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Entitled

Multi-scale Cloud Interactions over the Maritime Continent (MC) on the Fate of Approaching Madden-Julian Oscillation (MJO)

Principal Investigator: Joshua Xiouhua Fu
Institution: University of Hawaii at Manoa

Total proposed cost: $491,351
Budget period: Mar., 2016 – Feb., 2019

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Multi-scale Cloud Interactions over the Maritime Continent (MC) on the Fate of Approaching Madden-Julian Oscillation (MJO)

PI: Joshua Xiouhua Fu  
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PROJECT SUMMARY

The Madden-Julian Oscillation (MJO) is a dominant climate mode in the tropics with a quasi-oscillating period of 30-60-days. The MJO usually develops in western equatorial Indian Ocean and manifests as a couplet between organized multi-scale cloud systems and planetary-scale baroclinic circulations. As the MJO propagates eastward, the associated large-scale dynamical and thermo-dynamical fields modulate the occurrences of tropical cyclones and extreme hydrological events worldwide either directly or through teleconnections, which makes the MJO a primary source for extended-range weather forecasting. Present-day weather and climate models, however, still have a variety of systematic errors in the simulation and prediction of the MJO. One of them is known as ‘Maritime Continent (MC) Prediction Barrier’ problem, which means model MJO having difficulty to propagate over the MC, thus considerably limiting model capability in forecasting MJO’s downstream modulations of tropical cyclones over Pacific and Atlantic basins and extreme events over North America.

This model deficiency reflects our lack of understanding on the complex interactions between the MJO and the MC, let alone to realistically representing these interactions in weather and climate models. Sitting in the middle of Indo-Pacific warm pools with a sea surface temperature higher than 28°C year-round, the huge amount of moisture and heat in the lower troposphere along with complex islands and shallow-seas makes the MC a center of multi-scale convective systems. It is the intricate interplays among approaching MJOs, the multi-scale convective systems and complex orography over the MC that determine the downstream MJO evolutions: Smoothly transitioning into western Pacific, rapidly decayed, or intensified. The island-sea heating contrasts over the MC foster strongest precipitation diurnal cycle around the MC islands. The associated rainy systems are very deep thunderstorms, which are lack in surrounding Indian and western Pacific Oceans. The intertropical convergence zone over the MC also moves north and south seasonally, thus resulting in different MJO passages over the MC: through the South China Sea in boreal summer, while through the Timor Sea in winter. This suggests that the MJO-MC interactions are season dependent. The proposed study will gear to advance our understanding of the major multi-scale cloud interactions that determine the fates of approaching MJOs over the MC in boreal-summer and winter as well as to assess their representations in present-day weather and climate models.
In recognizing the complexity of the issue we intend to address, a combined diagnostic, regional and global modeling approach has been proposed. The cloud and precipitation properties from the CloudSat, CALIPSO, and other A-Train satellites along with reanalysis data from the NCEP-CFSR and NASA-MERRA will be used to construct the composites of clouds, precipitation, and dynamical and thermo-dynamical fields for different MJO types, respectively, in boreal summer and winter. The composite MJO evolutions will be compared with that from the Subseasonal-to-Seasonal (S2S) hindcasts to assess present-day model capability in representing different MJO passages over the MC. Well-designed numerical experiments with regional and global models, then, will be carried out to examine the respective roles of major factors (e.g., diurnal cycle, annual cycle, orography et al.) over the MC on determining the fates of approaching MJOs. The pathways to improve the representations of MJO-MC interactions and to alleviate the ‘Maritime Continent Prediction Barrier’ problem will also be explored. The proposed research will contribute to reducing systematic error in global models, thus making weather-climate forecasting more skillful and future climate projection more reliable.
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A. SELECTED PUBLICATIONS FROM PREVIOUS SUPPORT


B. PROJECT DESCRIPTION

1. Scientific Background

The Madden-Julian Oscillation (MJO, Madden and Julian 1972; Wang 2005; Zhang 2005) is the most prominent intraseasonal variability in the tropics. The canonical features of the MJO have been depicted as a couplet between a large-scale convective envelope and first-baroclinic planetary-scale circulation moving eastward along the equator (Madden and Julian 1972). The large convective envelope later is recognized as a composition of multi-scale cloud systems (Nakazawa 1988; Lau et al. 1991; Sui and Lau 1992). Although the essential elements of the MJO are confined in the tropics, its impacts actually reach over the globe through tropical-extratropical teleconnection (Higgins et al. 2000; Zhang 2013; and Dole 2014). The associated large-scale dynamical and thermo-dynamical fields of the MJO and its teleconnection modulate the occurrences of extreme weather events (e.g., Tropical Cyclones, flooding, and drought et al.) worldwide, which makes the MJO a primary source for extended-range weather forecasting.

The MJO-related convective envelope and circulation migrate north and south seasonally (Madden 1986; Wang and Rui 1990; Sobel et al. 2010). During boreal winter, the MJO action centers shift to the Southern Hemisphere and manifest as a dominant eastward-propagating circum-global mode. On its way eastward, the convective phase of the MJO spawns frequent occurrences of tropical cyclones (TC) over the tropical Indian Ocean (Bessafi and Wheeler 2006), Australian region, and the South Pacific Convergence Zone (Hall et al. 2001), occasionally over the South China Sea (SCS), and Western North Pacific (WNP). During boreal summer, the MJO action centers shift to the Northern Hemisphere and have a dominant northward-propagating component (also known as Boreal-summer Intraseasonal Oscillation, Wang and Xie 1997), along with an eastward circum-global component (Fu and Wang 2004; Wang et al. 2006). On its way downstream, the MJO modulates tropical cyclone activities over the Indian Ocean (Fu and Hsu 2011), the SCS/WNP (Liebmann et al. 1994), the Eastern North Pacific (ENP), Gulf of Mexico, and Atlantic Main-Development-Region (Molinari et al. 1997; Maloney and Hartmann 2000; Mo 2000; Higgins and Shi 2001; Klotzbach 2010).

