). The period leading up to convection initiation is dominated by shallow cloud populations, primarily cumulus and stratocumulus. Over the WEIO domain, gradual reduction in shallow clouds and a corresponding increase in deep convective clouds occur during the week leading to the onset (between day  $-10$  and  $-4$ ). Whereas, over the EEIO domain, a more rapid reduction in shallow cloud occurrence and enhancement of deep clouds is observed. This faster transition is consistent with the rapid development of convective instability over the region, documented in the previous section.

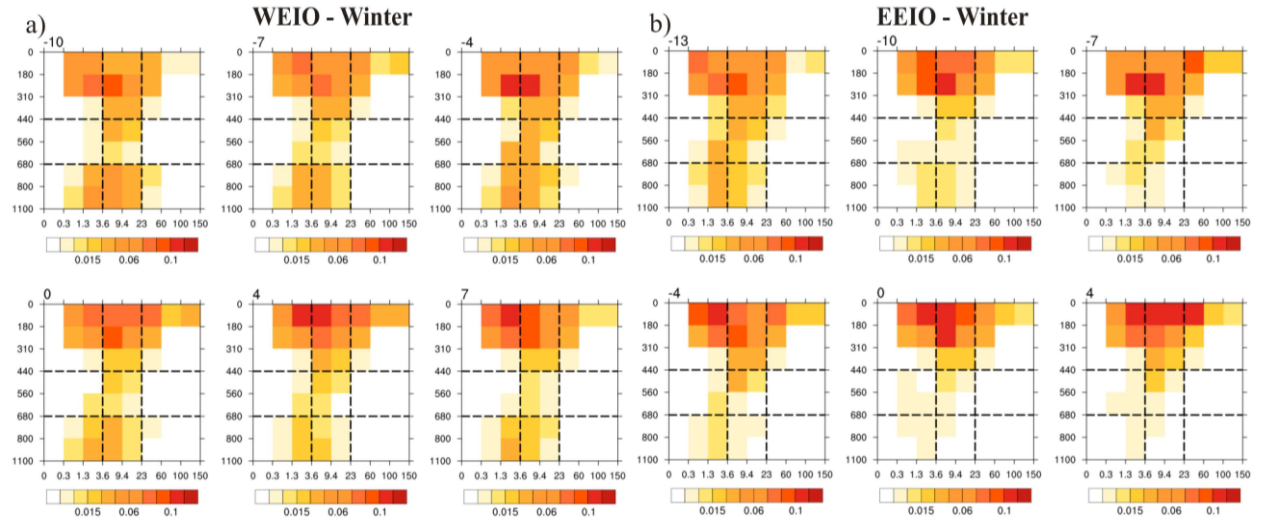


Figure 2.6: Normalized cloud occurrence frequency (cloud-top pressure vs. optical thickness; CTP-TAU joint histogram) at different lead-lag days (indicated on the top left corner of each figure) relative to the OMI based MJO initiation day over the (a) WEIO and (b) EEIO domains during winter season. Day  $-4$  ( $-7$ ) corresponds to time of convection initiation over the WEIO (EEIO) domain respectively.

## 2.4 Summary and Conclusions

The Indian Ocean is widely recognized as a primary region of MJO convective initiation, but the background state varies strongly across the basin and between seasons. The eastern equatorial Indian Ocean (EEIO), as part of the warm pool, is characterized by warm SSTs, high moisture and large scale ascent, making a environment thermodynamically favorable for deep convection. In contrast, the western equatorial Indian Ocean (WEIO) is characterized by a shallow thermocline and mixed layer, seasonal reversal of circulation, and is highly sensitive to oceanic and atmospheric forcing, making it susceptible to convective triggering even with a slight oceanic or atmospheric perturbation, despite the prevailing background subsidence.

Motivated by this diversity evident within the Indian ocean basin this study tries to identify and characterize the MJO initiations across the Indian Ocean basin using an Objective method based on OLR MJO Index(OMI). A total of 83 MJO convective initiations were identified for the 1979-2021 period with 41 occurring during winter and 42 during summer. These initiations are aggregated over 2 preferred subregions over the Indian Ocean- the western equatorial Indian Ocean and eastern equatorial Indian Ocean. These two categories are diverse in many aspects including the frequency of initiations, convective strength, tropospheric column destabilization, cloud evolution and interannual variability controls. WEIO initiations are more frequent with convective initiations displaced south of the equator during winter while it is displaced north of the equator during summer in progression with the seasonal shift in the warm SST regions over western equatorial Indian Ocean. EEIO initiations are less frequent but anchored at the equatorial region in both seasons and are associated with relatively strong convective strength compared to the WEIO category.

Examination of the precursor MJO convective state across these diverse convective initiation categories exhibit differences across the seasons. The Winter initiations over both the WEIO and EEIO domains are preceded by quiescent MJO convective states while summer initiations over the respective categories are characterized by preceding strong MJO convection implying that winter Indian Ocean initiations are primary events while summer initiations are secondary in nature.

Investigation of the interannual variability influence on the Indian Ocean MJO convective initiations across the seasons suggest that the Indian Ocean dipole exerts a strong influence on summer Indian Ocean initiations: with positive IOD favoring WEIO initiations while negative IOD favoring EEIO initiations. Thus, IOD acts as a basin wide switch altering the region of Indian Ocean MJO convective initiation during summer. During winter the MJO convective initiations are not sensitive to the IOD influence suggesting that IOD control is minimal and the intraseasonal processes are majorly controlling these initiations.

During summer season the northward propagation of MJO convective anomalies are embedded within the monsoon background characterized by the southwesterly monsoon circulation and strong north-south moisture gradient apart from the east-west gradient. Together with the interannual variability in this background these factors can complicate the processes

leading to MJO convective initiation. Thus, further winter MJO convective initiations are focused on as the interannual variability influence is minimal and the local intraseasonal processes are predominantly contributing towards the MJO initiation processes.

The instability buildup in the tropospheric column is an indicator of upcoming convection. Analysis of the instability buildup for the winter initiations show marked differences between the initiation regions. Over the EEIO, column instability strengthens rapidly reaching a value double that over WEIO within about 9 days' time. Over WEIO, the instability builds up gradually over a time scale of about 2 weeks and over both the domains this instability buildup is driven mainly by the lower tropospheric equivalent potential temperature buildup. This difference in pace and strength of the buildup of instability is reflected in the vertical motions, cloud evolution and OLR evolution over the 2 domains. The vertical omega velocity transitions from downward( indicated by negative anomalies) to upward (indicated by positive anomalies) about 5-6 days before initiations in the PBL over EEIO compared to only 2-3 days before initiation over WEIO. The cloud evolution during the week leading to initiation show a rapid shallow to deep convective transition over EEIO leading to a large abundance of deep convective clouds by initiation while it is gradual over WEIO with relatively less abundance of deep convective clouds by initiation. Consistent with this is the relatively stronger negative OLR anomalies following the initiation over EEIO compared to WEIO.

All of these point to two contrasting MJO convective regimes over the western and eastern part of the Indian Ocean with EEIO characterized by a thermodynamically more favorable environment with rapid destabilization and stronger convection while the WEIO is characterized by gradual and weaker destabilization and convection. These pronounced seasonal and regional diversity in the MJO convective initiations in terms of instability buildup, cloud evolution and interannual variability controls highlight the importance of exploring the factors leading to these differences. These findings suggest that in order for a model to predict MJO convective initiations skillfully it should capture these diverse convective regimes and the processes leading to it.

# **Chapter 3**

## **Preconditioning of Instability and Moistening Prior to Indian Ocean MJO Initiation: Role of Large-Scale Circulation Responses**

### **3.1 Introduction**

The Madden-Julian Oscillation (MJO) convective initiation marked by the shift from a dormant convective state to a large-scale organized MJO convective state (Straub, 2013; Ling et al., 2013; Matthews, 2008) remains one of the least understood aspects of MJO, exhibiting limited predictability compared to its propagation (Seo et al., 2009). Consequently, numerous mechanisms have been proposed to explain MJO initiation, spanning a range of spatial and temporal scales and all of these ultimately converge on the buildup of tropospheric column instability-majorly by the tropospheric column moistening essential for convective onset, thus setting the stage for the MJO convective outbreak.

One such notable mechanism is the Recharge Discharge mechanism involving the gradual local column moistening and instability buildup with clouds progressively deepening and moistening the troposphere from the surface upward leading to deep convection and precipitation, which ultimately stabilizes the column (Bladé and Hartmann 1993; Kemball-Cook & Weare, 2001); a process taking about 10-20 days. However, MJO initiations can occur on a much shorter time scale as shown by DYNAMO case studies(Powell & Houze, 2015; Johnson & Ciesielski, 2013) and other composite studies(Xu & Rutledge, 2016) where the moistening and convection buildup happens rapidly with timescales shorter than 7 days. This suggests that multiple processes might be playing together and the relative dominance of the process and its magnitude determine how strong and rapid the instability buildup and associated convection initiation is.

One such pathway leading to instability buildup involves the Rossby response to preceding suppressed convection- either locally generated (Matthews, 2008; Ling et al., 2013) or part of a prior MJO event (Zhao et al., 2013; Maloney & Wolding, 2015; Li et al., 2015; Takasuka & Satoh, 2020). The equatorial easterlies part of this anticyclonic Rossby response to the west of suppressed convection anomalies transport moisture depending on the strength of background moisture gradient, thus preconditioning the region for the MJO convective initiation. This downstream forcing has been recognized as a key factor leading to MJO initiations in the Indian Ocean basin, based on reanalysis-based composite studies(Matthews, 2000; Mei et al., 2015; Zhao et al., 2013; Takasuka & Satoh, 2020; Wang & Li, 2022), case studies(Li et al., 2015), and model studies(Maloney & Wolding, 2015; Takasuka et al., 2018).

Prior MJO convection and the associated Kelvin waves can also trigger MJO convection once it reaches the initiation region after circuiting the globe by inducing boundary layer convergence, upward motions and increased moistening(Matthews, 2000; Kikuchi & Takayabu, 2003; Seo & Kim, 2003; Powell & Houze, 2015; Snide et al., 2021). However, some reanalysis and modeling studies argue that Kelvin waves are not critical for Indian Ocean MJO initiation (Zhao et al., 2013; Li et al., 2015), though they may influence the convective intensity once initiated (Zhao et al., 2013; Takasuka & Satoh, 2020).

Other mechanisms include the high-frequency Mixed Rossby–Gravity (MRG) waves, in triggering MJO initiations over the southwestern equatorial Indian Ocean by inducing off equatorial convergence(Takasuka et al., 2018; Takasuka et al., 2019; Takasuka & Satoh, 2020; Takasuka et al., 2021); extratropical Rossby waves penetrating into the tropics and influencing the Indian Ocean MJO initiation (Ray & Zhang, 2010; Zhao et al., 2013; Mei et al., 2015).

In Chapter 2 of the thesis, two preferred locations of MJO initiations were identified over the Indian Ocean, one over the western equatorial Indian Ocean (WEIO) and another over the eastern equatorial Indian Ocean (EEIO). It was observed that even though the frequency of occurrence of EEIO initiations was lower than the WEIO initiations, the EEIO initiations were preceded by stronger and rapidly intensifying destabilization while the WEIO convection initiations were preceded by a relatively weaker buildup of instability. The EEIO MJO convection initiations were also observed to be much stronger than the WEIO initiations. In this Chapter, the

thermodynamic processes leading to this contrast in the instability build up over the two regions are further investigated.

## 3.2 Data and Methods

Daily mean values of specific humidity, zonal and meridional winds, and vertical velocity data from ERA5 reanalysis (Hersbach et al., 2020), with a horizontal resolution of  $1^\circ \times 1^\circ$  at standard pressure levels (1000, 925, 850, 700, 500, 300, and 200 hPa) are used for analyzing the instability buildup and moistening processes over the two initiation domains. The analysis for the winter season is carried out using data from November–March for the period from 1979–2022.

The Moist Static Energy(MSE) is computed by the below equation:

$$MSE = C_p T + L_v q + gZ \quad (3.1)$$

Where the first term on rhs represent the internal energy, second term represents the latent heat energy and the third term represents the potential energy. In order to study the intraseasonal variability a 20-90 day Lanczos filter is applied to the MSE.

The processes leading to planetary boundary-layer (PBL) moistening prior to convective initiations are examined by calculating the PBL moisture budget over the initiation regions, following the moisture tendency equation (Yanai et al., 1973) adapted for the MJO by several earlier studies (Hsu and Li, 2012, Zhao et al 2013, Wang & Li 2022, etc). The intraseasonal moisture tendency is derived by applying a 20-90 day Lanczos filter (Duchon, 1979; indicated by the primes) to the moisture tendency equation.

$$(dq/dt)' = -(V \cdot \nabla q)' - (\omega \partial q / \partial p)' - (Q_2/L)' \quad (3.2)$$

The first term on the rhs represents the horizontal advection of moisture, and the second term represents the vertical advection of moisture. The third term  $-Q_2/L$ , called as the apparent moisture source term, is calculated as a residual, and it accounts for surface latent heat fluxes, evaporation of cloud condensate and precipitation and other subgrid scale processes which can contribute to the moisture tendency. The budget terms in equation 3.2 are first calculated at individual pressure levels and then vertically integrated between the 1000 and 700 hPa pressure levels.

## 3.3 Results and discussion

### 3.3.1 Instability Buildup Prior to Convection Initiation

The moist static energy (MSE) buildup in the period leading to the convective initiation over the two domains during the winter season is examined in Figure 3.1. Convective initiation is defined, as the time when the OLR anomaly averaged over the initiation domain turns negative. As shown in Chapter 2, OLR zero-crossing coincides with the onset of large-scale mid-tropospheric vertical ascent, and is often used as an indicator of initiation of deep convection (Zhao et al., 2013; Mie et al., 2015). The OLR anomalies transition from positive to negative at day -4 over the WEIO and around day -7 over the EEIO initiation domain, relative to the OMI based initiation dates and the instability parameter turns positive over the WEIO (EEIO) domain about 10-14 (7-9) days preceding the convection initiation day (Figure 2.5). The intraseasonal anomalies of MSE, specific humidity and temperature averaged over the WEIO and EEIO domain during the pre-initiation period are examined (Figure 3.1) to better understand the destabilization of the troposphere prior to the onset of convection. Consistent with the contrasting evolution of  $\theta_e$  observed over the two domains (Figure 2.5 e-f), a gradual development of positive MSE anomalies from the PBL to the upper troposphere is observed over the WEIO, while a rapid development is observed over the EEIO (Figure 3.1 a & b). Over WEIO initiation domains, positive MSE anomalies are observed in the PBL at even day -15, ie. ten days preceding the convection initiation day, which then slowly spreads to the mid-upper troposphere around the time of convection initiation. Over the EEIO domain on the other hand, the MSE builds up in the PBL and lower troposphere during the five-day period preceding the convection initiation. Examination of the evolution of the humidity (Figure 3.1 c & d) and temperature anomalies (Figure 3.1 e & f) indicate that, while the increase in MSE in the mid-lower troposphere is mainly due to the moisture build up in the lower atmosphere, in the drier upper troposphere, the MSE anomalies are mainly due to the temperature anomalies. During the period preceding the initiation, positive humidity anomalies are first observed in the PBL, which then gradually (rapidly) penetrate to the mid-tropospheric levels over the WEIO (EEIO) domain, respectively. A similar preconditioning of MSE and humidity anomalies was also reported by previous studies (Zhao et al., 2013; Ling et al., 2013), who noted moistening of the lower troposphere about ten days before the convection initiation. Moistening of the boundary layer leads to destabilization of the lower troposphere, instigating



shallow convection, which advects moisture upward, eventually leading to moistening of the mid-troposphere and destabilization of the tropospheric column (Kiladis et., al 2005, Johnson et al., 1999). The dominant role of shallow convection in moistening the mid-tropospheric levels, is evident in Figure 2.6, as the week leading up to the convection initiation is dominated by shallow cloud populations. Thus, destabilization of the tropospheric column begins with PBL moistening, and the higher amplitude of PBL moisture anomalies observed over the EEIO implies a higher level of instability over the region. Or, in other words, the stronger destabilization of the tropospheric column over EEIO arises mainly due to the more efficient and rapid moisture preconditioning of the PBL over the region.