The MJO often develops over the western equatorial Indian Ocean and intensifies over the central-eastern Indian Ocean. Once reaching the Maritime
Continent (MC), the organized convection and circulation of the MJO will be disrupted and modified by the intricate land-sea-terrain distributions (Figure 1) and associated complex multi-scale variability in this region (Wang and Rui 1990; Nitta et al. 1992; Chang et al. 2005a,b; and Hirata et al. 2013). In both winter and summer, a minimum intraseasonal variance exists in the MC flanked by much larger variances in the Indian Ocean and western Pacific (Figure 2). The weakening of the MJO during its passage over the MC has long been known as ‘Maritime Continent Barrier (MCB)’ (Wang and Rui 1990; Nitta et al. 1992). The exaggeration of this barrier in Numerical Weather Prediction (NWP) models has been referred as ‘Maritime Continent Prediction Barrier (MCPB)’, which is a persistent systematic error in present-day weather and climate models (Fu et al. 2013). The MCPB problem severely hinders our capability in extended-range forecasting of MJO’s downstream modulations of tropical cyclone activities in Pacific and Atlantic basins as well as the extreme events in mid-latitude regions (Weickmann 1983; Adames and Wallace 2014). This persistent model bias reflects our lack of understanding to the complex interactions between the MJO and the MC, let alone to realistically representing these interactions in global weather and climate models.

Although the mean intraseasonal variance is reduced over the MC, the fates of individual MJO events are largely case dependent, as a result of peculiar interactions between the incoming MJO events and the atmosphere-ocean large-scale environmental states over the MC. Hirata et al. (2013) divided the boreal-winter MJOs into three types based on their fates after interacting with the MC: (1) Half of the approaching MJO events only experience slightly amplitude reduction over the MC, then quickly regain their intensity after moving into the western Pacific; the another half either (2) drastically decay or (3) significantly intensify during their passages over the MC. To understand the unique MJO-MC interactions resulting in different fates of approaching MJOs is a fundamental need to realistically represent these interactions in models and the skillful prediction of the downstream impacts of individual MJO events. The proposed study will gear to close this knowledge gap and reveal misrepresented processes in present-day weather and climate models. In the remaining of this section, we will briefly review our current understanding of the MJO-MC interactions in following three aspects: (i), cloud regime changes during MJO passage over the MC; (ii), processes that weaken the MJOs over the MC; (iii), processes that help move the MJOs over the MC; followed by our proposed scientific objectives and questions.

1.1, Cloud Regime Changes during MJO Passage over the MC

It is well-known that the active phase of a typical MJO event over open oceans include three stages analogous to a giant Mesoscale Convective System (MCS, Houze 2004; Mapes et al. 2006): (1) the lower-tropospheric moisture preconditioning; (2) the development of organized deep convection; (3) the development of extensive stratiform clouds (Kemball-Cook and Weare 2001; Kikuchi and Takayabu 2004; Kiladis et al. 2005; Fu et al. 2006; Benedict and Randall 2007; Johnson et al. 2013). Once formed, the MJO could function as a self-sustained circum-global mode in an idealized aqua-planet world (e.g., Blade and Hartmann 1993; Wang and Li 1994; Stephens et al. 2004). On the eastern side of the MJO
convective envelope, suppressed phase prevails. The planetary-boundary-layer (PBL) convergence forced by the emanated Kelvin wave acts to moisten the PBL and lower-troposphere (Wang and Li 1994). The prevalent downward solar radiation produces SST warming on both diurnal and intraseasonal time scales (Stephens et al. 2004), which will further moisten the lower troposphere by enhancing surface evaporation and SST-gradient-driven convergence. Shallow cumulus/congestus clouds are most popular cloud type in this stage due to large-scale subsidence. The lower-tropospheric moisture preconditioning, eventually, leads to the development of organized deep convection, followed with trailing stratiform clouds. Accompanying the development of new MJO convective systems on the east, the surface cooling, convective downdraft, and Rossby-wave-driven equatorward dry air advection associated with the old MJO act to dissipate itself. The continuous iterations of the above processes result in a sustained circum-global MJO modes as depicted in many theoretical studies (e.g., Neelin et al. 1987; Lau and Peng 1987; Wang and Li 1994; Thual et al. 2014; Deng et al. 2015).

In the real world, however, most MJO events developed in the Indian Ocean will experience weakening at least twice on their way eastward, first over the MC, then over the central-eastern Pacific cold tongue region (Wang and Rui 1990). Some MJO events completely dissipate with the disruptions of the MC and the cold tongue (Hendon and Salby 1994). The others that survive these damping spots will move around the globe and excite another event over the Indian Ocean, which are called successive MJO events (Matthews et al. 2008).

The complex land-sea-terrain distributions (Figure 1) and unique multiscale convective systems in the MC (Chang et al. 2005a,b; Tangang et al. 2008; Moron et al. 2015) have been attributed as the primary reasons for the alterations of approaching MJOs (e.g., Wang and Li 1994; Inness and Slingo 2006; Hirata et al. 2013). The convective systems over the MC and those over the surrounding Oceans have drastic differences. Very deep thunderstorms with frequent lightning occur over the MC rather than over surrounding Indian and western Pacific Oceans (Cecil et al. 2015). The occurrences of cloud electrification and lightning require the accretion of supercooled waters onto ice particles to produce graupel and/or hail in strong updrafts. This contrast of convective cloud regimes indicates that the MJO-related clouds experience drastic changes in cloud microphysics during their passages over the MC. Using TRMM precipitating radar (PR) observations, Morita et al. (2006) noticed that when the MJO convective envelope approaches the MC, its leading edge (over the MC) is not only populated with shallow cumulus and congestus clouds, as in the open oceans, but also with very deep thunderstorms. This cloud regime change of approaching MJO has been corroborated with in-situ measurements over Sumatra (Kodama et al. 2006). The MJO suppressed-to-active transitioning processes, therefore, are quite different over the MC and over the open oceans. In the open oceans, it is primarily a cloud deepening process. Over the MC, in addition to the deepening, cloud shoaling is also a major process (Morita et al. 2006). These characteristic cloud regime changes have also been confirmed with the CloudSat and CALIPSO cloud retrievals by Riley et al. (2011) and Del Genio et al. (2012) and lightning data from the ground-based World Wide Lightning Location Network (WWLLN) by Virts and Houze (2015).
It is also well-known that the mature stage of MJO convective envelope is dominant with the MCSs (Mapes et al. 2006), which are often organized into superclusters (Nakazawa 1988; Sui and Lau 1992; Hendon and Liebmann 1994). Using clouds and precipitation properties retrieved from the MODIS and AMSR-E onboard the A-Train *Aqua* satellite, Yu and Houze (2010) analyzed the geographic characteristics of the MCSs over global tropics. They found that the separated MCSs are dominant over the Maritime Continent, while the connected MCSs (also known as ‘superclusters’ or ‘super convective systems’ in Nakazawa 1988 and Mapes and Houze 1993) are dominant over the tropical Indian Ocean and western Pacific Ocean. The separated MCSs cover much smaller area than the connected MCSs and have much shorter life span. It is suggested that the persistent strong diurnal cycle over the Maritime Continent interrupts the development of individual MCSs within a day, while the MCSs over the warm oceans can continuously develop beyond the diurnal time scale under favorable conditions (Chen and Houze 1997). Yu and Houze (2013) further composited the MCSs as a function of MJO phases over the MC and surrounding tropical Indian and western Pacific Oceans and revealed that the dominant MCSs at the mature phase of the MJO over the warm oceans are superclusters, but are separated MCSs over the MC.

The above results suggested that the dominant cloud regimes of the MJO life cycle over the MC are significantly different from those over the surrounding Oceans. The persistent diurnal cycle over the MC has been speculated to be the fundamental cause of these differences (Chen and Houze 1997; Yuter and Houze 1998). But, the essential physical processes leading to such changes are still unknown. How such cloud regime changes will impact the fates of approaching MJOs, in particular, for boreal-summer eastward-propagating MJOs and in what degree such cloud regime changes have been represented in present-day weather and climate models are still open issues. The proposed study will gear to close this knowledge gap with the CloudSat, CALIPSO clouds retrievals and other satellite data along with regional and global modeling experiments.

1.2, Processes that Weaken the MJOs over the MC

The essential dynamics of the MJO involves the interactions among diabatic heating released from multi-scale cloud systems, associated large-scale circulations, and underlying sea/land surfaces (Wang 2005). The major fuel sources sustaining the MJO originate from the PBL and lower-tropospheric moisture convergence (Wang and Li 1994) and surface evaporation (Maloney and Sobel 2004) driven by the baroclinic quadrupole circulations associated with the Rossby-Kelvin-wave couplet (Gill 1980; Wang 1988; Rui and Wang 1990; Majda and Stechmann 2009; Liu and Wang 2012). The reduced fuel supply by the complex land-sea-terrain distributions over the MC has been speculated as the primary reason for the weakening of the passing MJOs (Wang and Li 1994; Wang and Xie 1997, 1998; Zhang and Hendon 1997).

Some potential processes that will weaken the MJOs moving over the MC have been summarized by Wang and Xie (1998) as following: (a), reducing the coupled instability by prohibiting air–sea interaction (Zhang and Hendon 1997); (b), raising the level of maximum latent heat release, which weakens the interaction
between convective heating and atmospheric Kelvin waves (e.g., Miyahara 1987); (c), decreasing availability of moisture supply due to continuing release of energy during the enhanced diurnal rainfall (Wang and Li 1994); and (d), increasing surface dissipation over the island topography (Wang and Xie 1997).

Although many possible reasons have been put forward to explain the MJO weakening over the MC, only a few studies have been conducted to test the raised hypotheses. Inness and Slingo (2006) have conducted a series of idealized numerical experiments to assess the impacts of the MC orography and configurations. After comparing the cases with and without Sumatra orography, the authors found that it is the blocking effects of the orography that significantly weaken the MJO signal over the MC although the orographic height in the model is much lower than that in reality. The weakening is primarily caused by the blocking of the low-level westerly and eastward-propagating Kelvin-wave signal associated with the approaching MJO. The authors also showed that when the incoming MJO is weaker, it dissipates faster. This result may partially explain the MCPB problem plagued present-day weather-climate models because most of them significantly underestimate the MJO intensity (Lin et al. 2006; Hung et al. 2013). Zhu et al. (2010) examined the impacts of the MC on the Boreal-summer Intrasessional Oscillation through comparing two 10-year atmosphere-only runs forced with climatological SST. The control run (CTL) keeps the original MC configuration. The sensitivity run (NO-MC) removes all islands over (90°E-160°E, 10°S-10°N) and fills the gaps with interpolated SST. The resultant eastward-propagating MJO component in the NO-MC is much stronger than that in the CTL. The enhanced MJO in the NO-MC has been explained as a combined effect of increased seasonal-mean surface moisture, rainfall, and reduced surface friction and diurnal cycle over the MC.

A data-assimilation technique has been used by Oh et al. (2013) to assess the impacts of diurnal cycle on the MJO passage over the MC. Two five-year (2000-2004) simulations have been conducted. In the control simulation (CTL), both 6-hourly NCEP-R2 atmospheric fields and 3-hourly TRMM 3B42 precipitation rate have been nudged into the model. In the sensitivity simulation (NO_DIURNAL), all nudging variables have been averaged into daily-mean without any diurnal variation. The authors found that the boreal-winter MJO in the NO_DIURNAL is much stronger than that in the CTL. Diagnosis showed that the rainfall over the MC during the MJO dry phase is smaller in the NO_DIURNAL than that in the CTL. The reduced rainfall is accompanied with higher PBL moist static energy and larger convective instability, thus leading to stronger moisture convergence and intensified MJO during the active phase. This result showed that the persistent diurnal cycle over the MC weakens the approaching MJO by continuously tapping on the lower-tropospheric moist static energy as suggested in previous studies (e.g., Wang and Li 1994; Zhang and Hendon 1997; Slingo et al. 2003).