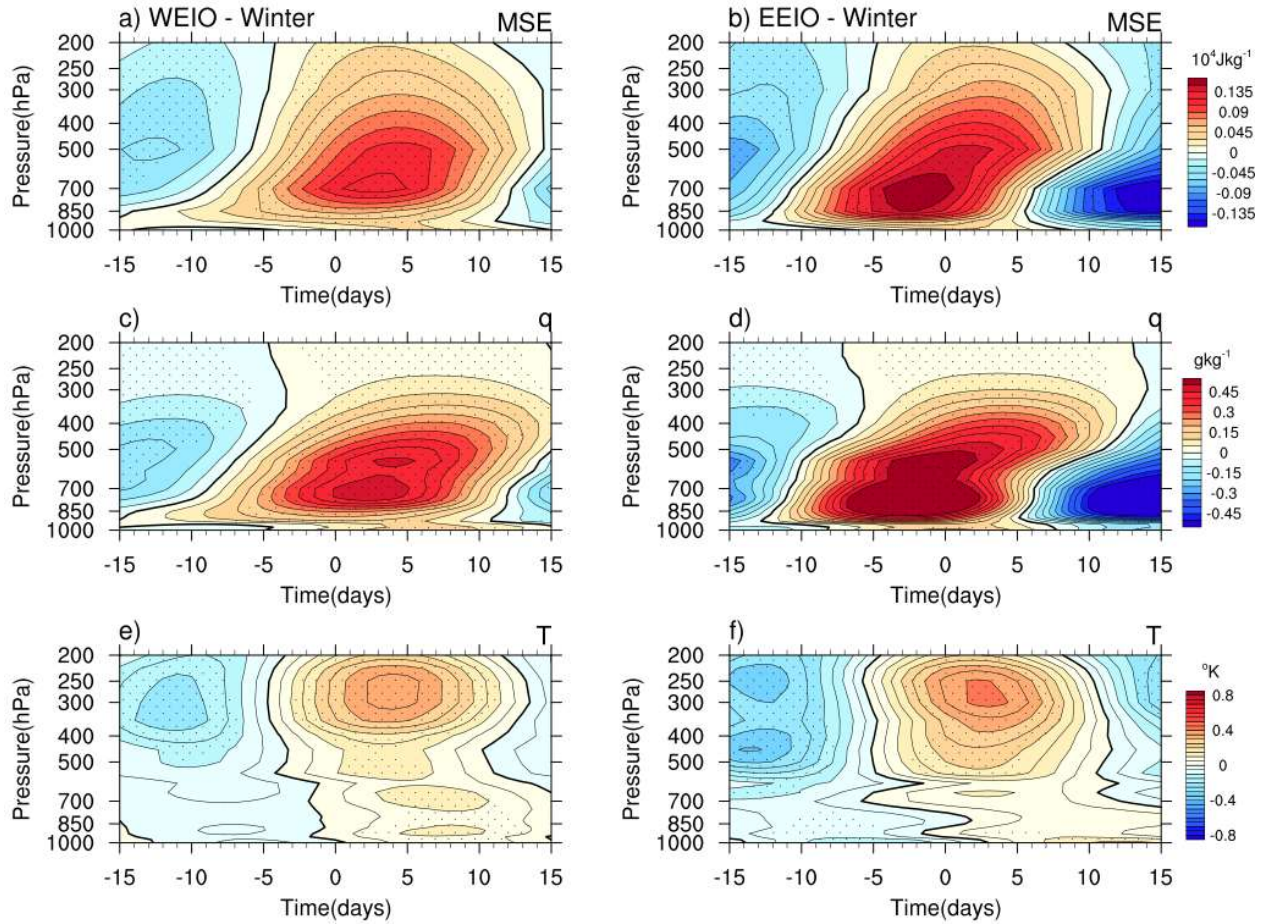


Figure 3.1: Lead-lag composite evolution of 20–90-day filtered moist static energy MSE (a–b) ( $10^4 \text{ J kg}^{-1}$ ), specific humidity  $q$  (c–d) ( $\text{g kg}^{-1}$ ), and temperature  $T$  (e–f) ( $^{\circ}\text{K}$ ) anomalies relative to the winter MJO initiations over the WEIO (left panel) and EEIO (right panel) domains. Day-0 correspond to the OMI based initiation day.

Temperature anomalies also contribute to the MSE, particularly in the upper troposphere (Figure 3.1e & f). Negative temperature anomalies are observed in the upper troposphere during the period preceding the convection initiation, which transitions to positive temperature anomalies as deep convection develops. The cold temperature anomalies extend from about 200 hPa to 500 hPa over the WEIO, and over the EEIO, they exhibit a much stronger amplitude and extend from the tropopause level to about 700 hPa. These anomalies result from radiative cooling under clear sky conditions during the suppressed convection state. Latent heat release associated with shallow convection would offset the cooling in the lower troposphere. The upper-mid tropospheric cooling observed during the period preceding the convection initiation were also reported by earlier studies (Zhao et al., 2013; Ling et al., 2013) and it contributes to driving the atmosphere unstable. EEIO events display a later but sharper increase of MSE, aided by both the rapid moistening of the lower troposphere along with a stronger amplitude mid-tropospheric cooling. These together drives the tropospheric column more unstable over the EEIO as compared to the WEIO. Deep convective heating warms the tropospheric column, and the upper to mid-troposphere temperature anomalies transition from negative to positive around the time of convective initiation. Positive temperature anomalies develop in the lower troposphere later on, as cold air advection associated with the convective downdrafts would tend to lower the temperature at these levels (Betts, 1976).

### 3.3.2 Planetary boundary layer moisture budget analysis

As noted in the previous section, PBL moistening is key to the destabilization of the atmosphere in the pre-initiation stage and distinct differences are observed in the PBL moistening over the WEIO and EEIO domains. To quantify the relative contributions of different processes to PBL moistening, the PBL specific humidity (vertically integrated between 1000 hPa & 700 hPa) budget was examined during the ten-day window period preceding the convection initiation over the two domains (Figure 3.2). The moisture budget terms were derived following Eq. (3.2) during the ten day period from day -14 to day -5 (day -17 to day -8) over the WEIO (EEIO) domain respectively. The intraseasonal moisture tendency in the PBL is expressed as a resultant of the horizontal and vertical advection of moisture in the intraseasonal timescale and an apparent moisture source term ( $-Q_2/L$ ) which takes into account the sub-grid scale moisture fluxes resulting from evaporative processes.

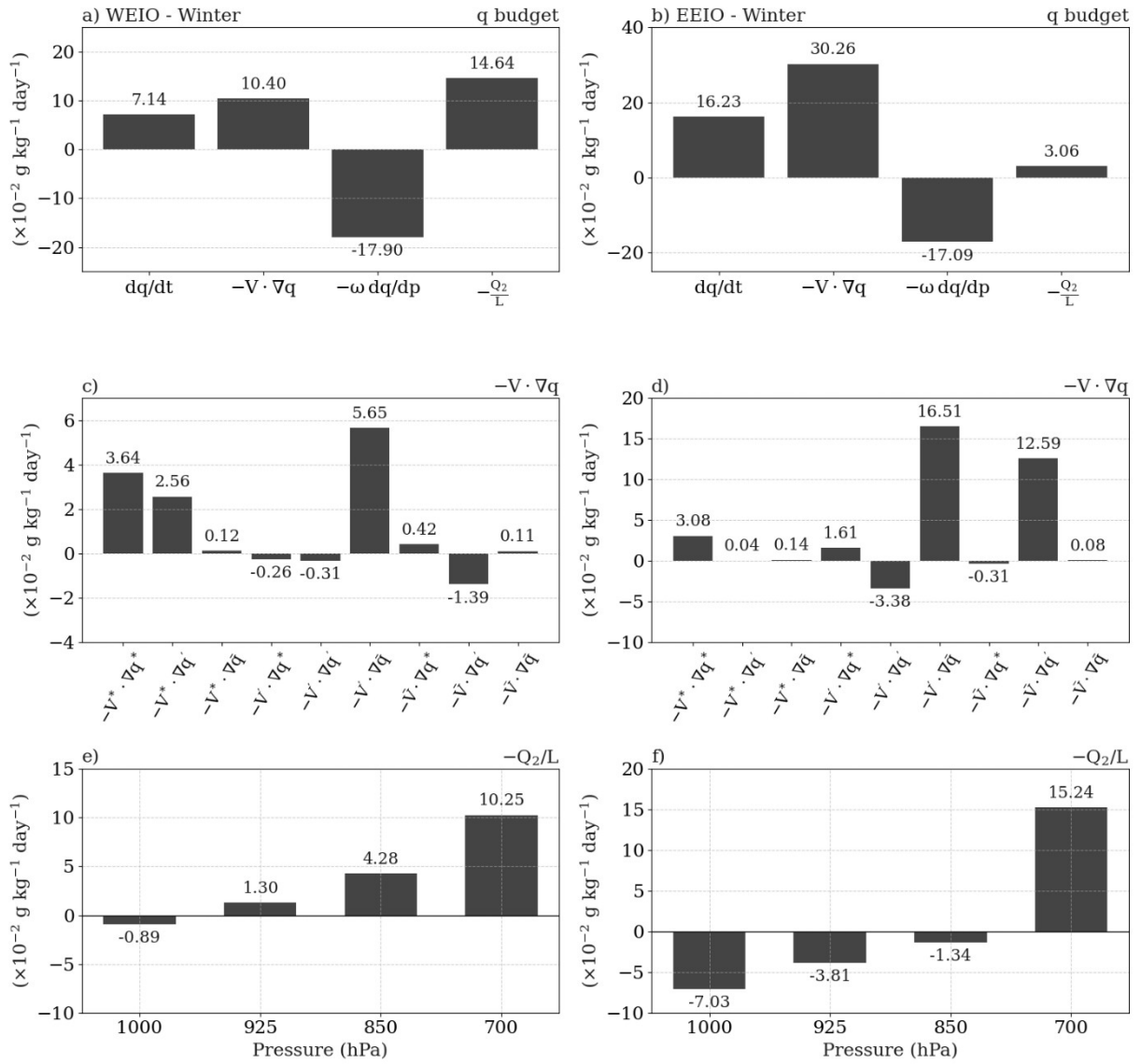


Figure 3.2: Composites of 20-90 day filtered vertically integrated (from 1000 hPa to 700 hPa) specific humidity budget terms for MJO convective initiations occurring over the a) WEIO and b) EEIO. c) and d) are same as a) and b) but show the different time-scale contributions to the horizontal advection of specific humidity. e) and f) show the 20-90 day filtered apparent moisture source term at different pressure levels in the lower troposphere for MJO convective initiations occurring over the WEIO and EEIO.

During winter, the moisture tendency in the pre-initiation stage over the EEIO domain is more than twice the moisture tendency over the WEIO domain (Figure 3.2 a & b), supporting the rapid PBL moistening observed in the earlier analysis. The highest contribution from the moisture

tendency is from the apparent moisture source term ( $-Q_2/L$ ) over the WEIO domain, while its contribution to the moisture tendency is much smaller over the EEIO domain. If  $-Q_2/L$  at 1000hPa is taken as a measure of surface evaporative processes, it can be seen that its contribution to the PBL moistening is not significant (Figure 3.2 e & f). Also, it is well known that the surface latent heat flux amplitudes over the western and eastern equatorial Indian Ocean domains are very similar during the winter season (Mohan et al., 2023). Apparently, the large amplitude of the moisture source term over the WEIO results from evaporation of cloud or precipitation droplets in the PBL due to subsidence-induced warming. The relative cloud fraction of shallow clouds over the WEIO domain at day -15 is more than three times the value over the EEIO domain (Figure 3.3 c & d). The shallow cloud fraction declines during the period leading to convection initiation and concurrently the specific humidity buildups in the PBL (Figure 3.3 a & c). The contribution of vertical advection of humidity to the moisture tendency is large, but negative over both domains, implying that the large scale subsidence during the pre-initiation stage leads to drying of the boundary layer. Zhao et al. (2013) noted that, as opposed to the significant role played by vertical advection of PBL moisture in facilitating MJO eastward propagation (Hsu and Li 2012), it opposes PBL moistening in the case of convection initiation. Horizontal advection of humidity in the PBL on the other hand, emerges as the major contributor to PBL moistening over the EEIO domain and the second largest contributor over the WEIO domain. The horizontal advection term over EEIO is approximately three times larger than that over WEIO. In short, over the EEIO domain, the PBL moistening results from the competing effects of horizontal and vertical advection processes, while over the WEIO domain, horizontal advection and evaporative processes in the PBL together works against the subsidence effects, in moistening the PBL.

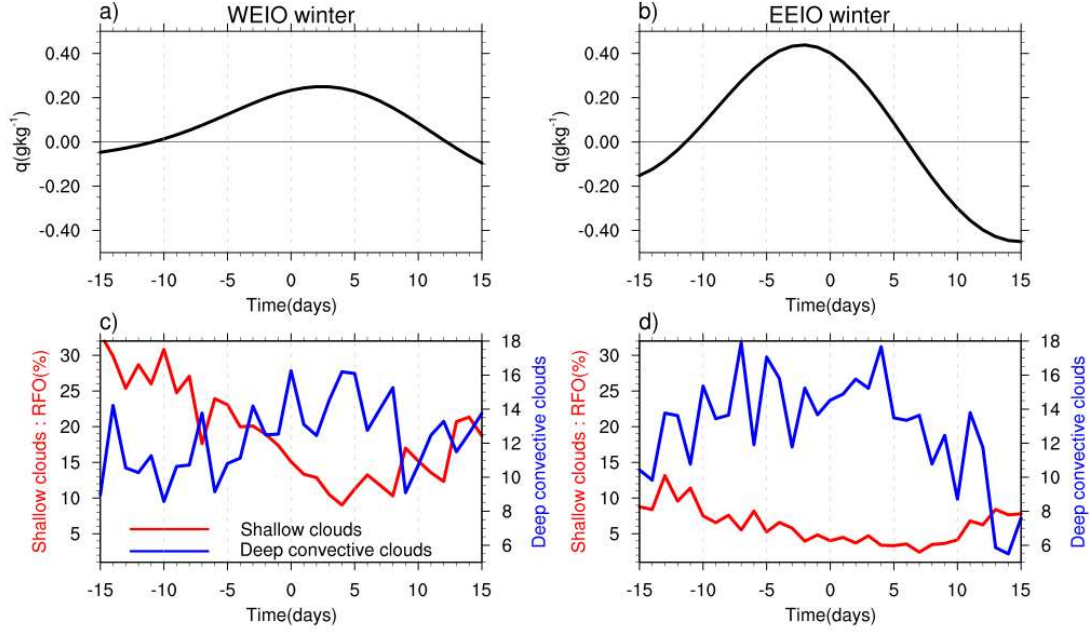


Figure 3.3: Composite boreal winter time evolution of 1000-700 hPa averaged specific humidity( $q$ ) relative to OMI based initiation day(lag 0) for (a) WEIO and (b) EEIO (top panels) initiation domains. Bottom panels(c-d) are similar to top panels(a-b) except that the relative frequency of occurrence (in %) for shallow clouds (red; left Y-axis) and deep convective clouds (blue; right Y-axis) are shown.

The contributions of synoptic, intraseasonal, and time mean state to the intraseasonal horizontal advection of PBL moisture is further examined by calculating the horizontal advection terms involving the wind and moisture fields decomposed to  $< 20$  days, 20–90 days and  $> 90$  days timescales respectively (Figure 3.2 c & d)

$$u = \bar{u} + u' + u^*; v = \bar{v} + v' + v^*; q = \bar{q} + q' + q^*$$

The bar, prime and asterix symbols denotes the low frequency background state ( $> 90$  day), the intraseasonal (20–90 day) and high frequency ( $< 20$  day) components respectively.

Advection of the mean moisture field (low frequency component) by the intraseasonal wind anomalies and the advection of intraseasonal moisture anomalies by the mean winds emerge as the main contributors to the horizontal advection over EEIO. Over WEIO, on the other hand, advection of the mean moisture field by the intraseasonal wind anomalies and the synoptic-scale

components dominate the total intraseasonal horizontal advection of moisture in the PBL. The zonal and meridional contributions to the horizontal advection were also examined (figure not included) and the zonal wind advection was found to be more than the meridional wind advection.

The establishment of intraseasonal wind anomalies over the Indian Ocean prior to WEIO and EEIO convection initiations and the processes governing the observed differences in horizontal moisture advection over the two domains are addressed in the remaining sections.

### 3.3.3 Planetary boundary layer circulation responses and horizontal moisture advection

Several of the MJO initiation studies (Ling et al., 2013; Zhao et al., 2013; Mie et al., 2015; Li et al., 2015) have noticed the establishment of easterly wind anomalies in the lower troposphere over the Indian Ocean as a prominent precursor to MJO convective initiation. Lag–longitude Hovmöller diagrams of intraseasonal OLR and 850-hPa zonal wind anomalies (Figure 3.4) shows the eastward propagation of suppressed convection anomalies and 850 hPa easterly wind anomalies preceding the convection initiations over the WEIO and EEIO domains. The easterly wind anomalies follow the positive OLR anomalies with a certain time lag and are observed over the WEIO (EEIO) domains about 10 (14) days preceding the day of convection initiation. Previous studies (Seo & Kim, 2003; Jiang and Li, 2005; Matthews, 2008; Ling et al., 2013) indicate that the Rossby and/or Kelvin response to the preceding MJO state may be responsible for the establishment of these wind anomalies. According to these theoretical studies, an MJO convective event may be triggered over the western Indian Ocean through the frictional convergence induced by the Rossby wave response to the suppressed convective state over the eastern Indian Ocean or the Kelvin wave response to an enhanced convective state over the West Pacific (part of the previous MJO). Through observational analysis and numerical simulations, Zhao et al (2013) demonstrated that an upstream forcing through a circumnavigating Kelvin wave is unlikely to initiate MJO convection over the Indian Ocean domain and affirmed the importance of local Rossby wave response to the suppressed MJO state. In this study, winter MJO initiations over both domains are primary in nature, since relatively quiescent conditions prevail over the region at even five weeks prior to the initiation day (Figure 2.2 & 2.3) and there is no indication of any convective activity associated with the preceding MJO cycle over the West Pacific. It is also evident from Figure 3.4 (a & b), that a continuous eastward propagating signal of easterly wind anomalies indicative of a circum-



navigating Kelvin wave is not present prior to the convection initiations over both the domains. Hence the easterly wind anomalies in the weeks preceding the convection initiation may be attributed to the downstream Rossby response to the suppressed convection state.

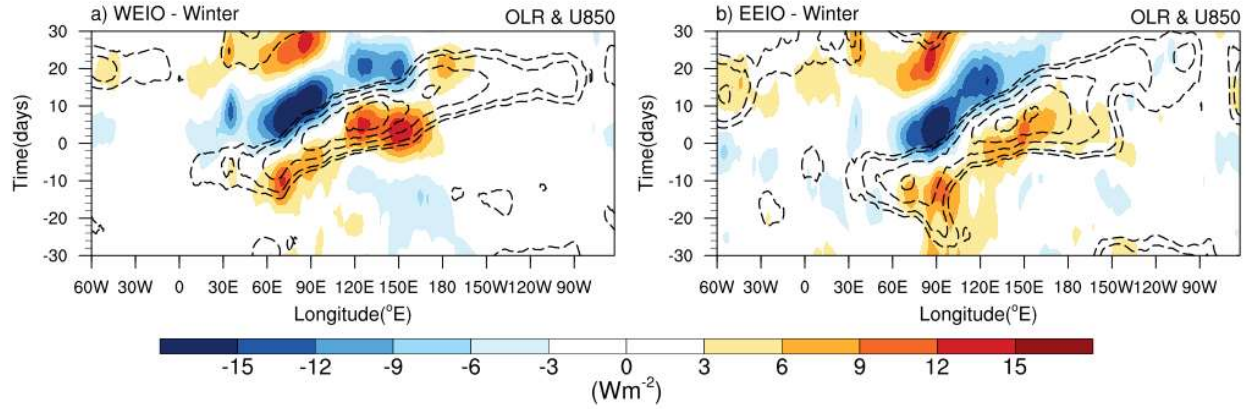


Figure 3.4: Lead-lag Composites of 20-90 day filtered OLR (shading) and 850 hPa easterly (black dashed contours) anomalies, relative to the MJO initiation days over the WEIO (a) and EEIO (b) during boreal winter, meridionally averaged between 10°S and 10°N latitudes.

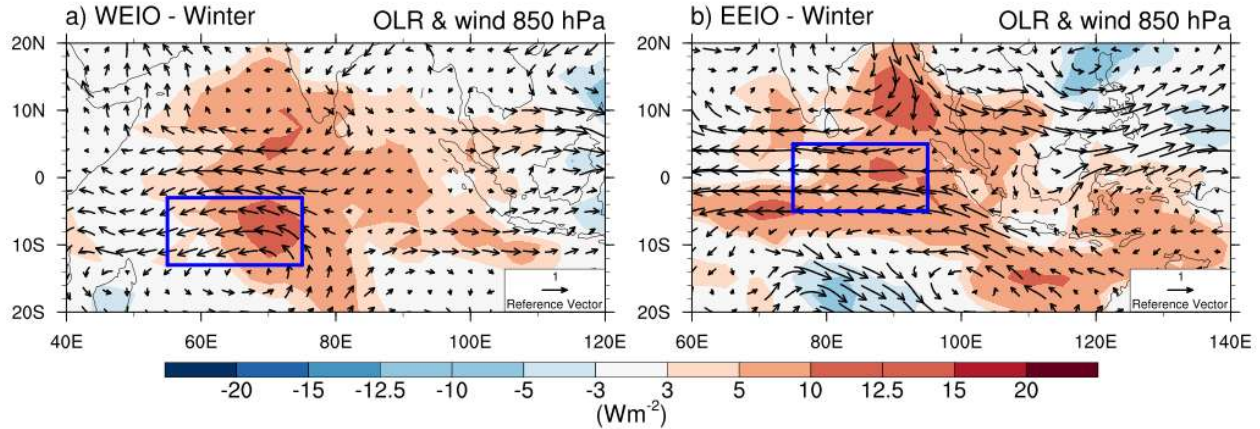


Figure 3.5: a) 20-90 day filtered OLR and 850 hPa wind ( $\text{ms}^{-1}$ ) anomalies averaged from 15 to 5 days before the MJO convective initiations occurring over the WEIO. b) Same as a), but averaged from 18 to 8 days before the MJO convective initiations occurring over the EEIO. Blue boxes indicate the MJO initiation domains.

The composite maps of intraseasonal OLR and 850-hPa wind anomalies averaged over the 10-day period preceding the convection initiations over the two domains (−15 to −5 lag days for WEIO and −18 to −8 for EEIO) are shown in Figure 3.5. The suppressed convection is centered

over the west-central equatorial Indian Ocean in the case of WEIO initiations and over the eastern Indian Ocean and Maritime continent in the case of EEIO initiations. This suggests that the location of the suppressed convection over the Indian Ocean may be indicative of the region where MJO convection initiation is likely to happen. The circulation anomalies are consistent with a Gill-type equatorial wave response to a suppressed convection state, with anticyclonic Rossby gyres straddling the equator (Figure 3.5 a & b), to the west of the region of suppressed convection. Associated with the Rossby response, equatorial easterly wind anomalies are observed to the west of the suppressed convection domain, which would advect moisture westward and destabilize the atmospheric column for convection. PBL moisture budget analysis indicates that, over the EEIO PBL moisture tendency is mainly driven by horizontal advection and the moisture advection processes mainly involves the low frequency background state and the intraseasonal timescales. Advection of the mean moisture field by the intraseasonal wind anomalies and the advection of intraseasonal moisture anomalies by the mean winds together contributes to the horizontal advection over the region. Over WEIO, where horizontal advection plays second fiddle in the PBL moisture dynamics, the intraseasonal horizontal advection of moisture is mainly through advection of the mean moisture field by the intraseasonal wind anomalies and advective processes involving synoptic-scale disturbances. Advection of intraseasonal moisture anomalies by the mean winds on the other hand, does not make a significant contribution to the total horizontal advection.

Over both domains, advection of the mean moisture field by the intraseasonal wind anomalies – i.e., the easterly wind anomalies generated as a downstream Rossby response to the suppressed convection state, plays a major role in the PBL moistening. This is possible because the background moisture field over the domain exhibits an east-west gradient, peaking over the Maritime Continent. The mean winds are westerly over the equatorial Indian Ocean and through the intraseasonal circulation responses involving weakening of the westerlies, or generation of easterly wind anomalies, moisture would get advected to the Indian ocean initiation regions. The efficiency of horizontal moisture advection over the two initiation domains would depend on the amplitude of the zonal humidity gradient and the strength of the easterly wind anomalies. Composites of PBL averaged background humidity and intraseasonal winds over the Indian Ocean, averaged during the 10-day period preceding the convection initiation over the WEIO and EEIO domains are shown in Figure 3.6 (a & b) and the meridional averaged amplitudes of the two fields over the respective domains are shown Figure 3.6 (c & d). The low frequency (background)



specific humidity composites in Figure 3.6 (a & b) are very similar, which brings out a pattern of mean specific humidity being highest over the Maritime Continent and EEIO and decreasing westward to the western Indian Ocean. The zonal background moisture gradient and the anomalous easterlies exhibit a higher amplitude over the EEIO domain, during the period preceding the convection initiation in the respective domains (Figure 3.6 c & d), indicating a more efficient westward moisture advection into EEIO domain as compared to the WEIO domain. Meanwhile, over the WEIO, the weaker easterlies interact with the weaker zonal moisture gradient, resulting in a less efficient horizontal moisture advection over the region. This explains the rapid rate of PBL moistening and faster instability growth over the EEIO domain, prior to convective initiation. Though significant meridional gradients are also observed in the specific humidity field over the two domains, the relatively weaker intraseasonal meridional wind anomalies do not make as much an impact and the horizontal moisture advection during winter season is mainly through the zonal wind anomalies.

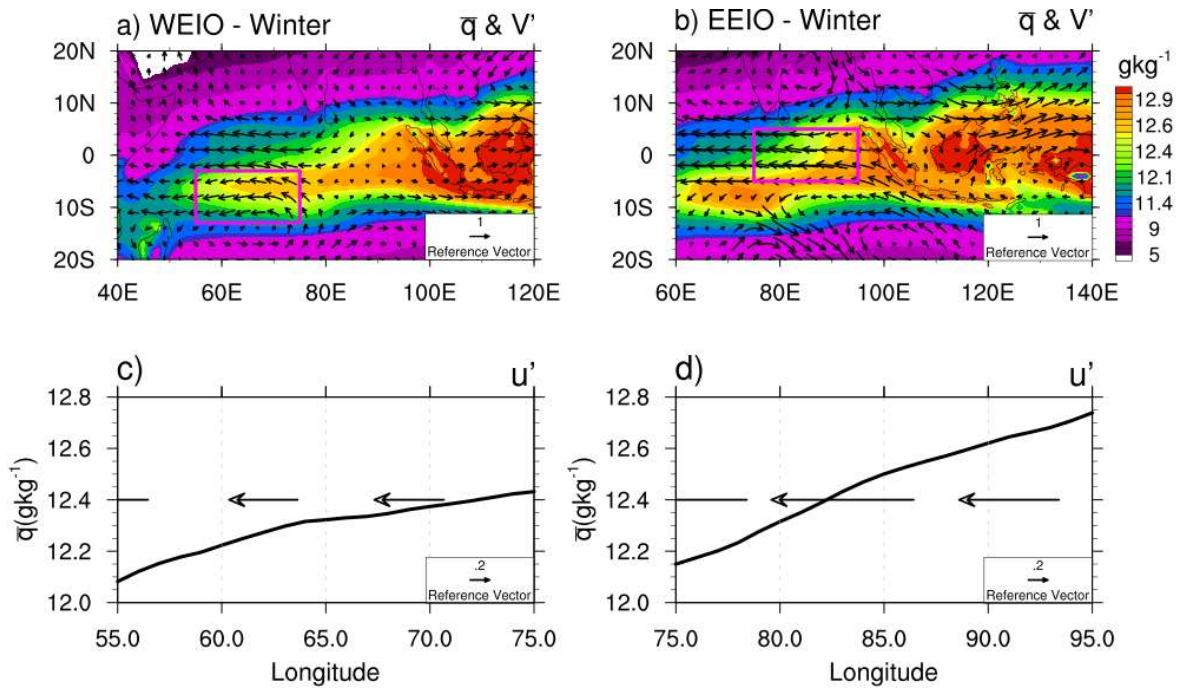


Figure 3.6: Composites of vertically averaged (from 1000 hPa to 700 hPa) low-frequency (period greater than 90-days) specific humidity (shading;  $\text{g kg}^{-1}$ ) and intraseasonal (20–90-day filtered) wind (vectors;  $\text{m s}^{-1}$ ) anomalies for MJO convective initiations occurring over the WEIO (left column) and EEIO (right column). a) The maps of low-frequency specific humidity and intraseasonal wind anomalies averaged from 15 to 5 days before the MJO convective initiations occurring over the WEIO. b) same as a) but averaged from 18 to 8 days before the MJO convective initiations occurring over the EEIO. c) and d) show longitudinal distributions of the low-frequency specific humidity and intraseasonal wind anomalies

### 3.4 Summary and Conclusions

This chapter examines the processes leading to the contrast in destabilization of the atmospheric column prior to MJO convective initiation over the Western Equatorial Indian Ocean(WEIO) and Eastern Equatorial Indian Ocean(EEIO) regions. The instability buildup over both the regions, during preinitiation stage, is primarily due the planetary boundary layer(PBL) moistening together with the cooling in the mid-to upper troposphere. However, the strength and rate of growth of these factors leading to instability buildup differs with rapid and strong PBL moistening together with strong mid to upper tropospheric cooling over EEIO versus gradual moistening and weaker cooling over WEIO.

As PBL moistening is a key factor leading to atmospheric destabilization over both regions the processes leading to the PBL moistening is diagnosed using PBL moisture budget analysis. The analysis suggests that the PBL moistening over the WEIO is primarily contributed by the apparent moisture source term and secondly by the horizontal advection term both acting against the drying induced by the vertical downward motions. Over EEIO PBL moistening is dominated by horizontal advection process, with values about three times that over WEIO, while the apparent moisture source term is very small and these processes together counteract against the subsidence induced drying which is of comparable magnitude of that over WEIO. Further investigation of processes contributing to the apparent moisture source term shows that it is majorly by the evaporation of shallow clouds and precipitation under the lower tropospheric warming induced by subsidence evident during the preinitiation stage rather than by the surface evaporative processes.

The different time scale contributions to the horizontal advection term are also examined. Over the EEIO the primary contributor towards horizontal advection is the intraseasonal and mean interaction terms and secondary contributor is the advection of intraseasonal moisture by the mean winds. Over the WEIO again the dominant contributor is the advection of mean moisture by the intraseasonal winds while the secondary contributor is by the synoptic scale interaction term.

Further as the advection of mean moisture by the intraseasonal winds plays a dominant role over both regions the horizontal distribution of mean moisture and the factors triggering the intraseasonal winds are examined. The background moisture over the Indian Ocean, for both initiation categories, is characterized by strong zonal gradient with high values over Maritime

continent decreasing westward towards the western equatorial Indian Ocean. The intraseasonal winds with equatorial easterlies are part of the anticyclonic Rossby wave response to the suppressed convection during the preinitiation state for both categories which advects the moisture westward towards the respective initiation domains. Over the EEIO, the large amplitude intraseasonal easterlies together with sharp zonal gradient of background moisture lead to efficient and rapid moistening while the weaker easterlies and weaker background zonal moisture gradient over WEIO leads to weaker moistening by horizontal advection. This thus explains the processes leading to the contrast in the PBL moistening processes over the two initiation domains thus leading to the differences in the strength and rate of tropospheric column destabilization.

These results suggest that the relative importance of individual processes leading to MJO convective initiations depends very much on the region of initiation thus pointing to the need to consider the MJO initiations based on the region of initiations. It also points to the importance of improving the model representation of advective processes- with realistic background moisture and intraseasonal processes- along with the cloud and precipitation evaporative processes which are found to be important for Indian Ocean MJO convective initiations.

# Chapter 4

## Role of MRG in Indian Ocean MJO Convective Initiation and Predictability

### 4.1 Introduction

Recent studies have highlighted the potential role of equatorial synoptic scale disturbances—especially Mixed Rossby-Gravity(MRG) waves—in the convective initiation of the MJO. Previously considered as contributing to the propagation of MJO(Straub & Kiladis, 2003; Yang & Ingersoll, 2011), these high frequency disturbances have been shown to trigger the MJO convective initiations over the Western Equatorial Indian Ocean especially during boreal winter (Takasuka et al., 2019, 2021; Takasuka & Satoh, 2020)

In this proposed mechanism the upper tropospheric MRG disturbances present during the suppressed MJO phase are amplified under the influence of favorable background conditions and further lead to the dispersion of eddy kinetic energy (EKE) downward and eastward (Takasuka et al., 2019, 2021; Takasuka & Satoh, 2020). The consequent lower tropospheric MRG wave packets induce off equatorial convergence which may trigger the MJO convection. Takasuka et al., 2021 further show that the background conditions over the upper troposphere over the Indian Ocean—characterized by the strong easterlies and Walker cell convergence over the WEIO – is conducive for the amplification of the upper tropospheric MRGs during the suppressed MJO state and disperse EKE downward and eastward leading to the development of lower tropospheric MRGs that initiate MJO convection. However, this proposed mechanism has so far been demonstrated majorly using a single case study, thus leaving room for the testing of the robustness of this process for MJO convective initiations over the WEIO.

Chapter 2 of the thesis identified that the Indian Ocean MJO convective initiations are mainly concentrated over the WEIO and EEIO. In the WEIO the initiations tend to occur off the equator, over South Western Equatorial Indian Ocean during boreal winter and North Western

Equatorial Indian Ocean during boreal summer. Whereas, in the EEIO initiations are concentrated symmetrically about the equator irrespective of the season.

This suggests that lower tropospheric MRG, with its off-equatorial convergence, can potentially influence the off-equatorial WEIO MJO initiations, while its role must be limited for the equatorial EEIO initiations. Also, the upper-tropospheric walker cell convergence and easterlies are oriented towards the WEIO, thus suggesting that the top down energy dispersion mechanism could be important for WEIO, while the walker cell divergence over the EEIO might inhibit the amplification of MRG there thus leading to a minimal role of top down energy dispersion for EEIO initiations. Finally, whether the MRG plays an important role for the boreal summer MJO initiations is not known. Motivated by these considerations, the present chapter first examines the statistics of MRG activity preceding MJO convective initiation and how this statistics varies between different seasons and different initiation regions over the Indian Ocean. Further the importance of top down MRG energy dispersion mechanism proposed by Takasuka et al., 2021 is qualitatively examined across the cases. Finally the chapter examines whether the presence of MRG precursor can enhance the MJO convective initiation skill by in using model reforecasts from the subseasonal to seasonal prediction(S2S) project.

## **4.2 Data and Methods**

This section describes the method used to identify MJO initiations that are preceded by MRG, as well as the approach taken to investigate the top-down dispersion mechanism of MRG. Additionally, it discusses the details of reforecast data used to assess whether MRG enhances the predictability of MJO convective initiations and explains how model skill is quantified.

### **4.2.1 Identification of MJO Initiation Events**

MJO initiation events are identified using the objective method described in subsection 2.2.2 of data and methods section of Chapter 2, applied to boreal winter (November–March) and summer (May–September) for the period 1979–2022. This procedure yields 41 winter initiation cases in total, consisting of 27 WEIO and 14 EEIO initiations and 42 summer initiation cases with 25 WEIO and 17 EEIO initiations. The initiation day is defined as the lag when the intraseasonal OLR anomaly crosses zero over the respective initiation region.

## 4.2.2 Detection of MRG Activity Using EMD

MRG activity data used in this study is obtained from Suhas et al. (unpublished manuscript) where the Empirical Mode Decomposition (EMD) technique is applied to 5°S–5°N averaged 850-hPa meridional winds to identify the MRG activity. This dataset provides the timing and location of lower-tropospheric MRG activity for the 1979–2022 period.