Based on the available observational and modeling studies, this proposal plans to advance our understanding of the impacts of following three factors on the MJO passages over the MC: (1), diurnal cycle; (2), annual cycle; and (3), orography. Sitting in the middle of Indo-Pacific warm pools with a SST higher than 28°C year-round, the huge amount of moisture and heat in the lower troposphere along with complex islands and shallow-seas makes the MC a center of multi-scale convective systems.
The land-sea contrasts driven by persistent solar diurnal cycle foster strongest precipitation diurnal variations in this area (Kikuchi and Wang 2008; Rauniyar and Walsh 2011; and Peatman et al. 2014). The annual-mean rainfall over the MC concentrates around the islands, e.g., Sumatra, Borneo, Sulawesi, and New Guinea (Figure 1) rather than the surrounding marginal seas (e.g., Kikuchi and Wang 2008; Sobel et al. 2010), which has been attributed to the strong diurnal convective systems driven by land-sea and mountain-valley breezes (Qian 2008). In contrast to this islands-concentrated annual-mean rainfall distribution, the precipitation associated with the MJO tends to skirt around these mountainous islands (Figures 2&3). In both boreal winter and summer, once encountering the Sumatra islands, the MJO convective envelope will split into two parts, respectively, moving northward and southward (Wang and Rui 1990; Wu and Hsu 2009; Peatman et al. 2014; Fu and Wang 2004; Wang et al. 2006). Some superclusters within the MJO convective envelope are able to penetrate into the Java Sea, but quickly dissipate on their way eastward (Kodama et al. 2006). The fact that the primary MJO passages over the MC avoid the strong diurnal-cycle centers (the mountainous islands) supports the notion that the strong diurnal cycle over the MC acts to weaken the approaching MJO. But, the specific role of SST diurnal cycle in surrounding marginal seas and the impact of islands-related diurnal cycle on boreal-summer eastward-propagating MJO component are still unknown.

In addition to the strong diurnal cycle, the MC also experiences significant annual variations known as ‘Maritime Continent monsoon’ (Chang et al. 2005b; Moron et al. 2015). The wet season of the MC is during boreal winter, when southerly cross-equatorial flows establish a monsoon trough with strong surface westerly around 10°S between Java-New Guinea islands and Australia. The resultant monsoon rainfall extends eastward from the Timor Sea all the way to the South Pacific Convergence Zone. In boreal summer, the huge heating received over the massive Asian continent and northwest Pacific pulls the intertropical convergence zone off the equator (Schneider et al. 2014) and establishes an Asian-northwest-Pacific summer monsoon trough around 15°N (Webster et al. 1998). The resultant meridional overturning circulation suppresses the deep convective systems over the MC region, particularly the southern MC from Java islands to New Guinea, thus leading to the dry season of the MC. The fact that the solar annual cycle moves the intertropical convergence zones away from the equator suggests it playing an unfavorable role for MJO passages over the MC. Our preliminary sensitivity experiments (Figure 4) also suggest that both the diurnal cycle and annual cycle act to weaken the MJOs passing over the MC. The involved physical processes and potential seasonal dependence of their impacts require further investigation.

The mountains over the MC islands (Figure 1) play complex roles on the MJO passages over the MC (Matthews 2000; Hsu et al. 2004; Hsu and Lee 2005; Shibagaki 2006; Inness and Slingo 2006; Qian 2008; Wu and Hsu 2009). The mountains on the west coast of Sumatra block the low-level westerly of the approaching MJOs and force the associated Rossby-wave vortices to split. Some superclusters within the MJO convective envelope are able to cross the Sumatra islands, but rapidly decay on their way eastward (Shibagaki et al. 2006). In boreal winter, major convective systems of the MJOs, then, take a southern route along the
Timor Sea eastward (Wu and Hsu 2009). Once reaching New Guinea, the high mountains on this island will block the incoming westerly and associated convective systems again and force them splitting, then, moving into the western Pacific near the equator and around 10°S, respectively. The mountains on the MC islands also considerably intensify the diurnal cycle (Qian 2008), thus, act to weaken the passing MJOs indirectly too (Oh et al. 2013). On the other hand, the deep easterly ahead of approaching MJO convective envelope interacts with the MC islands and produces PBL convergence zones on the eastern sides of these islands, which help the MJO convection move over the MC and enter the western Pacific (Matthews 2000; Hsu et al. 2004; Hsu and Lee 2005). How the competitive effects of the MC islands will impact the fates of approaching MJOs is still unknown and will be one of our proposed researches.

1.3, Processes that Help Move the MJOs over the MC

Although the Maritime Continent poses as a hostile region for eastward-propagating MJOs, many of them survive the MC and move into western Pacific (Wang and Rui 1990; Matthews 2008; Kim et al. 2014). A few of them even intensify on their passages over the MC (Hirata et al. 2013). This section briefly reviews three possible factors that help the MJO move over the MC: (i), coherent positive SST anomaly; (ii), orography-induced PBL convergence; (iii), preconditioning from a robust dry phase.

Krishnamurti et al. (1988) revealed that significant coherent intraseasonal SST anomalies are associated with tropical intraseasonal variability and envisioned that "a combination of atmospheric internal instabilities and external SST forcing on intraseasonal time scales may enhance the atmospheric responses toward an eventual satisfactory simulation of intraseasonal oscillation". The positive (negative) SST anomaly is usually generated in front of (behind) the intraseasonal convective envelope. The coherent positive SST anomaly ahead helps the organization, development, and propagation of the MJO (e.g., Krishnamurti et al. 1992; Flatau et al. 1997; Wang and Xie 1998; Waliser et al. 1999; Woolnough et al. 2000; Fu and Wang 2004; Stephens et al. 2004; Fu et al. 2015). The composites of three different types of boreal-winter MJOs over the MC by Hirata et al. (2013) clearly showed contrast SST anomalies associated with each type of the MJOs. For the smoothly transitioning type, robust coherent positive SST anomaly is observed over all the marginal seas of the MC (e.g., the Timor Sea, SCS, and eastern marginal sea of New Guinea); for the eastward rapidly decayed case, only scattered positive SST patches exist over the MC marginal seas. For the boreal-summer eastward-propagating MJO component, coherent positive SST anomaly is found in the SCS and Philippines Sea, which lead the MJO convection pass over the MC (Figure 3).

When the convective envelope of the MJO develops in the equatorial Indian Ocean, the elevated heating of the MJO will force a Kelvin-wave response along with low-level easterly on its eastern side (Gill 1980; Wang and Li 1994). The layer of the easterly anomalies is from surface up to 400-500-hPa (Matthews 2000; Hsu et al. 2004; and Kiladis et al. 2005), which is much higher than all the mountains on the MC islands. The interactions between this deep easterly layer and islands’ orography generate PBL convergences on the eastern sides of these islands. This
orographic effect has been attributed as an important factor for the successful crossing of Indian Ocean MJO over the MC (Matthews 2000; Hsu et al. 2005; Hsu and Lee 2005), but has not been documented with advanced satellite data (e.g., from TRMM and A-Train; Riley et al. 2011; Del Genio et al. 2012; Yu and Houze 2013; and Peatman et al. 2014; et al.).

In addition to the low-level easterly driven by the MJO-related diabatic heating mentioned in the above, a strong dry phase over the MC and western Pacific will also force near-equatorial easterly anomaly over the MC, which is associated with a pair of anti-cyclonic circulations straddling the equator (Matthews 2000; Lin et al. 2007; Zhao et al. 2013; Ling et al. 2013; Kim et al. 2014). The interactions between the dry-phase-driven easterly anomaly and the MC islands further enhance the PBL convergences ahead of the approaching MJO, thus favoring the eastward propagation of the MJO over the MC. This mechanism has been viewed as an essential factor determining the fates of MJO passages over the MC by Kim et al. (2014), who found that the MJOs stalled (propagated) over the MC lack (are associated with) a strong dry phase in western Pacific. Kim et al. (2014) went further to suggest that the easterly anomaly associated with the Kelvin-wave response to the approaching MJO alone is not sufficient to support the MJO propagation over the MC. In addition to forcing low-level easterly anomaly, the dry phase over the MC will also induce positive SST anomaly over the marginal seas and suppress the synoptic activities (e.g., Borneo vortices) over the MC (Chang et al. 2005a). All these effects favor the MJO propagation over the MC.

The proposed research is expected to advance our understanding to the respective roles of the aforementioned three factors (i.e., positive SST anomaly, orography-induced PBL convergence and a robust dry phase) on the passages of the MJOs over the MC and the underlying physical processes. Questions like whether one factor is enough or combined three factors are needed to propagate the MJOs over the MC and in what degree these factors have been represented in present-day weather and climate models will be investigated.

1.4, Scientific Objectives and Questions

The overarching goal of this proposal is to advance our understanding of the major physical processes determining the fates of approaching MJOs over the MC in boreal-summer and winter as well as to assess their representations in present-day weather and climate models. We will focus on the major factors identified from the above review (e.g., the diurnal cycle, annual cycle, positive SST anomaly, and orography) and investigate their respective roles on determining three different MJO passages over the MC (i.e., smoothly transitioning, rapidly decayed and intensified) in boreal summer and winter. At the same time, we are also aware of that the ‘Maritime Continent Barrier’ problem is a complex issue that requires an interdisciplinary approach with a community-wide effort. The planned ‘Year of the Maritime Continent’ program is such an effort. It is also expected that our proposed study will contribute to this community endeavor.

The scientific questions we plan to address in this study are listed in the following:
(1), what are the clouds-precipitation properties and dynamical-thermo-dynamical features associated with three different MJO types passing over the MC? Are there significant differences between boreal summer and winter?
(2), what are the respective roles of diurnal cycle, annual cycle, positive SST anomaly, orography, and a strong dry phase over the MC on determining the fates of approaching MJOs? Do these factors play different roles in boreal summer and winter?
(3), in what degree have the essential physical processes determining the fates of approaching MJOs over the MC been represented in regional and global models?

2, Data, Models, and Methodology

In boreal winter and summer, the MJOs take different routes to move over the MC. In boreal winter (summer), the major convective systems of the approaching MJOs turn south (north) after encountering the Sumatra and move eastward from the Timor Sea (South China Sea) to western Pacific. Many previous studies have focused on winter MJO passages over the MC, while little attention has been paid to the summer counterparts. In recognizing possibly different mechanisms working in boreal summer and the significance of MJO downstream modulations of tropical cycle activities over the WNP, ENP, Gulf of Mexico and Atlantic basin in summer, we will pay special attention in this study to the processes governing the summer MJO passages over the MC.

Data: The datasets will be used in this study include: (1), cloud properties retrieved from the CloudSat, CALIPSO, MODIS, MISR, and ISCCP; precipitation properties from the TRMM and GPM; TMI SST; and NOAA OLR; (2), reanalysis datasets (NCEP-CFSR, NASA-MERRA); (3), the hindcasts from S2S models; (4), in-situ measures from the planned YMC field campaign.

Models: The WRF regional model developed at NCAR and a suite of atmosphere-only and coupled global models developed and used in the University of Hawaii at Manoa (ECHAM-HAM, Zhang et al. 2012; UH-POEM, Xiang et al. 2012; and UH-ESM, Cao et al. 2015) will be utilized in this study to carry out a variety of well-designed numerical experiments to address the specific scientific questions raised in subsection 1.4. All these models have been run on local machines: UH HPC and UH/SOEEST/IPRC clusters.