In the present study this MRG event data is used to identify if an MJO initiation is associated with a preceding MRG or not. Initiation cases are classified as “preceded by MRG” if a lower-tropospheric MRG event occurs in the 10 days prior to initiation (based on OLR zero crossing) within a region-specific longitudinal window: 30°–80°E for WEIO and 30°–130°E for EEIO. All other initiations are classified as “not preceded by MRG.” The MRG activity detection was performed relative to the OLR zero crossing day over the respective initiation regions, which is about 4 days prior to the OMI-based initiation day for WEIO and about 7 days earlier for EEIO. For consistency across figures and discussions throughout this chapter, all lag references are presented relative to the OMI based initiation day(lag 0) unless specifically mentioned.

## 4.2.3 Diagnostics of MRG Structure and Energetics

To isolate MRG variability, a 3.5–8 day bandpass filter is applied using a 101-weight Lanczos filter(Duchon, 1979). Only westward-propagating components (zonal wavenumbers  $-1$  to  $-15$ ) are retained. Lower-level MRG activity is represented by the 1000–800 hPa average of the filtered meridional winds, while upper-level MRG activity is represented by the 200–300 hPa averaged meridional winds.

MRG Wave energy accumulation and evolution are examined by calculating eddy kinetic energy (EKE):

$$EKE = \frac{1}{2}(u'^2 + v'^2) \quad (4.1)$$

Where  $u'$  and  $v'$  are the MRG filtered winds. To highlight the envelope of wave packets, EKE is smoothed with an 11-day running mean(Takasuka et al., 2021). The EKE tendency is calculated using the smoothed EKE, enabling identification of amplification periods at different levels.

## 4.2.4 S2S model reforecasts

The database made available as a part of S2S project(Vitart et al., 2017) provides reforecasts and real-time forecasts from multiple operational centers for the subseasonal to seasonal time scale. While models from different operational forecasting centers across the world are part of the S2S project, only CMA and NCEP provide a sufficient number of initiation cases both with and without preceding MRG activity. For this reason, these two models are used for skill assessment. The details of these two model reforecasts are given below:

- CMA reforecast: 60-day integrations, T106L40 resolution, 4 ensemble members, daily initialization, ocean-coupled at  $1^{\circ} \times 1^{\circ}$ , reforecast period 1994–2014.
- NCEP reforecast: 44-day integrations, T126L64 resolution, 4 ensemble members, daily initialization, ocean-coupled at  $0.5^{\circ} \times 0.25^{\circ}$ , reforecast period 1999–2010.

## 4.2.5 Synoptic and MJO Signal Extraction in S2S models

The MRG-related signals in the model reforecasts are extracted by 1st removing a 11 day running mean which essentially remove the high frequency variability and then that is subtracted from the raw field of interest which will separate the high frequency signal. To isolate the MJO signal in models, an Empirical Orthogonal Function(EOF) projection method which extracts the MJO convective features from raw OLR using a real time version of OMI index(ROMI) is used(Section 4.2.6; next section). Observational verification uses ROMI derived from daily NOAA interpolated OLR (Liebmann & Smith, 1996).

## 4.2.6 ROMI Calculation in Models

Because the conventional OLR MJO Index (OMI) requires time filtering which removes the end point data, which is not possible in limited reforecast windows, the Real-time OLR MJO Index (ROMI; Kiladis et al., 2014) is constructed which does not require filtering.

The procedure is broadly similar to that of Wang et al., 2019 and is briefly described below:

1. Compute model-specific reforecast climatology for each calendar day.
2. Remove the observed climatology from observed NOAA OLR values (restricted to the model reforecast years) to form observed anomalies.

3. Calculate model OLR anomalies by subtracting the model climatology (Calculated in step 1).
4. Attach the 40-day observed OLR anomaly preceding initialization day to the model anomalies, remove the previous 40-day mean, and apply a 9-day running mean to the resultant field with tapering towards the end points.
5. Project the resultant anomalies onto day-of-year EOFs developed by Kiladis et al., 2014 to obtain ROMI1 and ROMI2 indices.

### 4.2.7 Model MJO Skill Metric

The MJO convective initiation skill is quantified in the model reforecasts using the bivariate correlation (Rashid et al., 2011) of observed and model ROMI components at a particular lead time  $\tau$ :

$$Cor(\tau) = \frac{\sum_{t=1}^N (ROMI1_{obs}(t) \times ROMI1_{mod}(t, \tau) + ROMI2_{obs}(t) \times ROMI2_{mod}(t, \tau))}{\sqrt{\sum_{t=1}^N (AMP_{obs}(t))^2} \times \sqrt{\sum_{t=1}^N (AMP_{mod}(t, \tau))^2}} \quad (4.2)$$

Where the  $ROMI1_{obs}(t)$  &  $ROMI2_{obs}(t)$  are the observed values of the ROMI at time  $t$  and  $ROMI1_{mod}(t, \tau)$  &  $ROMI2_{mod}(t, \tau)$  are the corresponding model reforecast values for lead time  $\tau$ . Amplitude at time  $t$  in equation 4.2 is defined as:

$$AMP(t) = \sqrt{(ROMI1(t))^2 + (ROMI2(t))^2} \quad (4.3)$$

For the model reforecasts, the dynamic skill for any lead day  $\tau$  is calculated as the mean of the correlations across the ensemble members:

$$DYN(\tau) = \sum_{i=1}^M COR(\tau)_i \quad (4.4)$$

where  $M$  is the number of ensemble members. Skill is computed separately for initiations preceded and not preceded by MRG activity.

### 4.2.8 Observational Datasets

Observed OLR is taken from NOAA interpolated daily OLR (Liebmann & Smith, 1996) with daily temporal resolution and  $2.5^\circ$  by  $2.5^\circ$  spatial resolution. Meridional wind at multiple tropospheric levels is from ERA5 reanalysis (Hersbach et al., 2020), available from 1979–2022 at  $1^\circ \times 1^\circ$



resolution with hourly temporal resolution made into daily mean. The meridional wind data at the lower tropospheric(1000, 950, 900, 850 and 800) and upper tropospheric(200,250 and 300 hPa) pressure levels are used to investigate the variations of lower and upper level meridional circulations associated with MRG.

## 4.3 Results and discussion

### 4.3.1 MRG activity preceding MJO Onset:

An analysis of association of MRG waves across 41 Indian Ocean MJO initiation events during boreal winter found that 39% (16 out of 41) demonstrated significant preceding lower-tropospheric MRG activity during the 10 days preceding the MJO initiation. When examining subregions, the Western Indian Ocean (WEIO) showed that 40% of initiations (11 out of 27) were linked to precursor MRG signals, while the Eastern Indian Ocean (EEIO) had 35% (5 out of 14 cases) suggesting that the MRG influence could be relatively more over WEIO compared to EEIO. These Indian Ocean MJO initiation cases classified as MRG preceded for WEIO and EEIO for winter season are given in Table 4.1

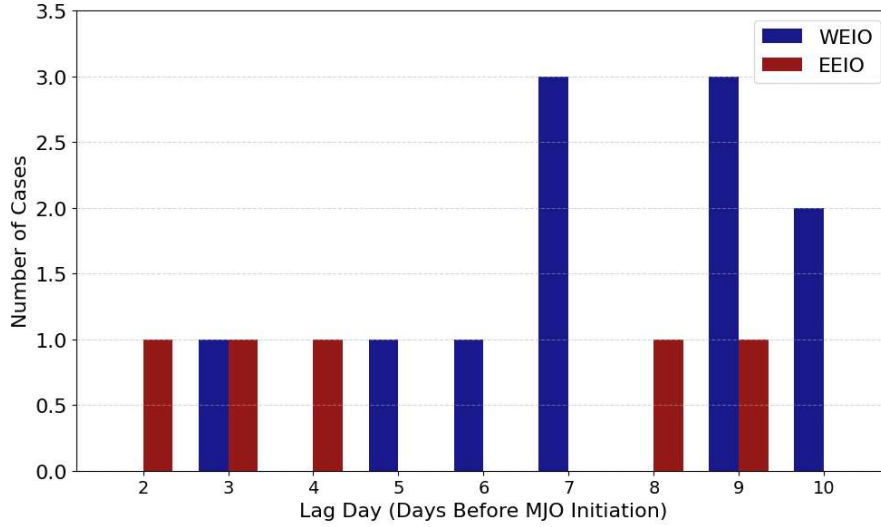
| Region      | Case No. | MJO Initiation Date<br>(YYYY-MM-DD) |
|-------------|----------|-------------------------------------|
| <b>WEIO</b> | 1        | 2016-11-08                          |
|             | 2        | 1987-03-01                          |
|             | 3        | 2020-11-08                          |
|             | 4        | 2006-01-03                          |
|             | 5        | 2014-02-04                          |
|             | 6        | 1986-03-05                          |
|             | 7        | 2017-01-19                          |
|             | 8        | 1980-12-26                          |
|             | 9        | 2014-11-13                          |
|             | 10       | 1999-03-08                          |
|             | 11       | 1994-01-31                          |
| <b>EEIO</b> | 1        | 1979-02-18                          |
|             | 2        | 1982-12-17                          |
|             | 3        | 1997-01-22                          |
|             | 4        | 2015-02-08                          |
|             | 5        | 2017-12-28                          |

*Table 4.1: Winter WEIO and EEIO MJO Initiation dates with Preceding Lower-Level MRG Activity.*

In contrast, during the boreal summer, only 11%(5 out of 42) of MJO initiation events were associated with preceding lower level MRG activity with 12% in the WEIO(3 out of 25) and 11% in the EEIO(2 out of 17). This much lower number of MJO initiation cases with preceding MRG during summer suggest that MRG might not play an important role in MJO initiation for this season. Thus, the further analyses are constrained to the boreal winter MJO initiations.

Figure 4.1 shows the histogram of the lag times for the lower tropospheric MRG activity prior to the MJO initiation based on the OLR zero crossing day for both WEIO and EEIO initiations. For the WEIO initiations, the MRG events typically occur 3-10 days preceding the MJO initiation with a majority aggregated around the 7-10 days window suggesting a typical time window for the influence of MRG. For the EEIO, lead times, with limited sample, ranges from 2 to 9 days and there is no preference of shorter or longer lead times of MRG influence.

The WEIO seems particularly conducive to the triggering of the MJO convective initiation through MRG wave-driven off equatorial convergence majorly due to factors such as a) Presence of mean WEIO MJO convective initiation over the off equatorial Western Indian Ocean evident in chapter 2(Figure 2.1a) where the significant contribution of synoptic-scale processes to PBL moistening is evident(Figure 3.2c); b) The background upper tropospheric easterlies and its convergence associated with walker cell over the WEIO which leads to an environment conducive for the strengthening of the upper tropospheric MRG waves(Takasuka et al., 2021). The resulting upper tropospheric EKE buildup has been shown to lead to lower tropospheric MRG wave packet formation via downward and eastward MRG energy dispersion(Takasuka et al., 2019, 2021; Takasuka & Satoh, 2020). This along with the fact that relatively large number of MRG preceded MJO convective initiations are present over WEIO suggests a focused examination of WEIO in the context of MRG.



*Figure 4.1. Frequency distribution of Boreal Winter MJO initiation events over western(blue) and eastern(red) Indian Ocean corresponding to lower-tropospheric Mixed Rossby-Gravity (MRG) wave activity at different lags relative to MJO initiation day. MJO initiation here is 4(7) days preceding OMI based initiation day for WEIO(EEIO). The x-axis denotes the lag (days) relative to the OLR zero-crossing–based MJO initiation day. The y-axis indicates the number of instances of MJO initiations where MRG activity was present on that lag day.*

Hence, the following subsections will thoroughly examine the role of MRG waves in MJO convective initiation focusing on the boreal winter WEIO initiation category by examining few representative examples of MRG preceded MJO convective initiations.

Figure 4.1 depicts representative examples of lower tropospheric MRG activity preceding MJO convective initiation for 4 WEIO MJO initiation cases. In these Hovmöller diagrams of intraseasonal OLR anomalies averaged over 10°S–5°S (shading) together with MRG-filtered lower tropospheric(1000–800 hPa average) meridional winds averaged over 5°S–5°N (black contours) relative to the OMI based initiation day(lag 0) show distinct westward propagating convection and cross equatorial circulation perturbations of alternating signs over the Indian Ocean region. The day of lower tropospheric MRG activity identified by the EMD method is marked with the horizontal dashed purple line, and the WEIO initiation domain is indicated with green vertical lines.

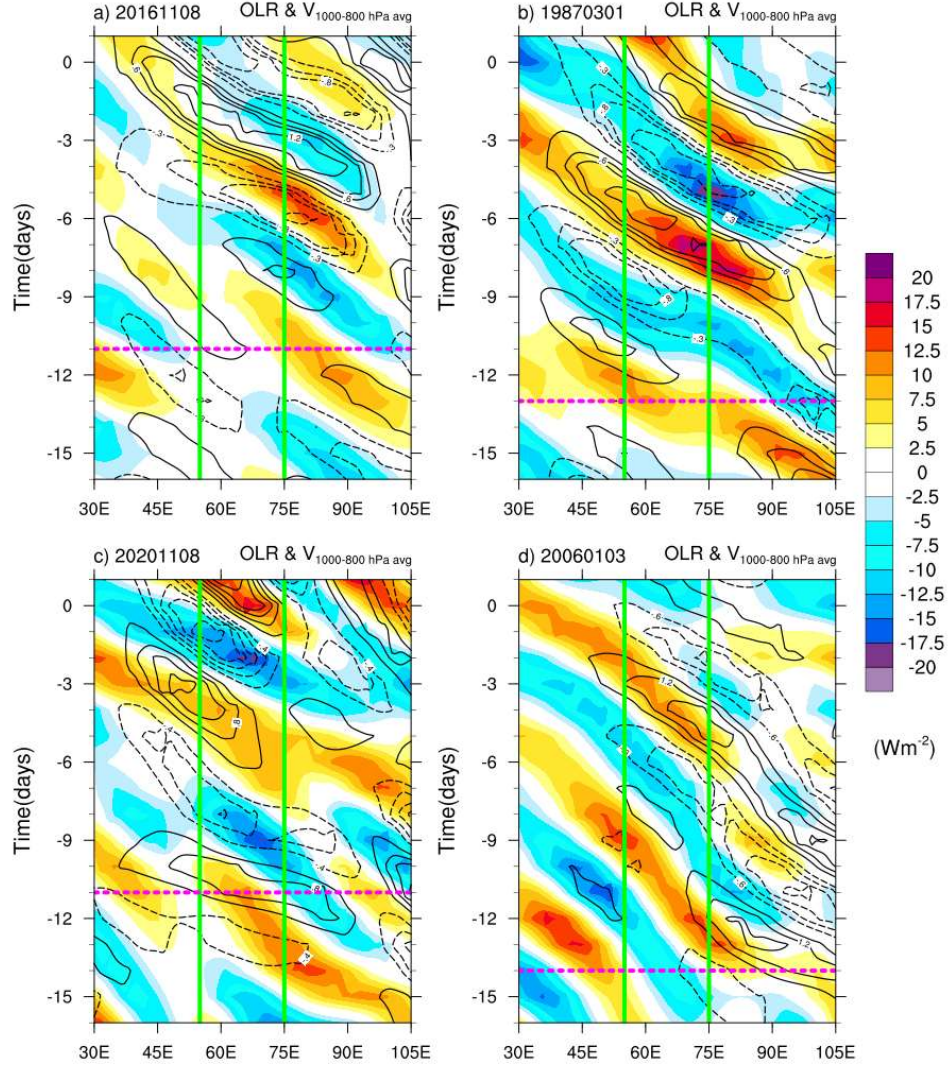


Figure 4.2: Hovmöller diagram of MRG-related anomalies preceding 4 WEIO MJO convective initiation cases( a) 8 November 2016, b) 01 March 1987, c) 8 November 2020 & d) 3 January 2006): The figures depict 10°S–5°S averaged MRG filtered OLR (shaded;  $W m^{-2}$ ) and 5°S–5°N averaged 1000–800 hPa MRG filtered meridional wind (with northerlies and southerlies depicted by dashed and solid contours respectively ;  $m s^{-1}$ ). Zero lag marks the OMI-based MJO initiation day. The identified MRG activity day is shown by the dashed purple horizontal line, and green vertical lines indicate the WEIO initiation domain.

Across the cases depicted in figure 4.2 the EMD-based MRG southerly detection coincides with the emergence of cross equatorial southerly arrival (black dashed contours) over or near the WEIO MJO initiation region approximately 5–10 days prior to the OMI-defined MJO convective initiation day. Following the emergence of these weak MRG activity over the initiation domain, the cross equatorial MRG flow of alternating signs strengthen as is the case with the off equatorial

convective signals captured by shaded OLR anomalies, meridionally averaged south of the equator. The observed phasing between the south equatorial convective anomalies and the low level cross equatorial circulation anomalies, where convective anomaly maximum (depicted by the negative OLR values) slightly lead the northerly anomalies(dashed black contours) is consistent with the canonical coupled MRG wave structure. Later the northerly anomalies typically accompanied by south equatorial convergence, along with associated south equatorial convective anomalies reach the initiation region near the OMI initiation day(lag 0), suggesting their important role in initiating off equatorial western equatorial MJO convection.

Thus the MRG activity identified by the EMD method correspond closely to the cross equatorial southerly development over or near the WEIO MJO initiation region suggesting that the EMD based method successfully isolated physically consistent MRG events. These MRG waves strengthen in the following days with MRG northerlies (typically accompanied by south equatorial convergence) contributing towards the MJO convective initiation. This role of MRG in inducing MJO convective initiation and propagation commencing from WEIO is consistent with a series of studies based on field observations (Takasuka et al. 2019, 2021), reanalysis data( Takasuka and Satoh, 2020) and model simulations (Takasuka et al., 2018). The following section investigates the processes leading to the lower level MRG formation and strengthening (seen in this section) focusing on the top down EKE dispersion mechanism proposed by Takasuka et al., 2021.