In recognizing the complexity of the issue we intend to address, a combined diagnostic (3.1), regional (3.2) and global (3.3) modeling approach has been planned in order to achieve the proposed objectives. Both Wheeler-Hendon index (Wheeler and Hendon 2004) and individual variables (e.g., OLR, 200-hPa velocity potential) will be used to determine the MJO types over the MC (Hirata et al. 2013), respectively, for boreal winter and summer. Composites of clouds, precipitation, SST, divergence and other fields associated with different MJO types at two seasons will be constructed with Satellite and reanalysis data. The composite MJO evolutions will be compared with the hindcasts from S2S models to assess model capability in

1 Subseasonal-to-seasonal prediction project (Vitart, et al. 2012); More details can be found online at https://www.wmo.int/pages/prog/arep/wwrp/new/S2S_project_main_page.html.
2 Year of the Maritime Continent (Zhang, 2014); More details can be found online at http://www.bmkg.go.id/ymc.
representing different MJO passages over the MC. Well-designed numerical experiments with regional and global models, then, will be carried out to examine the respective roles of diurnal cycle, annual cycle, positive SST anomaly, orography, and a strong dry phase over the MC on determining the fates of approaching MJOs in boreal winter and summer.

3, Research Tasks

3.1, Diagnostic Study

3.1a, Boreal-summer MJOs over the MC

In comparing to the boreal-winter MJOs, little is known about the physical processes governing the MJO passages over the MC in boreal summer (MJJASO). In fact, about half of the boreal-summer intraseasonal disturbances over the tropical Indian Ocean only propagate northward without any eastward propagating component. The others propagate both northward and eastward (Wang and Rui 1990; Fu et al. 2003). What distinguish these two types of boreal-summer intraseasonal disturbances remains unknown. Almost all previous MJO studies with advanced satellite data, such as from the A-Train, focus on boreal winter (e.g., Tromeur and Rossow 2010; Lau and Wu 2010; Yu and Houze 2013; and Virts and Houze 2015) or mix-up both winter and summer (e.g., Riley et al. 2011; Del Genio et al. 2012). Jiang et al. (2011) has used CloudSat data to investigate the vertical hydrometer structures of Boreal-summer Intraseasonal Oscillation with a focus on northward-propagating component rather than the eastward-propagating MJO component. The faithful representation of the interactions between eastward-propagating MJO component and the MC in boreal summer is a pre-request for skillful extended-range forecasting of TC clustering over the ENP, Gulf Mexico and Atlantic basin.

In this subsection, we will first categorize the boreal-summer MJO types based on their fates after reaching the MC with the method similar as that used in Wheeler and Hendon (2004) and Hirata et al. (2013). Since the primary passage of MJO convective systems in summer is along 10°N (Figures 2, 3), we will average the anomalies of OLR, 850-hPa and 200-hPa zonal winds between 5°S and 15°N and then conduct extended EOF analysis. The target time period is from 2007 to 2015. As defined in Hirata et al. (2013), the MJOs with the amplitudes of both normalized PC1 and PC2 larger than 1 are smoothly transitioning cases; the MJOs with PC1 (PC2) larger (smaller) than 1 are eastward decayed cases; the MJOs with PC1 (PC2) smaller (larger) than 1 are eastward intensified cases. Intra-seasonally (20-90-day) filtered OLR, surface precipitation, and 200-hPa velocity potential will be further used to verify the effectiveness of this MJO categorization method.

Before the composites, all satellite and reanalysis datasets will be interpolated onto same horizontal (e.g., 2.5° x 2.5°) and vertical coordinates. Based on the selected three MJO types, composites of individual phases before, above, and after the MC will be constructed with satellite and reanalysis data. Three types of composites will be produced: (1), horizontal plots cover a box of (20°S-20°N, 80°E-180); (2), vertical cross-sections between 80°E and the Dateline averaged over 5°S-
vertical profiles as a function of MJO phases in eastern Indian Ocean, over the MC and in western Pacific. The composite variables include SST, OLR, precipitation, divergence, overturning circulations, vertical profiles of clouds and precipitation properties. The precipitation and cloud diurnal cycles will also be composited with TRMM and ISCCP as a function of MJO phases for different MJO types. It is expected that this effort will reveal the cloud regime changes associated with different MJO passages over the MC in boreal summer and the potential roles of diurnal cycle, positive SST anomaly, and orographic effects on determining the fates of incoming MJO events.

3.1b, Boreal-winter MJOs over the MC
This subtask largely duplicates the above analyses (3.1a) but with a boreal-winter (NDJFMA) focus. Being aware of that the convective systems of boreal-winter MJOs primarily skirt around the large islands and take a route along about 10°S on their passages over the MC, the average of OLR, U850-hPa and U200-hPa will be done over 15°S-5°N instead of the 15°S-15°N used in Wheeler and Hendon (2004) or 5°S-5°N used in Hirata et al. (2013). Same composites as in the above (3.1b) will be constructed to reveal the cloud regime changes associated with different MJO passages over the MC in boreal winter and the potential roles of diurnal cycle, positive SST anomaly, and orographic effects on determining the fates of incoming MJO events.

3.1c, MJO-MC Interactions in S2S Models
Based on the information of different MJO types derived from the above analyses (3.1a,b), the dates when the convection of individual MJO events reaches a maximum in the eastern Indian Ocean will be recorded. Then, the corresponding hindcasts from S2S datasets with similar initial dates will be selected. The forecasted downstream evolutions of different MJO types will be compared to the observed MJO evolutions obtained from the above analyses (3.1a,b). The capability of S2S models on reproducing each type of MJO passage over the MC will be assessed. The ‘Maritime Continent Prediction Barrier’ problems associated with each type of MJO passage will be identified. Finally, the possible pathways to improve model representations of the MJO passages over the MC will be explored in 3.3c.