### 4.3.2 Case Study Evidence: Upper and Lower Tropospheric MRG Activity and EKE Accumulation

While investigation across the cases in the previous subsection suggests that MRG activity precedes a significant fraction of WEIO initiations, case-based analyses in this section provide additional insight into the formation and strengthening of lower tropospheric MRG through the examination of vertical phasing of upper- and lower-level MRG meridional circulation anomalies and their relationship with EKE buildup. The Time–longitude sections of MRG-filtered meridional wind at 200–300 hPa and 1000–800 hPa, combined with MJO-filtered OLR anomalies (panels b & c of figure 4.3-4.6), for four such representative WEIO events confirm this vertical phasing, indicating that upper-level processes disperse energy downward to lower levels leading to MJO convective initiation and propagation. These 4 cases are described below in detail.



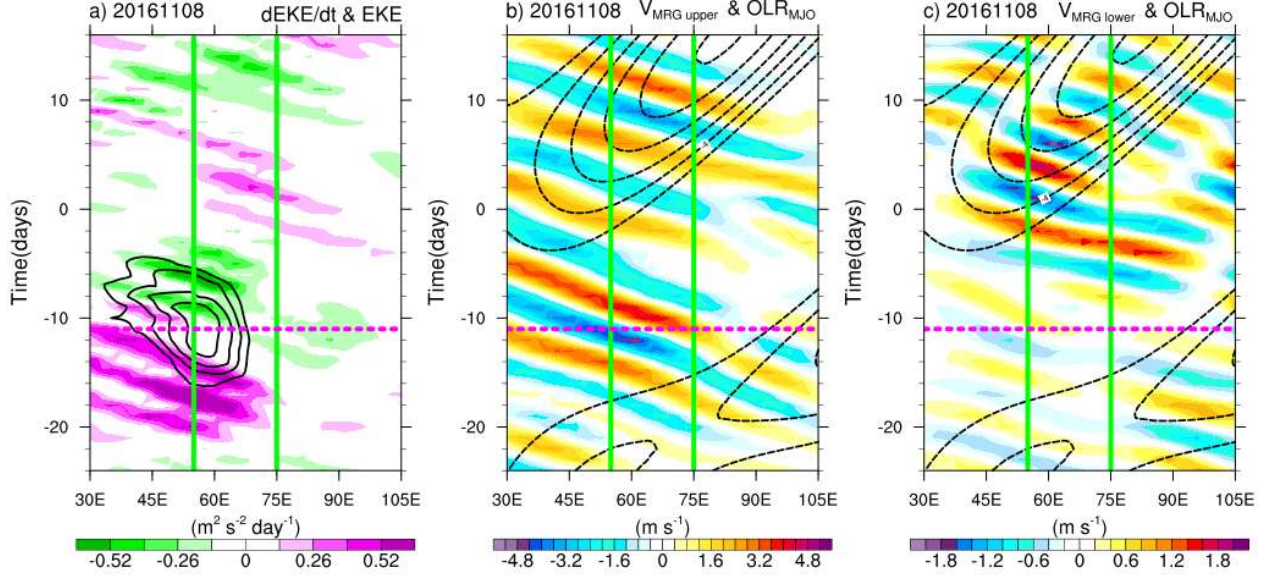


Figure 4.3: (a) Time–longitude Hovmöller diagram of Mixed Rossby–Gravity (MRG)-associated eddy kinetic energy (EKE) tendency (shading;  $\text{m}^2 \text{s}^{-2} \text{day}^{-1}$ ) and EKE (contours;  $\text{m}^2 \text{s}^{-2}$ ) averaged over  $10^\circ \text{S}$ – $10^\circ \text{N}$ . (b) and (c) Time–longitude Hovmöller diagrams of MRG-filtered meridional wind ( $v$ ) averaged over  $5^\circ \text{S}$ – $5^\circ \text{N}$  at the upper (200–300 hPa average) and lower (1000–800 hPa average) troposphere, respectively (shading;  $\text{m s}^{-1}$ ), with MJO-filtered outgoing long-wave radiation (OLR) anomalies (contours;  $\text{W m}^{-2}$ ) averaged over  $10^\circ \text{S}$ – $10^\circ \text{N}$ . The purple dashed line marks the day of MRG activity identified by empirical mode decomposition (EMD) method; green vertical lines denote the MJO initiation region. All panels correspond to the 8 November 2016 MJO initiation event, showing the vertical phasing of upper- and lower-level MRG activity and its relationship to MJO convective development and propagation.

During the 8 November 2016 initiation (Figure 4.3), upper level EKE tendencies of significant magnitude emerged (Figure 4.3a) around lag -21 day (17 days before MJO initiation) from the  $45$ – $75^\circ \text{E}$  domain, exhibiting westward propagation followed by strong EKE accumulation over the WEIO, peaking in the  $50$ – $65^\circ \text{E}$  domain between lag -14 to -9 days (5 to 10 days before initiation). Upper-level northerly anomalies (Figure 4.3b) appeared as early as lag -20 (16 days preceding initiation) near  $75^\circ \text{E}$ , followed by amplifying southerlies propagating westward that reached maximum strength between  $55$ – $65^\circ \text{E}$  at lag -16 to -14, coinciding with the timing of EKE accumulation. Initially, lower tropospheric undulations of MRG circulation were weaker (Figure 4.3c); however, southerly anomalies emerged near lag -11 (about 7 days before initiation) over the initiation region, coinciding with the EMD identified MRG activity. Subsequently, alternating northerly and southerly winds in the lower troposphere propagated westward. These lower-level

MRG signals intensified after initiation and became embedded within the eastward-propagating MJO convection.

The 8 November 2020 event displayed a similar phasing(Figure 4.4). Upper-tropospheric EKE tendencies of significant magnitude developed between 30°–65°E(Figure 4.4a) from lag -14 to -4 days( 10 days before to the day of initiation), followed by strong EKE accumulation centered over 30°–45°E during lag -11 to lead +4 (7 days before to 8 days after initiation). Northerly anomalies in the upper-level propagated westward from 55°E from lag -15 day (11 days before initiation) followed by southerlies around 60°E at lag -12(8 days preceding initiation), which strengthened as they propagated westward. In the lower troposphere, MRG southerly anomalies developed near lag -11(7 days before initiation) over the initiation region (55°E-75°E; Figure 4.4c), again consistent with the EMD identification, followed by northerlies around lag -8 to -4(4 days before to initiation day). In the following days alternating MRG cross equatorial circulations propagated westward, but their group propagated eastward, aligning with the MJO convective envelope at and beyond MJO initiation at lag -4.

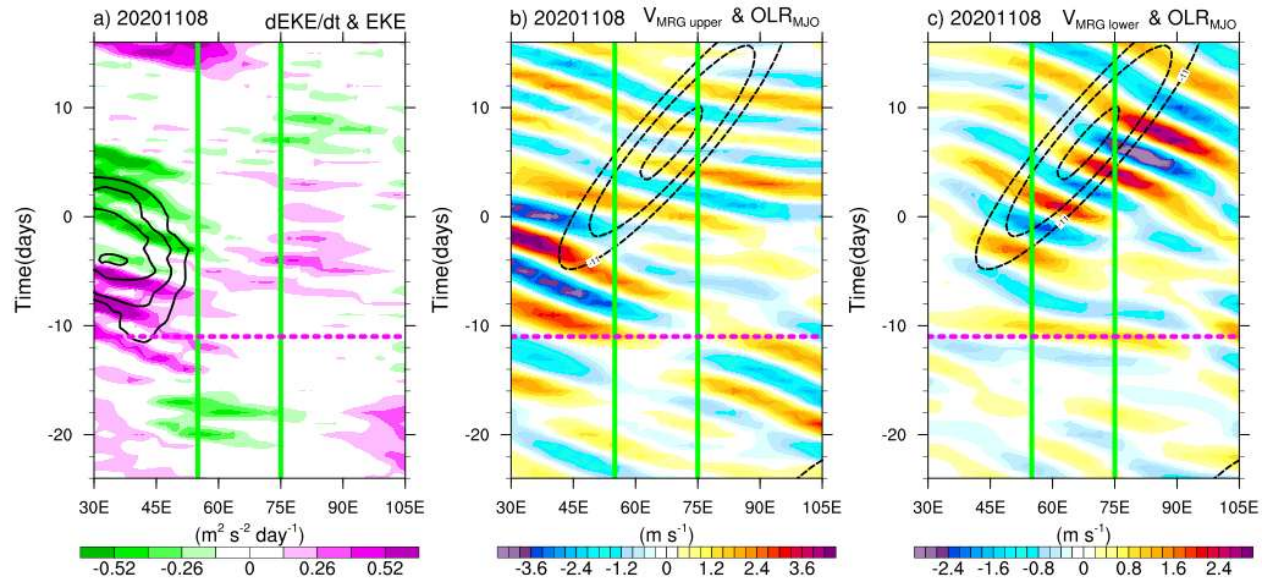


Figure 4.4: Same as Figure 4.3, but for the MJO initiation event on 8 November 2020.

The 01 March 1987 case(Figure 4.5) provided evidence of a earliest EKE accumulation and delayed MJO eastward propagation. Positive upper-level EKE tendencies were evident as early as lag -24( 20 days preceding initiation) over 30°–75°E region(Figure 4.5a), with EKE accumulation evident over 35-65°E from lag -20(16 days preceding initiation) onward, with

maximum EKE accumulation between 45°–60°E between lag -13 to -8 (in the 9 to 4 day window preceding initiation). Upper level northerlies propagated westward from 75°E to 40°E during lag -20 to -16 (16 to 12 days preceding initiation; Figure 4.5b), amplifying over the initiation region, followed by alternating southerly and northerly anomalies. At low levels, southerlies emerged near lag -13 (9 days preceding initiation) over the initiation region (Figure 4.5c), coinciding with the EMD-identified MRG activity. MJO convection began near lag 0, but its eastward propagation became apparent only from lag +2 to +6 days (6–10 days after initiation) when the westward-propagating low-level MRG structures were embedded within the eastward-propagating MJO convective envelope.

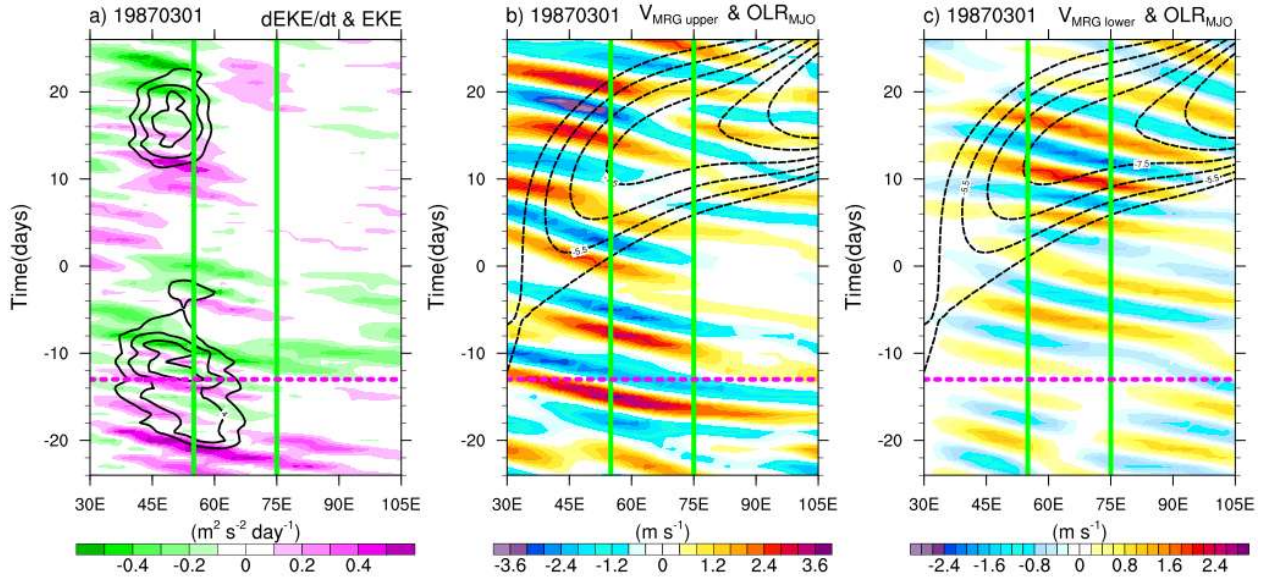


Figure 4.5: Same as Figure 4.3, but for the MJO initiation event on 01 March 1987.

A similar vertical phasing was also evident in the 03 January 2006 initiation (Figure 4.6). Positive upper-level EKE tendencies appeared from lag -22 (18 days preceding initiation) across 30°–60°E (Figure 4.6a), followed by additional activity over 55°–75°E from lag -18 (14 days before initiation) onward. EKE accumulation peaked first over 30°–45°E around lag -14 (10 days preceding initiation) and later over 55°–75°E at lag -10 (6 days before initiation). Upper-level northerlies intensified across 30°–55°E at lag -16 (12 days preceding initiation; Figure 4.6b), followed by westward-propagating southerlies at lag -14, concurrent with the strongest EKE accumulation. In the lower tropospheric levels, southerlies propagated westward between 35°–60°E from lag -14 to -8 (4 to 10 days preceding initiation; Figure 4.6c), close to the EMD-identified



activity. Alternating anomalies subsequently propagated westward and were eventually embedded within the eastward-propagating MJO convective envelope after initiation.

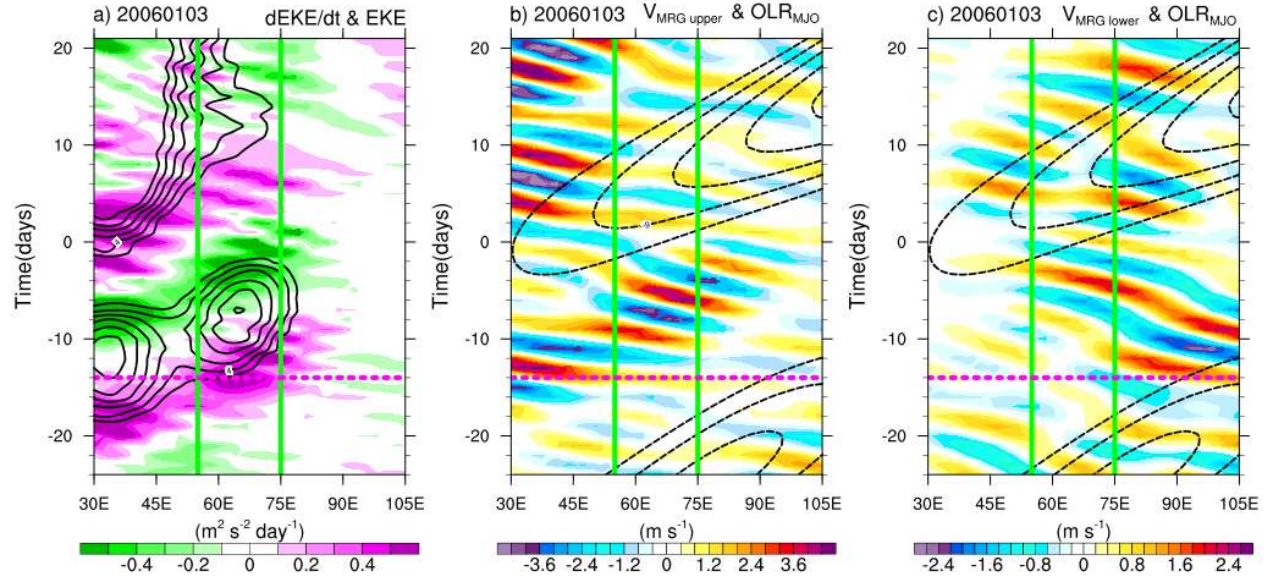


Figure 4.6: Same as Figure 4.3, but for the MJO initiation event on 3 January 2006

Similarly, the remaining WEIO MJO initiations with preceding MRG are analyzed and the sequence of upper level MRG amplification along with EKE accumulation and later lower level MRG packet formation and strengthening and MJO initiation and propagation with eastward propagating MJO convective envelope involving the fine scale westward propagating MRG meridional wind perturbations are observed in a total of 8 out of 11 cases(given in table 4.2) including the 4 cases discussed above.

| Case No. | MJO Initiation Date<br>(YYYY-MM-DD) | Top down Mechanism<br>evident |
|----------|-------------------------------------|-------------------------------|
| 1        | 2016-11-08                          | Y                             |
| 2        | 1987-03-01                          | Y                             |
| 3        | 2020-11-08                          | Y                             |
| 4        | 2006-01-03                          | Y                             |
| 5        | 1999-03-08                          | Y                             |
| 6        | 1980-12-26                          | Y                             |
| 7        | 1986-03-05                          | Y                             |
| 8        | 2014-11-13                          | Y                             |
| 9        | 2014-02-04                          | —                             |
| 10       | 1994-01-31                          | —                             |
| 11       | 2017-01-19                          | —                             |

*Table 4.2: List of WEIO MJO initiation events with preceding lower-level MRG activity, indicating presence or absence of top-down energy dispersion inferred based on the vertical phasing of upper and lower level MRG activity and Eddy Kinetic Energy(EKE) evolution.*

In summary, across all analyzed WEIO MJO initiation events, 8 cases including the four investigated in detail above and additional 4 MRG preceded cases (figure not shown), a consistent vertical phasing is evident in which upper-tropospheric MRG anomalies and associated EKE tendencies appear approximately 10-20 days before MJO onset followed by accumulation over the WEIO sector. Lower-tropospheric MRG activity emerges within approximately 5-10 days of initiation. Subsequently alternating MRG meridional circulation features propagate westward, embedded within the eastward-moving MJO convection.

Although the timing and intensity of these precursors vary among events, the recurrent sequence of upper-level amplification and following lower-level activity provides event-based support for a top-down energy dispersion mechanism. These results are consistent with the findings of Takasuka et al., 2021 and demonstrate that upper-level MRG waves and associated energy buildup play a critical role in leading to lower-level disturbances that precondition the lower troposphere for MJO convective initiation over the WEIO.

### 4.3.3 Role of MRG Waves in MJO initiation Predictability in S2S Model reforecasts

Now that the role of MRG precursor for the Indian Ocean MJO convective initiation is evident in a large number of cases one interesting question is whether these MRGs can enhance the predictability of MJO convective initiations. The MRGs typically have a periodicity ranging from

3-10 days and in this time window it may act as a source of predictability for the MJO convective initiations. In this section the influence of MRG representation on the predictability of MJO convective onset was examined using model reforecasts part of the S2S project.

While the S2S database contains reforecasts from multiple operational centers, only the NCEP CFSv2 and CMA BCC\_CSM1.2 models provided a sufficient number of initiation cases both with and without preceding MRG activity to enable meaningful comparison. The NCEP model provides 44-day reforecasts initialized daily over the years from 1999 to 2010, while the CMA model provides 60-day reforecasts initialized daily for the year spanning from 1994 to 2014. Both models have relatively small ensemble sizes of four members, but their daily reforecast frequency ensures that initiation cases with and without MRG waves are well sampled, in comparison to other models part of the S2S project. Table 4.3 summarizes the details of the CMA and NCEP model reforecasts along with the number of Indian Ocean MJO initiation cases captured with and without preceding MRG.

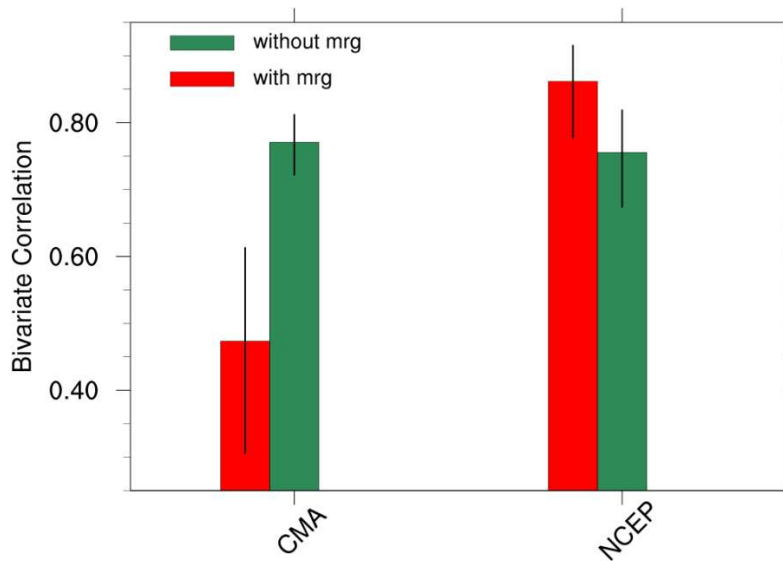
| Model            | Reforecast Period | Reforecast Frequency | Ensemble Size | No. of Initiations (-2 to +2 day range) |             |
|------------------|-------------------|----------------------|---------------|-----------------------------------------|-------------|
|                  |                   |                      |               | With MRG                                | Without MRG |
| CMA (BCC_CSM1.2) | 1994–2014         | Daily                | 4             | 25                                      | 80          |
| NCEP (CFSv2)     | 1999–2010         | Daily                | 4             | 15                                      | 35          |

*Table 4.3: S2S model reforecast details—including reforecast period, frequency, and ensemble size—along with the number of Indian Ocean MJO initiation cases captured with and without preceding MRG activity considering a 5 day window centered on initiation day. Initiation cases are identified by matching initiation dates or days within the  $\pm 2$ -day window falling on model lead day 7.*

In model reforecasts the MJO initiation cases were identified by matching the OMI-based initiation dates with model reforecasts at lead day 7, using a  $\pm 2$ -day window around the OMI-based initiation day. Note that all the Indian Ocean MJO convective initiations with and without preceding MRG are considered for this analysis. Model skill was quantified using the bivariate correlation between the reforecast ROMI with the NOAA satellite OLR based ROMI for the target OMI-based MJO initiation day.

Figure 4.7 shows the bivariate correlation of Indian Ocean MJO convective initiation skill separated by the presence(red) or absence(green) of a precursor lower tropospheric MRG

event. The NCEP model has significantly higher skill when initiation is preceded by MRG activity, with bivariate correlation values approaching 0.85 compared to  $\sim 0.75$  for cases without MRG. In contrast, the CMA model displays the opposite behavior: skill is lower in cases with preceding MRG ( $\sim 0.45$ ) compared to those without ( $\sim 0.75$ ).



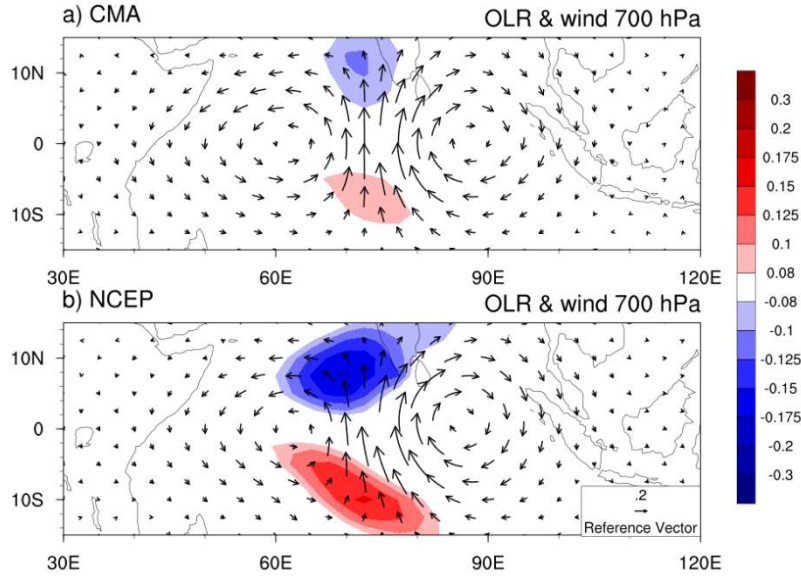
*Figure 4.7: Bivariate Correlation of MJO convective Initiation Predicted One Week in Advance in CMA and NCEP model reforecasts. The correlation is shown for cases with Precursor MRG (Red) and cases without MRG (Green). The vertical black line represents the 95% confidence interval of the bivariate correlation. Initiation cases are identified by matching initiation dates or days within the  $\pm 2$ -day window centered on initiation day falling on model lead day 7.*

These contrasting results highlight possibly the importance of correctly representing MRG and its convective coupling in these subseasonal forecast models. In NCEP the higher skill when MRG precursors are present likely suggests that the model is able to utilize the additional predictability provided by synoptic-scale MRG disturbances. In CMA, the degradation of skill in MRG-related cases likely points to deficiencies in either the simulation of MRG waves themselves or in their interaction with convection. The MRG representation in the models are further explored in the next section.

#### 4.3.4 MRG–Convection Coupling in CMA & NCEP Model reforecasts

The difference in forecast skill between NCEP and CMA identified in the previous subsection can be possibly linked to their representation of MRG and the associated convection coupling. Figure

4.8 illustrates the horizontal structure of these interactions, based on correlations between spatial maps of OLR anomalies and 700 hPa winds with a 700hPa meridional wind reference time series averaged over 5°S–5°N and 70°–80°E domain considering all the available daily reforecasts from the NCEP and CMA models. To isolate synoptic-scale variability, 11-day smoothed field was subtracted from the raw reforecast data before calculating the correlation, ensuring that the retained signal contains the high-frequency synoptic disturbances.



*Figure 4.8: Horizontal MRG structure evident in OLR(shade) and 700 hPa winds(vectors) in a) CMA & b) NCEP model reforecasts. Spatial maps of individual fields (wind at 700 hPa and OLR) are correlated with the 700 hPa meridional wind reference time series (averaged over 5S-5N & 70-80E). All available model reforecasts are included for individual models, with 11-day smoothed values removed from the raw reforecast field before correlation calculation.*

In the NCEP model(Figure 4.8b), enhanced convection north of the equator and suppressed convection south of the equator form the antisymmetric convective pattern characteristic of MRG waves. This convective signature is tightly coupled with cross-equatorial southerly wind anomalies, with the active convection north of the southerlies where convergence of southerlies is evident and suppressed convection south of the southerlies where divergence associated with the southerlies are evident resulting in a convection-circulation relation that is consistent with observations. On the other hand, the CMA model exhibits weaker and less organized convective patterns. The convective anomalies are relatively weaker even though the cross-equatorial meridional wind vectors(southerlies) are of similar magnitude as compared to NCEP. This suggest

that the coupling between winds and convection is not properly captured in the CMA model. These weaker representation of MRG circulation-convection coupling could be possibly leading to the reduced forecast skill of MJO initiation in CMA when preceded by MRG. While it cannot be determined from this analysis alone whether the weak MRG convective coupling representation arises from model physics, resolution, or the representation of initial conditions, the comparison shows that the representation of MRG–convection coupling is a prerequisite in determining MJO initiation skill.

## 4.4 Summary and Conclusions

This chapter has demonstrated the important role of precursor MRG waves in the lower troposphere during MJO initiation over the Indian Ocean and explored their implications for subseasonal prediction. Analysis of lower tropospheric MRG activity preceding the Indian Ocean MJO convective initiations suggest that during boreal winter approximately 40% of WEIO initiations and 35% of EEIO initiations were preceded by identifiable low-level MRG activity. In contrast boreal summer witnessed only very less number of MRG preceded MJO initiations with 12% over WEIO and 11% over EEIO MJO initiations suggesting that MRG might not play an important role for boreal summer initiations. Thus the subsequent analysis focused on the winter cases over the WEIO where MRG preceded MJO initiations are relatively more. Also the off equatorial convective initiation region along with the background circulation conditions are conducive for the MRG influence on initiation over WEIO.

For these winter WEIO cases, MRG preceded MJO initiations are characterized by lower levels MRG associated cross equatorial circulation and off equatorial convection strengthening towards the MJO initiation day over the WEIO MJO initiation domain. One proposed mechanism for the formation and strengthening of such lower level MRG is the top down EKE dispersion mechanism proposed by Takasuka et al., 2021. Examination of this mechanism for the boreal winter WEIO MRG preceded MJO initiations suggest that the majority of MRG preceded MJO initiation cases(8 out of 11) exhibited a clear top–down energy dispersion mechanism similar to the 4 cases demonstrated(Figure 4.3-4.6), in which upper-tropospheric EKE amplification and MRG strengthening preceded the emergence of lower-level MRG wave packets that became embedded within the eastward-propagating MJO convective envelope thus providing event based evidence for the mechanism proposed by Takasuka et al., 2021.

The analysis of subseasonal forecast models further showed that the predictability of Indian Ocean MJO convective initiations associated with MRG precursors depends strongly on model representation of MRG-convection coupling. In the NCEP model, forecast skill was significantly higher when MJO initiations were preceded by MRG activity, consistent with its strong MRG–convection coupling. In contrast, the CMA model displayed reduced skill in MRG-related cases compared to non MRG initiation cases, and is possibly linked to its weaker representation of the MRG circulation convection coupling. This comparison suggests that the beneficial role of MRGs in predictability of MJO convective initiation can only be realized when both initial conditions and model physics are able to capture the interaction between MRG wave dynamics and convection.

These findings provide three main contributions. First, they quantify the frequency of MRG precursors in observed Indian Ocean MJO convective initiation events both over WEIO and EEIO for winter and summer seasons. Second, they provide event-based supporting evidence for a top–down energy dispersion mechanism- proposed by Takasuka et al., 2021- in 8 out of 11 cases of boreal winter MJO initiations over WEIO. Third, they demonstrate that the role of MRGs in MJO onset prediction is model-dependent, with skill improvement only present when MRG–convection coupling is realistically represented.

Nonetheless, several limitations should be acknowledged. The classification of top–down dispersion was based on alignment of EKE tendency and vertical phasing of MRG signals; more direct and detailed diagnostics would strengthen the interpretation. On the modeling side, only NCEP and CMA were analyzed with limited sample because of reforecast availability, and conclusions therefore cannot be generalized to all S2S reforecasts without further investigation.

Despite these limitations, the results underscore the central importance of MRG dynamics in both the physical processes leading to MJO initiation and their representation in forecast systems. Accurate simulation of MRG–convection coupling, emerges as a prerequisite for skillful prediction of MJO initiation, highlighting an opportunity for targeted model development and evaluation of subseasonal predictions.

# Chapter 5

## Summary and Conclusions

Although the Equatorial Indian Ocean is considered a primary hub of MJO convective initiation (Zhao et al., 2013; Zhang & Ling, 2017), it is not a single homogeneous “initiation basin”. Within the basin itself, there are considerable zonal and seasonal contrasts. The Eastern equatorial Indian Ocean, characterized by high SSTs and moisture throughout the year, is conducive to deep convection, while over the western equatorial Indian Ocean, it is the distinctive upper ocean thermal structure and intraseasonal air-sea interaction processes that lead to convective initiations. This study identifies the major subregions of the Indian Ocean where MJO convective initiations occur and examines the thermodynamic and dynamic processes in detail that lead to intraseasonal convective initiation over these subregions.

Using an objective identification of convective initiations based on the OLR MJO Index (OMI) for the period 1979–2021, a total of 83 initiation events were identified, with 41 in boreal winter and 42 in boreal summer. Two preferred subregions emerged: the Western Equatorial Indian Ocean (WEIO) and the Eastern Equatorial Indian Ocean (EEIO). WEIO initiations are more frequent, and their convective centers tend to lie off the equator, displaced southward in winter and northward in summer, in progression with the seasonal migration of warm SSTs. EEIO initiations are less frequent but remain close to the equator in both seasons and are associated with stronger convective anomalies than their WEIO counterparts. The analysis of precursor MJO convective states showed that winter initiations are primary initiations, whereas summer initiations are secondary. The influence of interannual variability on the initiation region across seasons suggests that boreal summer initiations are modulated by the Indian Ocean Dipole (IOD), with positive IOD phases favoring WEIO initiations and negative IOD phases favoring EEIO initiations. In winter, however, the initiations are insensitive to IOD phase, indicating that local intraseasonal processes dominate. Subsequent analysis of thermodynamic precursors, focusing mainly on boreal winter initiations, suggests that convective initiation over the WEIO and EEIO occurs in two distinct thermodynamic regimes. Over the EEIO, instability strengthens rapidly (in the nine days preceding



initiation), while over the WEIO, it is more gradual (on a two-week timescale). These differences in instability buildup and its magnitude are reflected in the evolution of vertical motion, cloud populations, and outgoing longwave radiation: ascent in the lower troposphere begins earlier over the EEIO, the clouds transition quickly from shallow to deep convection, and the resulting negative OLR anomalies are stronger and more extensive at initiation than over the WEIO.

In Chapter 3, the major factors leading to this difference in thermodynamic instability buildup between the subregions were investigated in detail. The relatively rapid destabilization of the EEIO initiation category arises from a combination of pronounced moistening in the planetary boundary layer (PBL) and strong, deep negative temperature anomalies above the PBL. Because PBL moisture buildup is the key driver of tropospheric column instability—and develops gradually over the WEIO but rapidly over the EEIO—a PBL specific humidity budget analysis was carried out to determine what controls these contrasting destabilization pathways. Over the EEIO, the PBL moistening is primarily by horizontal advection. In contrast, over the WEIO, the dominant contributor to PBL moistening is the moisture source ( $-Q_2/L$ ) term, with a non-negligible secondary contribution from horizontal advection. Further exploration of factors leading to the moisture source ( $-Q_2/L$ ) term over WEIO suggests that the significant contribution is by the evaporation of cloud and precipitation due to subsidence induced lower-level warming in the preinitiation stage. The major contribution to the horizontal advection process in both regions was found to rely on the interaction between intraseasonal easterlies and the background PBL moisture, which exhibits a strong zonal gradient with high values over the Maritime Continent and decreasing westward. The easterlies, which emerge as a Rossby response to suppressed convective anomalies, are strong over the EEIO and act on the steep moisture gradient there to produce rapid PBL moistening. Over the WEIO, weaker easterlies and a weaker zonal moisture gradient result in a smaller contribution from horizontal advection. In this way, the combination of intraseasonal Rossby responses and background moisture gradients explains why the EEIO is characterized by rapid moistening and destabilization compared to WEIO.