3.2, Regional Modeling Experiments
3.2a, Impacts of Diurnal Cycle
As mentioned in subsection 1.2, the persistent strong diurnal cycle over the MC has long been viewed as an obstacle for MJO propagation from Indian Ocean to western Pacific (Wang and Li 1994; Zhang and Hendon 1997; Inness and Slingo 2006). Both our preliminary result (Figure 4) and Oh et al. (2013)'s findings showed that the overall role of solar-driven diurnal cycle is the weakening of MJOs passing over the MC. The recent diagnostic study of Peatman et al. (2014), however, suggests that “the accurate representations of the diurnal cycle and its scale interaction appear to be necessary for models to simulate the MJO successfully”
because large part of the MJO precipitation signal in the MC is accounted for by
changes in the amplitude of the diurnal cycle. Rauniyar and Walsh (2011) also
found that the diurnal maximum of precipitation is much larger (smaller) over the
islands than over the marginal open seas (e.g., the Timor Sea) during suppressed
(active) MJO. It is possible that solar-driven diurnal cycle (i.e., land-sea and
mountain-valley breezes) during suppressed phase acts to weaken the incoming
MJO by releasing PBL moist static energy ahead (Wang and Li 1994; Oh et al. 2013),
while the diurnal cycle driven by surface-cloud-radiation feedbacks (Chen and
Houze 1997) over the marginal open seas (such as the waters over the primary
passage of winter MJO) contributes to sustain the MJO moving over the MC.

This subtask is designed to test the respective impacts of solar-driven diurnal
cycle around the MC islands and surface-cloud-radiation driven diurnal cycle over
the open marginal seas on different MJO types passing over the MC in boreal winter
and summer. Typical MJO events will be selected from the analyses conducted in
subsections 3.1a, b. Three simulations with regional WRF model will be conducted
for each event: (1), with solar diurnal cycle and parameterized SST diurnal cycle
(Webster et al. 1996); (2), without solar diurnal cycle; (3) without SST diurnal cycle.
All experiments will have an active domain of (80°E-Dateline, 30°S-30°N). Lateral
boundary conditions will be constrained with reanalysis data. The initial dates will
correspond to the dates derived in subsections 3.1c. 20-day integrations will be
carried out for each experiment to capture the MJO evolutions over the MC.

3.2b, Impacts of Annual Cycle

In this subsection, two suites of idealized long-term simulations with
regional WRF model have been planned to assess the impacts of the annual cycle
over the MC on MJO passages. All simulations will have an active domain over (80°E-
Dateline, 30°S-30°N). Two sets of idealized lateral boundary conditions will be
produced with reanalysis data: set-1), climatological annual cycle plus a recursive
composite MJO cycle; set-2), climatological mean plus the same MJO cycle. Then, two
10-year simulations will be carried out. In the first simulation (CTL), the set-1
lateral boundary conditions along with solar and climatological SST annual cycles
will be used. In the second simulation, the set-2 lateral boundary conditions along
with annual-mean solar radiation and SST will be used. The differences of MJO
evolutions over the MC between these two runs will reveal the impacts of MC annual
cycle.

3.2c, Impacts of Orography

The orography over the MC impacts MJO passages through blocking the
incoming MJOs (Inness and Slingo 2006; Kodama et al. 2006), intensifying diurnal
cycle (Qian 2008), and inducing PBL convergence (Hsu et al. 2004; Hsu and Lee
2005). The experiments planned in this subsection are expected to shed light on the
importance of realistic representations of these orographic effects on the MJO
downstream evolutions over the MC.

Same MJO events as in subsection 3.2a will be targeted. Three 20-day
simulations for each event will be carried out: (1), with full orographic heights; (2)
reducing orographic heights to half; (3) with flatten islands only. The differences of
MJO evolutions over the MC among these three experiments will tell the significance of realistic representations of the MC orography.

3.3, Global Modeling Experiments

3.3a, Nudging Experiments

As discussed in section 1.1, the cloud regimes of approaching MJOs experience drastic changes on their passages over the MC. In order to assess model capability in representing these cloud-regime changes, nudging model dynamical and thermo-dynamical fields to reanalysis is a proven strategy (Zhang et al. 2014).

In this subsection, we will nudge the divergence, vorticity, temperature, surface pressure and SST from the CFSR and MERRA onto the ECHAM-HAM every 6 hours. The nudging coefficients for individual variables will follow that used in Fu et al. (2011). The nudging period will be from 2007 to 2015. The resultant clouds, and precipitation outputs will be composited based on different MJO types for boreal winter and summer. The model composites, then, will be compared to the observational composites derived in subsections 3.1a,b to identify any misrepresented cloud processes of the ECHAM-HAM during MJO passages over the MC. Possible pathways to make improvement will be explored in subsection 3.3c.

Similar nudging experiments (with diurnal cycle and without diurnal cycle) as used by Oh et al. (2013) will be conducted to further assess the impacts of diurnal cycle on MJO passages over the MC, in particular, during boreal summer. Regional nudging experiments aiming to distinguish the impacts of the diurnal cycle around the MC islands and the diurnal cycle over the marginal open seas on the MJO passages will also be conducted.

3.3b, Transpose-AMIP Experiments

Transpose-AMIP experiments have been used to evaluate model reproducibility of TOGA COARE MJOs (Boyle et al. 2008) and of the clouds associated with Southern Ocean mid-latitude cyclones during the ‘Year of Tropical Convection’ period (Williams et al. 2013). Since all integrations are initialized with observation-constrained reanalysis data, it is an efficient way to assess model capability in reproducing different MJO types and to quickly identify the misrepresented fast model processes (e.g., cloud microphysics and macrophysics). In this study, the ECHAM-HAM will be initialized with the CFSR and MERRA for all MJO events selected in subsection 3.1c. The ensemble forecasts from the initialized ECHAM-HAM will be evaluated with the observational composites obtained in subsections 3.1a,b. The model processes leading to fast error growth associated with ‘Maritime Continent Prediction Barrier’ problems will be identified. The findings from this study will also be used to design extra sensitivity experiments planned for subsection 3.3c.