A striking observation in Chapter 3 is the role of synoptic disturbances in PBL moistening, particularly for the winter WEIO category, where convection initiates off the equator. This, combined with previous case-study work by Takasuka et al. (2021), which suggested a top-down Mixed Rossby–Gravity (MRG) wave mechanism for MJO convective initiation, motivated a

detailed investigation of MRG disturbances in Chapter 4. A systematic analysis of MRG activity showed that these waves play a significant but seasonally modulated role in MJO convective initiation. During boreal winter, roughly 40% of WEIO initiations and 35% of EEIO initiations were preceded by identifiable low-level MRG activity whereas in summer MRG preceded initiation were very less frequent with about only 12% of WEIO and 11% of EEIO initiations exhibiting such precursors. Further focusing on winter WEIO events, where off-equatorial initiation and background circulation conditions are most conducive to MRG influence, the majority of MRG-preceded cases displayed a clear top-down energy dispersion mechanism: upper-tropospheric MRG amplification during the suppressed phase was followed by the emergence of lower-tropospheric MRG wave packets leading to MJO initiation and eastward propagation with MRGs embedded within the eastward-propagating MJO convective envelope. This provides multi-event evidence that the previously proposed mechanism of Takasuka et al. (2021) operates in a substantial fraction of winter WEIO initiations. Furthermore, whether the presence of MRG preceding MJO convective initiations can influence the skill of MJO initiations was explored using reforecasts from two subseasonal prediction models: NCEP and CMA, part of the S2S project. The comparison showed that the impact of MRG precursors on forecast skill depends crucially on how well each model represents MRG-convection coupling. In the NCEP(CMA) model, forecast skill for Indian Ocean MJO convective initiation was significantly higher(lower) in MRG-preceded cases than in non-MRG cases, consistent with a realistic(less-realistic) representation of MRG convection circulation coupling. These results suggest that MRGs can serve as a valuable source of predictability for MJO convective initiation, provided that both the initial conditions and model physics accurately capture the interaction between MRG wave dynamics and convection.

Taken together, the results of this thesis provide a coherent, process-based picture of MJO convective initiation over the Indian Ocean. They demonstrate that Indian Ocean MJO convective initiation is not a single, basin-wide phenomenon, but instead consists of regionally and seasonally distinct regimes defined by WEIO and EEIO environments, as well as by winter and summer backgrounds. The location and rate of instability buildup, and hence the eventual convective strength of the MJO, are controlled by the interplay between intraseasonal circulation responses to suppressed convection and the zonally varying background moisture distribution. High-frequency equatorial MRG waves furnish a dynamical pathway linking upper-tropospheric wave activity to

lower-tropospheric wave activity and convergence and convective triggering in a significant subset of winter WEIO events, and the ability of models to represent MRG convection coupling appears to be closely tied to their skill in predicting initiation.

# References

- Adames, Á. F., Wallace, J. M., & Monteiro, J. M. (2016). Seasonality of the structure and propagation characteristics of the MJO. *Journal of the Atmospheric Sciences*, 73(9), 3511-3526. <https://doi.org/10.1175/jas-d-15-0232.1>
- Banzon, V., Smith, T. M., Chin, T. M., Liu, C., & Hankins, W. (2016). A long-term record of blended satellite and in situ sea-surface temperature for climate monitoring, modeling and environmental studies. *Earth System Science Data*, 8(1), 165-176. <https://doi.org/10.5194/essd-8-165-2016>
- Benedict, J. J., & Randall, D. A. (2007). Observed characteristics of the MJO relative to maximum rainfall. *Journal of the atmospheric sciences*, 64(7), 2332-2354. <https://doi.org/10.1175/jas3968.1>
- Betts, A. K. (1976). The thermodynamic transformation of the tropical subcloud layer by precipitation and downdrafts. *Journal of atmospheric sciences*, 33(6), 1008-1020.
- Bladé, I., & Hartmann, D. L. (1993). Tropical intraseasonal oscillations in a simple nonlinear model. *Journal of Atmospheric Sciences*, 50(17), 2922-2939. [https://doi.org/10.1175/1520-0469\(1993\)050<2922:tioias>2.0.co;2](https://doi.org/10.1175/1520-0469(1993)050<2922:tioias>2.0.co;2)
- Cadet, D. L. (1986). Fluctuations of precipitable water over the Indian Ocean during the 1979 summer monsoon. *Tellus A*, 38(2), 170-177. <https://doi.org/10.1111/j.1600-0870.1986.tb00463.x>
- Duchon, C. E. (1979). Lanczos filtering in one and two dimensions. *Journal of Applied Meteorology (1962-1982)*, 1016-1022.
- Duvel, J. P., & Vialard, J. (2007). Indo-Pacific sea surface temperature perturbations associated with intraseasonal oscillations of tropical convection. *Journal of Climate*, 20(13), 3056-3082. <https://doi.org/10.1175/jcli4144.1>
- Fu, X., Lee, J. Y., Hsu, P. C., Taniguchi, H., Wang, B., Wang, W., & Weaver, S. (2013). Multi-model MJO forecasting during DYNAMO/CINDY period. *Climate Dynamics*, 41(3), 1067-1081. <https://doi.org/10.1007/s00382-013-1859-9>
- Fu, X., Lee, J. Y., Hsu, P. C., Taniguchi, H., Wang, B., Wang, W., & Weaver, S. (2013). Multi-model MJO forecasting during DYNAMO/CINDY period. *Climate Dynamics*, 41(3), 1067-1081. <https://doi.org/10.1007/s00382-013-1859-9>

Gadgil, S., & Asha, G. (1992). Intraseasonal variation of the summer monsoon I: Observational aspects. *Journal of the Meteorological Society of Japan. Ser. II*, 70(1B), 517-527. [https://doi.org/10.2151/jmsj1965.70.1b\\_517](https://doi.org/10.2151/jmsj1965.70.1b_517)

Goswami, B. N., & Mohan, R. A. (2001). Intraseasonal oscillations and interannual variability of the Indian summer monsoon. *Journal of climate*, 14(6), 1180-1198. [https://doi.org/10.1175/1520-0442\(2001\)014<1180:ioaivo>2.0.co;2](https://doi.org/10.1175/1520-0442(2001)014<1180:ioaivo>2.0.co;2)

Haertel, P. T., Kiladis, G. N., Denno, A., & Rickenbach, T. M. (2008). Vertical-mode decompositions of 2-day waves and the Madden–Julian oscillation. *Journal of the Atmospheric Sciences*, 65(3), 813-833. <https://doi.org/10.1175/2007jas2314.1>

Han, W., Liu, W. T., & Lin, J. (2006). Impact of atmospheric submonthly oscillations on sea surface temperature of the tropical Indian Ocean. *Geophysical Research Letters*, 33, L03609. <https://doi.org/10.1029/2005GL025082>

Han, W., Yuan, D., Liu, W. T., & Halkides, D. J. (2007). Intraseasonal variability of Indian Ocean sea surface temperature during boreal winter: Madden-Julian Oscillation versus submonthly forcing and processes. *Journal of Geophysical Research: Oceans*, 112(C4). <https://doi.org/10.1029/2006jc003791>

Hendon, H. H., & Salby, M. L. (1994). The life cycle of the Madden–Julian oscillation. *Journal of Atmospheric Sciences*, 51(15), 2225-2237.

Hermes, J. C., & Reason, C. J. C. (2008). Annual cycle of the South Indian Ocean (Seychelles-Chagos) thermocline ridge in a regional ocean model. *Journal of Geophysical Research: Oceans*, 113(C4). <https://doi.org/10.1029/2007jc004363>

Hersbach, H., Peubey, C., Simmons, A., Poli, P., Dee, D., & Berrisford, P. (2018). ERA report series. URL: <https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim>

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis [Dataset]. *Quarterly Journal of the Royal Meteorological Society*, 146(730), 1999–2049. <https://doi.org/10.1002/qj.3803>

Hoyos, C. D., & Webster, P. J. (2007). The role of intraseasonal variability in the nature of Asian monsoon precipitation. *Journal of Climate*, 20(17), 4402-4424. <https://doi.org/10.1175/jcli4252.1>

Hsu, H. H., Hoskins, B. J., & Jin, F. F. (1990). The 1985/86 intraseasonal oscillation and the role of the extratropics. *Journal of Atmospheric Sciences*, 47(7), 823-839. [https://doi.org/10.1175/1520-0469\(1990\)047<0823:tioatr>2.0.co;2](https://doi.org/10.1175/1520-0469(1990)047<0823:tioatr>2.0.co;2)

Hsu, P. C., & Li, T. (2012). Role of the boundary layer moisture asymmetry in causing the eastward propagation of the Madden–Julian oscillation. *Journal of Climate*, 25(14), 4914-4931. <https://doi.org/10.1175/jcli-d-11-00310.1>

Hsu, P. C., & Xiao, T. (2017). Differences in the initiation and development of the Madden–Julian oscillation over the Indian Ocean associated with two types of El Niño. *Journal of Climate*, 30(4), 1397–1415. <https://doi.org/10.1175/jcli-d-16-0336.1>

Huang, B., Liu, C., Banzon, V., Freeman, E., Graham, G., Hankins, B., ... & Zhang, H. M. (2021). Improvements of the daily optimum interpolation sea surface temperature (DOISST) version 2.1 [Dataset]. *Journal of Climate*, 34(8), 2923–2939. <https://doi.org/10.1175/jcli-d-20-0166.1>

Hubanks, P. A., King, M. D., Platnick, S. T. E. V. E. N., & Pincus, R. O. B. E. R. T. (2008). MODIS atmosphere L3 gridded product algorithm theoretical basis document. *ATBD Reference Number: ATBD-MOD-30*, 30, 96.

Jiang, X. A., & Li, T. (2005). Reinitiation of the boreal summer intraseasonal oscillation in the tropical Indian Ocean. *Journal of Climate*, 18(18), 3777–3795.

Jiang, X., Adames, Á. F., Zhao, M., Waliser, D., & Maloney, E. (2018). A unified moisture mode framework for seasonality of the Madden–Julian oscillation. *Journal of Climate*, 31(11), 4215–4224. <https://doi.org/10.1175/jcli-d-17-0671.1>

Johnson, R. H., & Ciesielski, P. E. (2013). Structure and properties of Madden–Julian oscillations deduced from DYNAMO sounding arrays. *Journal of the Atmospheric Sciences*, 70(10), 3157–3179. <https://doi.org/10.1175/jas-d-13-065.1>

Johnson, R. H., Rickenbach, T. M., Rutledge, S. A., Ciesielski, P. E., & Schubert, W. H. (1999). Trimodal characteristics of tropical convection. *Journal of climate*, 12(8), 2397–2418. [https://doi.org/10.1175/1520-0442\(1999\)012<2397:tcotc>2.0.co;2](https://doi.org/10.1175/1520-0442(1999)012<2397:tcotc>2.0.co;2)

Johnson, R. H., Rickenbach, T. M., Rutledge, S. A., Ciesielski, P. E., & Schubert, W. H. (1999). Trimodal characteristics of tropical convection. *Journal of climate*, 12(8), 2397–2418.

Kemball-Cook, S. R., & Weare, B. C. (2001). The onset of convection in the Madden–Julian oscillation. *Journal of climate*, 14(5), 780–793. [https://doi.org/10.1175/1520-0442\(2001\)014<0780:toocit>2.0.co;2](https://doi.org/10.1175/1520-0442(2001)014<0780:toocit>2.0.co;2)

Kikuchi, K., & Takayabu, Y. N. (2003). Equatorial circumnavigation of moisture signal associated with the Madden-Julian Oscillation (MJO) during boreal winter. *Journal of the Meteorological Society of Japan. Ser. II*, 81(4), 851–869. <https://doi.org/10.2151/jmsj.81.851>

Kiladis, G. N., Dias, J., Straub, K. H., Wheeler, M. C., Tulich, S. N., Kikuchi, K., ... & Ventrone, M. J. (2014). A comparison of OLR and circulation-based indices for tracking the MJO. *Monthly Weather Review*, 142(5), 1697–1715. <https://doi.org/10.1175/mwr-d-13-00301.1>

- Kiladis, G. N., Straub, K. H., & Haertel, P. (2005). Zonal and Vertical Structure of the Madden–Julian Oscillation. *Journal of the Atmospheric Sciences*, 62(8), 2790–2809. <https://doi.org/10.1175/jas3520.1>
- Kim, D., Kug, J. S., & Sobel, A. H. (2014). Propagating versus nonpropagating Madden–Julian oscillation events. *Journal of Climate*, 27(1), 111–125. <https://doi.org/10.1175/jcli-d-13-00084.1>
- Kim, H. M., Webster, P. J., Toma, V. E., & Kim, D. (2014). Predictability and prediction skill of the MJO in two operational forecasting systems. *Journal of Climate*, 27(14), 5364–5378. <https://doi.org/10.1175/jcli-d-13-00480.1>
- Kim, H., Vitart, F., & Waliser, D. E. (2018). Prediction of the Madden–Julian oscillation: A review. *Journal of Climate*, 31(23), 9425–9443. <https://doi.org/10.1175/jcli-d-18-0210.1>
- King, M. D., Platnick, S., Menzel, W. P., Ackerman, S. A., & Hubanks, P. A. (2013). Spatial and temporal distribution of clouds observed by MODIS onboard the Terra and Aqua satellites. *IEEE transactions on geoscience and remote sensing*, 51(7), 3826–3852.
- Klotzbach, P. J. (2010). On the Madden–Julian oscillation–Atlantic hurricane relationship. *Journal of Climate*, 23(2), 282–293. <https://doi.org/10.1175/2009jcli2978.1>
- Knutson, T. R., & Weickmann, K. M. (1987). 30–60 day atmospheric oscillations: Composite life cycles of convection and circulation anomalies. *Monthly Weather Review*, 115(7), 1407–1436. [https://doi.org/10.1175/1520-0493\(1987\)115<1407:daoclc>2.0.co;2](https://doi.org/10.1175/1520-0493(1987)115<1407:daoclc>2.0.co;2)
- Krishnamurti, T. N., & Subrahmanyam, D. (1982). The 30–50 day mode at 850 mb during MONEX. *Journal of Atmospheric Sciences*, 39(9), 2088–2095. [https://doi.org/10.1175/1520-0469\(1982\)039<2088:tdmamd>2.0.co;2](https://doi.org/10.1175/1520-0469(1982)039<2088:tdmamd>2.0.co;2)
- Krishnamurti, T. N., Oosterhof, D. K., & Mehta, A. V. (1988). Air–sea interaction on the time scale of 30 to 50 days. *Journal of Atmospheric Sciences*, 45(8), 1304–1322. [https://doi.org/10.1175/1520-0469\(1988\)045<1304:aiotts>2.0.co;2](https://doi.org/10.1175/1520-0469(1988)045<1304:aiotts>2.0.co;2)
- Krishnamurty, T. N., & Bhalme, H. N. (1976). Oscillations of a monsoon system Pt. I Observational aspects. *Journal of Atmospheric Sciences*, 33, 1937–1954. [https://doi.org/10.1175/1520-0469\(1976\)033<1937:ooamsp>2.0.co;2](https://doi.org/10.1175/1520-0469(1976)033<1937:ooamsp>2.0.co;2)
- Lau, K. M., & Chan, P. H. (1986). Aspects of the 40–50 day oscillation during the northern summer as inferred from outgoing longwave radiation. *Monthly Weather Review*, 114(7), 1354–1367. [https://doi.org/10.1175/1520-0493\(1986\)114<1354:aotdod>2.0.co;2](https://doi.org/10.1175/1520-0493(1986)114<1354:aotdod>2.0.co;2)
- Lau, K. M., & Chan, P. H. (1988). Intraseasonal and interannual variations of tropical convection: A possible link between the 40–50 day oscillation and ENSO?. *Journal of Atmospheric Sciences*, 45(3), 506–521. [https://doi.org/10.1175/1520-0469\(1988\)045<0506:iaivot>2.0.co;2](https://doi.org/10.1175/1520-0469(1988)045<0506:iaivot>2.0.co;2)

Li, T., Zhao, C., Hsu, P. C., & Nasuno, T. (2015). MJO initiation processes over the tropical Indian Ocean during DYNAMO/CINDY2011. *Journal of Climate*, 28(6), 2121-2135.

<https://doi.org/10.1175/jcli-d-14-00328.1>

Liebmann, B., & Smith, C. A. (1996). Description of a complete (interpolated) outgoing longwave radiation dataset. *Bulletin of the American Meteorological Society*, 77(6), 1275-1277.

Liebmann, B., & Smith, C. A. (1996). Description of a complete (interpolated) outgoing longwave radiation dataset [Dataset]. *Bulletin of the American Meteorological Society*, 77, 1275–1277. <https://www.jstor.org/stable/26233278>

Lim, Y., Son, S. W., & Kim, D. (2018). MJO prediction skill of the subseasonal-to-seasonal prediction models. *Journal of Climate*, 31(10), 4075-4094. <https://doi.org/10.1175/jcli-d-17-0545.1>

Ling, J., Li, C., Zhou, W., & Jia, X. (2014). To begin or not to begin? A case study on the MJO initiation problem. *Theoretical and applied climatology*, 115(1), 231-241. <https://doi.org/10.1007/s00704-013-0889-x>

Ling, J., Zhang, C., & Bechtold, P. (2013). Large-scale distinctions between MJO and non-MJO convective initiation over the tropical Indian Ocean. *Journal of the atmospheric sciences*, 70(9), 2696-2712. <https://doi.org/10.1175/jas-d-13-029.1>

Lorenc, A. C. (1984). The evolution of planetary-scale 200 mb divergent flow during the FGGE year. *Quarterly Journal of the Royal Meteorological Society*, 110(464), 427-441. <https://doi.org/10.1002/qj.49711046408>

Madden, R. A., & Julian, P. R. (1971). Detection of a 40–50 day oscillation in the zonal wind in the tropical Pacific. *Journal of Atmospheric Sciences*, 28(5), 702-708. [https://doi.org/10.1175/1520-0469\(1971\)028<0702:doadoi>2.0.co;2](https://doi.org/10.1175/1520-0469(1971)028<0702:doadoi>2.0.co;2)

Madden, R. A., & Julian, P. R. (1972). Description of global-scale circulation cells in the tropics with a 40–50 day period. *Journal of Atmospheric Sciences*, 29(6), 1109-1123. [https://doi.org/10.1175/1520-0469\(1972\)029<1109:dogsc>2.0.co;2](https://doi.org/10.1175/1520-0469(1972)029<1109:dogsc>2.0.co;2)

Maloney, E. D., & Hartmann, D. L. (2000). Modulation of eastern North Pacific hurricanes by the Madden–Julian oscillation. *Journal of climate*, 13(9), 1451-1460. [https://doi.org/10.1175/1520-0442\(2000\)013<1451:moenph>2.0.co;2](https://doi.org/10.1175/1520-0442(2000)013<1451:moenph>2.0.co;2)

Maloney, E. D., & Wolding, B. O. (2015). Initiation of an intraseasonal oscillation in an aquaplanet general circulation model. *Journal of Advances in Modeling Earth Systems*, 7(4), 1956-1976. <https://doi.org/10.1002/2015ms000495>



Masunaga, H., & Kummerow, C. D. (2006). Observations of tropical precipitating clouds ranging from shallow to deep convective systems. *Geophysical research letters*, 33(16). [\*\*https://doi.org/10.1029/2006gl026547\*\*](https://doi.org/10.1029/2006gl026547)

Matthews, A. J. (2000). Propagation mechanisms for the Madden-Julian oscillation. *Quarterly Journal of the Royal Meteorological Society*, 126(569), 2637-2651. [\*\*https://doi.org/10.1002/qj.49712656902\*\*](https://doi.org/10.1002/qj.49712656902)

Matthews, A. J. (2008). Primary and successive events in the Madden-Julian oscillation. *Quarterly Journal of the Royal Meteorological Society: A journal of the atmospheric sciences, applied meteorology and physical oceanography*, 134(631), 439-453. [\*\*https://doi.org/10.1002/qj.224\*\*](https://doi.org/10.1002/qj.224)

McPhaden, M. J. (1999). Genesis and evolution of the 1997-98 El Niño. *Science*, 283(5404), 950-954. [\*\*https://doi.org/10.1126/science.283.5404.950\*\*](https://doi.org/10.1126/science.283.5404.950)

Mei, S., Li, T., & Chen, W. (2015). Three-type MJO initiation processes over the western equatorial Indian Ocean. *Advances in Atmospheric Sciences*, 32(9), 1208-1216. [\*\*https://doi.org/10.1007/s00376-015-4201-0\*\*](https://doi.org/10.1007/s00376-015-4201-0)

Mohan, S., Ruchith, R. D., Rahul, S., & Shanas, P. R. (2023). Latent heat flux variability over the tropical Indian Ocean. *International Journal of Climatology*, 43(13), 6225–6242. [\*\*https://doi.org/10.1002/joc.8202\*\*](https://doi.org/10.1002/joc.8202).

Neena, J. M., Lee, J. Y., Waliser, D., Wang, B., & Jiang, X. (2014). Predictability of the Madden-Julian oscillation in the intraseasonal variability hindcast experiment (ISVHE). *Journal of Climate*, 27(12), 4531-4543. [\*\*https://doi.org/10.1175/jcli-d-13-00624.1\*\*](https://doi.org/10.1175/jcli-d-13-00624.1)

Powell, S. W., & Houze Jr, R. A. (2015). Effect of dry large-scale vertical motions on initial MJO convective onset. *Journal of Geophysical Research: Atmospheres*, 120(10), 4783-4805. [\*\*https://doi.org/10.1002/2014jd022961\*\*](https://doi.org/10.1002/2014jd022961)

Rao, S. A., & Yamagata, T. (2004). Abrupt termination of Indian Ocean dipole events in response to intraseasonal disturbances. *Geophysical Research Letters*, 31(19). [\*\*https://doi.org/10.1029/2004gl020842\*\*](https://doi.org/10.1029/2004gl020842)

Rashid, H. A., Hendon, H. H., Wheeler, M. C., & Alves, O. (2011). Prediction of the Madden-Julian oscillation with the POAMA dynamical prediction system. *Climate Dynamics*, 36(3), 649-661.

Ray, P., & Zhang, C. (2010). A case study of the mechanics of extratropical influence on the initiation of the Madden-Julian oscillation. *Journal of the Atmospheric Sciences*, 67(2), 515-528. [\*\*https://doi.org/10.1175/2009jas3059.1\*\*](https://doi.org/10.1175/2009jas3059.1)

- Reynolds, R. W., Smith, T. M., Liu, C., Chelton, D. B., Casey, K. S., & Schlax, M. G. (2007). Daily high-resolution-blended analyses for sea surface temperature [Dataset]. *Journal of climate*, 20(22), 5473-5496. <https://doi.org/10.1175/2007jcli1824.1>
- Rossow, W. B., & Schiffer, R. A. (1991). ISCCP cloud data products [Dataset]. *Bulletin of the American Meteorological Society*, 72(1), 2-20. [https://doi.org/10.1175/1520-0477\(1991\)072<0002:icdp>2.0.co;2](https://doi.org/10.1175/1520-0477(1991)072<0002:icdp>2.0.co;2)
- Rydbeck, A. V., & Jensen, T. G. (2017). Oceanic impetus for convective onset of the Madden–Julian oscillation in the western Indian Ocean. *Journal of Climate*, 30(11), 4299-4316. <https://doi.org/10.1175/jcli-d-16-0595.1>
- Saji, N. H., Goswami, B. N., Vinayachandran, P. N., & Yamagata, T. (1999). A dipole mode in the tropical Indian Ocean. *Nature*, 401(6751), 360-363. <https://doi.org/10.1038/43854>
- Schott, F. A., Xie, P., & McCreary, J. P. (2009). Indian Ocean circulation and climate variability. *Reviews of Geophysics*, 47(1). <https://doi.org/10.1029/2007RG000245>
- Schreck III, C. J., & Molinari, J. (2011). Tropical cyclogenesis associated with Kelvin waves and the Madden–Julian oscillation. *Monthly Weather Review*, 139(9), 2723-2734. <https://doi.org/10.1175/mwr-d-10-05060.1>
- Seo, K. H., & Kim, K. Y. (2003). Propagation and initiation mechanisms of the Madden-Julian oscillation. *Journal of Geophysical Research: Atmospheres*, 108(D13). <https://doi.org/10.1029/2002jd002876>
- Seo, K. H., Wang, W., Gottschalck, J., Zhang, Q., Schemm, J. K. E., Higgins, W. R., & Kumar, A. (2009). Evaluation of MJO forecast skill from several statistical and dynamical forecast models. *Journal of Climate*, 22(9), 2372-2388. <https://doi.org/10.1175/2008jcli2421.1>
- Sikka, D. R., & Gadgil, S. (1980). On the maximum cloud zone and the ITCZ over Indian longitudes during the southwest monsoon. *Monthly Weather Review*, 108(11), 1840-1853. [https://doi.org/10.1175/1520-0493\(1980\)108<1840:otmcza>2.0.co;2](https://doi.org/10.1175/1520-0493(1980)108<1840:otmcza>2.0.co;2)
- Snide, C. E., Adames, Á. F., Powell, S. W., & Mayta, V. C. (2022). The role of large-scale moistening by adiabatic lifting in the Madden–Julian oscillation convective onset. *Journal of Climate*, 35(1), 269-284. <https://doi.org/10.1175/jcli-d-21-0322.1>
- Straub, K. H. (2013). MJO initiation in the real-time multivariate MJO index. *Journal of Climate*, 26(4), 1130-1151. <https://doi.org/10.1175/jcli-d-12-00074.1>
- Straub, K. H., & Kiladis, G. N. (2003). Interactions between the Boreal Summer Intraseasonal Oscillation and Higher-Frequency Tropical Wave Activity. *Monthly Weather Review*, 131(5), 945-960. [https://doi.org/10.1175/1520-0493\(2003\)131<0945:IBTBSI>2.0.CO;2](https://doi.org/10.1175/1520-0493(2003)131<0945:IBTBSI>2.0.CO;2)

Takasuka, D., & Satoh, M. (2020). Dynamical roles of mixed Rossby–gravity waves in driving convective initiation and propagation of the Madden–Julian oscillation: General views. *Journal of the Atmospheric Sciences*, 77(12), 4211–4231. <https://doi.org/10.1175/jas-d-20-0050.1>

Takasuka, D., & Satoh, M. (2021). Diversity of the Madden–Julian oscillation: Initiation region modulated by the interaction between the intraseasonal and interannual variabilities. *Journal of Climate*, 34(6), 2297–2318. <https://doi.org/10.1175/jcli-d-20-0688.1>

Takasuka, D., Kohyama, T., Miura, H., & Suematsu, T. (2021). MJO initiation triggered by amplification of upper-tropospheric dry mixed Rossby-gravity waves. *Geophysical Research Letters*, 48(20), e2021GL094239. <https://doi.org/10.1029/2021gl094239>

Takasuka, D., Satoh, M., & Yokoi, S. (2019). Observational evidence of mixed Rossby-gravity waves as a driving force for the MJO convective initiation and propagation. *Geophysical Research Letters*, 46(10), 5546–5555. <https://doi.org/10.1029/2019gl083108>

Takasuka, D., Satoh, M., Miyakawa, T., & Miura, H. (2018). Initiation processes of the tropical intraseasonal variability simulated in an Aqua-Planet Experiment: What is the intrinsic mechanism for MJO onset?. *Journal of Advances in Modeling Earth Systems*, 10(4), 1047–1073. <https://doi.org/10.1002/2017ms001243>

Vialard, J., Foltz, G. R., Mcphaden, M. J., Duvel, J. P., & de Boyer Montégut, C. (2008). Strong Indian Ocean sea surface temperature signals associated with the Madden-Julian Oscillation in late 2007 and early 2008. *Geophysical Research Letters*, 35(19). <https://doi.org/10.1029/2008gl035238>

Vitart, F., Ardilouze, C., Bonet, A., Brookshaw, A., Chen, M., Codorean, C., ... & Zhang, L. (2017). The subseasonal to seasonal (S2S) prediction project database. *Bulletin of the American Meteorological Society*, 98(1), 163–173.

Waliser, D. (2011). Predictability and forecasting. In *Intraseasonal variability of the atmosphere-ocean climate system* (pp. 433–476). Berlin, Heidelberg: Springer Berlin Heidelberg.

Waliser, D. E., Lau, K. M., Stern, W., & Jones, C. (2003). Potential predictability of the Madden–Julian oscillation. *Bulletin of the American Meteorological Society*, 84(1), 33–50.

Waliser, D., & Lau, W. K. M. (2005). Intraseasonal variability in the atmosphere-ocean climate system. *Intraseasonal Variability in the Atmosphere-Ocean Climate System*, 80.

Waliser, D., & Lau, W. K. M. (2005). Intraseasonal variability in the atmosphere-ocean climate system. *Intraseasonal Variability in the Atmosphere-Ocean Climate System*, 80.

- Wang, B., & Rui, H. (1990). Synoptic climatology of transient tropical intraseasonal convection anomalies: 1975–1985. *Meteorology and Atmospheric Physics*, 44(1), 43–61. [\*\*https://doi.org/10.1007/bf01026810\*\*](https://doi.org/10.1007/bf01026810)
- Wang, S., Ma, D., Sobel, A. H., & Tippett, M. K. (2018). Propagation characteristics of BSISO indices. *Geophysical Research Letters*, 45(18), 9934–9943. [\*\*https://doi.org/10.1029/2018gl078321\*\*](https://doi.org/10.1029/2018gl078321)
- Wang, S., Sobel, A. H., Tippett, M. K., & Vitart, F. (2019). Prediction and predictability of tropical intraseasonal convection: Seasonal dependence and the Maritime Continent prediction barrier. *Climate Dynamics*, 52(9), 6015–6031. [\*\*https://doi.org/10.1007/s00382-018-4492-9\*\*](https://doi.org/10.1007/s00382-018-4492-9)
- Wang, T., & Li, T. (2022). Diversity of MJO initiation regions and processes. *Journal of Climate*, 35(20), 6721–6740. [\*\*https://doi.org/10.1175/jcli-d-21-0816.1\*\*](https://doi.org/10.1175/jcli-d-21-0816.1)
- Webster, P. J., Moore, A. M., Loschnigg, J. P., & Leben, R. R. (1999). Coupled ocean–atmosphere dynamics in the Indian Ocean during 1997–98. *Nature*, 401(6751), 356–360. [\*\*https://doi.org/10.1038/43848\*\*](https://doi.org/10.1038/43848)
- Wei, Y., Ren, H. L., Xiang, B., Wang, Y., Wu, J., & Wang, S. (2023). Diverse MJO genesis and predictability. *Bulletin of the American Meteorological Society*, 104(4), E792–E809. [\*\*https://doi.org/10.1175/bams-d-22-0101.1\*\*](https://doi.org/10.1175/bams-d-22-0101.1)
- West, B. J., Han, W., & Li, Y. (2018). The role of oceanic processes in the initiation of Indian summer monsoon intraseasonal oscillations over the Indian Ocean. *Journal of Geophysical Research: Oceans*, 123(5), 3685–3704. [\*\*https://doi.org/10.1029/2017jc013564\*\*](https://doi.org/10.1029/2017jc013564)
- West, B. J., Han, W., Zhang, L., & Li, Y. (2020). The role of oceanic processes in the initiation of boreal winter intraseasonal oscillations over the Indian Ocean. *Journal of Geophysical Research: Oceans*, 125(2), e2019JC015426. [\*\*https://doi.org/10.1029/2019jc015426\*\*](https://doi.org/10.1029/2019jc015426)
- Wheeler, M. C., & Hendon, H. H. (2004). An all-season real-time multivariate MJO index: Development of an index for monitoring and prediction. *Monthly weather review*, 132(8), 1917–1932. [\*\*https://doi.org/10.1175/1520-0493\(2004\)132<1917:aarmmi>2.0.co;2\*\*](https://doi.org/10.1175/1520-0493(2004)132<1917:aarmmi>2.0.co;2)
- Wu, X., & Deng, L. (2013). Comparison of moist static energy and budget between the GCM-simulated Madden–Julian oscillation and observations over the Indian Ocean and western Pacific. *Journal of climate*, 26(14), 4981–4993. [\*\*https://doi.org/10.1175/jcli-d-12-00607.1\*\*](https://doi.org/10.1175/jcli-d-12-00607.1)
- Xie, S.-P., Annamalai, H., Schott, F. A., & McCreary, J. P. (2002). Structure and mechanisms of South Indian Ocean climate variability. *Journal of Climate*, 15(8), 864–878. [\*\*https://doi.org/10.1175/1520-0442\(2002\)015<0864:Samosi>2.0.Co;2\*\*](https://doi.org/10.1175/1520-0442(2002)015<0864:Samosi>2.0.Co;2)

- Xu, W., & Rutledge, S. A. (2016). Time scales of shallow-to-deep convective transition associated with the onset of Madden-Julian Oscillations. *Geophysical Research Letters*, 43(6), 2880-2888. <https://doi.org/10.1002/2016gl068269>
- Yanai, M., Esbensen, S., & Chu, J. H. (1973). Determination of bulk properties of tropical cloud clusters from large-scale heat and moisture budgets. *Journal of Atmospheric Sciences*, 30(4), 611-627. [https://doi.org/10.1175/1520-0469\(1973\)030<0611:dobpot>2.0.co;2](https://doi.org/10.1175/1520-0469(1973)030<0611:dobpot>2.0.co;2)
- Yang, D., & Ingersoll, A. P. (2011). Testing the hypothesis that the MJO is a mixed Rossby-gravity wave packet. *Journal of the atmospheric sciences*, 68(2), 226-239.
- Yasunari, T. (1979). Cloudiness fluctuations associated with the Northern Hemisphere summer monsoon. *Journal of the Meteorological Society of Japan. Ser. II*, 57(3), 227-242. [https://doi.org/10.2151/jmsj1965.57.3\\_227](https://doi.org/10.2151/jmsj1965.57.3_227)
- Yokoi, T., Tozuka, T., & Yamagata, T. (2008). Seasonal variation of the Seychelles Dome. *Journal of Climate*, 21(15), 3740-3754. <https://doi.org/10.1175/2008jcli1957.1>
- Yoneyama, K., Zhang, C., & Long, C. N. (2013). Tracking pulses of the Madden-Julian oscillation. *Bulletin of the American Meteorological Society*, 94(12), 1871-1891. <https://doi.org/10.1175/bams-d-12-00157.1>
- Zhang, C. (2005). Madden-Julian oscillation. *Reviews of Geophysics*, 43(2). <https://doi.org/10.1029/2004rg000158>
- Zhang, C., & Ling, J. (2017). Barrier effect of the Indo-Pacific Maritime Continent on the MJO: Perspectives from tracking MJO precipitation. *Journal of Climate*, 30(9), 3439-3459. <https://doi.org/10.1175/jcli-d-16-0614.1>
- Zhang, C., & Yoneyama, K. (2017). CINDY/DYNAMO field campaign: Advancing our understanding of MJO initiation. In *The global monsoon system: Research and forecast* (pp. 339-348).
- Zhang, C., Gottschalck, J., Maloney, E. D., Moncrieff, M. W., Vitart, F., Waliser, D. E., ... & Wheeler, M. C. (2013). Cracking the MJO nut. *Geophysical Research Letters*, 40(6), 1223-1230. <https://doi.org/10.1002/grl.50244>
- Zhang, W., Huang, Z., Jiang, F., Stuecker, M. F., Chen, G., & Jin, F. F. (2021). Exceptionally persistent Madden-Julian Oscillation activity contributes to the extreme 2020 East Asian summer monsoon rainfall. *Geophysical Research Letters*, 48(5), e2020GL091588. <https://doi.org/10.1029/2020gl091588>
- Zhao, C., Li, T., & Zhou, T. (2013). Precursor signals and processes associated with MJO initiation over the tropical Indian Ocean. *Journal of Climate*, 26(1), 291-307. <https://doi.org/10.1175/jcli-d-12-00113.1>