Previous diagnostic studies (e.g., Hirata et al. 2013; Kim et al. 2014) have revealed that those Indian-Ocean MJOs with a coherent positive SST anomaly and strong dryness proceeding over the MC are able to smoothly move into western Pacific. In order to assess the respective contributions of the positive SST anomaly and the dryness-driven easterly anomaly, two more suites of hindcasts have been...
planned. In one suite, the intraseasonal positive SST anomaly will be removed during the hindcasts as we did in Fu et al. (2013, 2015). The differences of the MJO passages over the MC between the hindcasts with and without the positive SST anomaly will reveal the impacts of the SST anomaly. In another suite, we aim to assess the impacts of dryness-driven easterly on the MJO passages over the MC. Since the dry phase of the MJO is equivalent to a diabatic cooling region (Matthews et al. 2004; Seo and Son 2012), a scaled heating based on OLR anomaly as used in Seo and Son (2012) will be introduced over the dry region to offset the role of the dryness during the hindcasts. The resultant differences with the control runs conducted in the first part of this subsection will tell the impacts of the dry phase on the MJO passages over the MC.

Finally, if the modeling component of the YMC program plans to have hindcast inter-comparisons, we will submit a set of hindcasts with our models at University of Hawaii for the YMC period. If the in-situ measurements become available during the proposal period, preliminary validation with YMC data will be conducted.

3.3c, Other Sensitivity Experiments

Based on the findings from the above tasks, particularly from the nudged simulations in subsection 3.3a and the Transpose-AMIP experiments in subsection 3.3b, extra sensitivity experiments will be carried out to assess the impacts of those misrepresented physical processes on the MJO passages over the MC.

4. Impacts of the Proposed Work and Relevance to NASA Research Program

The proposed research will contribute to reducing systematic error (the MJO “Maritime Continent Prediction Barrier” problem) in global models, thus making weather-climate forecasting more skillful and future climate projection more reliable. The products generated in this study can be used to validate other community models. The proposed study specifically contributes to the ROSES 2015-NHH15ZDA001N-CCST: Application of Cloudsat, CALIPSO, and other satellite data to study cloud processes and improve their representations in weather and climate models.

5. Work Plan

Three research Tasks are proposed in this study. Dr. Fu will be the Principal Investigator (PI) in charge of the entire project. A Post-doc is needed to help process the data and run the regional model experiments. Progress is anticipated as follows:

**Year 1:** Focus on subtasks 3.1a (Fu&Post-doc), 3.1b (Fu&Post-doc), 3.3a (Fu).
**Year 2:** Focus on subtasks 3.2a (Post-doc&Fu), 3.2b (Post-doc&Fu), 3.1c (Fu&Post-doc).
**Year 3:** Focus on subtasks 3.2c (Post-doc&Fu), 3.3b (Fu), and 3.3c (Fu&Post-doc).

6. Data Sharing Plan

All data collected and derived from this project will be made available to others after the publications of relevant results.
Figure 1, the geography and topography of the Maritime Continent (Adopted from Wu and Hsu 2009).

Figure 2, observed intra-seasonal variances in OLR (W² m⁻²) for, (a) boreal winter (November-April) and (b) boreal summer (May-October) (Adopted from Sobel et al. 2010).

Figure 3, composite life cycle of the boreal-summer intraseasonal oscillation along with its eastward-propagating MJO component; green (lavender) contours show positive (negative) precipitation anomalies (mm day⁻¹); shading denotes SST anomalies (°C) (Adopted from Wang et al. 2006).

Figure 4, power spectra averaged over 10°S-10°N from 9-year simulations, (a) with solar diurnal cycle and annual cycle (CTL); (b) without solar diurnal cycle (NO_DC); (c) without solar diurnal cycle and annual cycle (NO_DC_AC).
C. References


Jiang, X., D. E. Waliser, J.-L. Li, and C. Woods, 2011: Vertical cloud structures of the boreal summer intraseasonal variability based on CloudSat observations and


D. CURRICULUM VITAE

PI: Dr. Joshua Xiouhua Fu, Associate Researcher
IPRC, SOEST, University of Hawaii at Manoa
1680 East West Road, POST Bldg. 409D, Honolulu, Hawaii 96822
Tel: 808-956-2629; Fax: 808-956-9425
E-mail: xfu@hawaii.edu

Education:
Ph. D., Meteorology, Department of Meteorology, University of Hawaii, 1998
M. S., Atmospheric Physics, Chinese Academy Sciences, 1988
B. S., Meteorology, Chengdu Meteorological College, 1985

Employment (1999-present):
Associate Researcher, IPRC, University of Hawaii, Jan. 2006-present
Assistant Researcher, IPRC, University of Hawaii, Jul. 2002-Dec. 2005
Postdoctoral Fellow, Wyrtki Center, University of Hawaii, Jan. 1999-Oct. 1999

Research interests:
Intraseasonal-to-Interannual Climate Variability
Earth System Modeling and Prediction
Ocean-Atmosphere Interaction
Development and Improvement of Earth System Model

Synergistic activity:
Referee for more than 18 national and international journals; proposal reviewer for
NSF, NOAA, and NASA.
Member of YOTC MJO Task Force: WCRP-CLIVAR/WWRP-THORPEX Year of Tropical
Convection (YOTC) 2009-2012
Member of US CLIVAR PPAI Panel: US CLIVAR Predictability, Prediction, and
Application Interface (PPAI) 2010-2013
Member of US CLIVAR Extreme Working Group, 2012-Present

Selected publications:
Fu, X., and P. Hsu, 2011: Extended-range ensemble forecasting of tropical


E. CURRENT AND PENDING SUPPORT

PI: Joshua Xiouhua Fu

Current support

Pending support
NASA-NNH15ZDA001N-PMM, Title: The Southern Ocean (SO) Clouds-Aerosol-Precipitation Interactions on Shaping the Inter-Tropical Convergence Zone (ITCZ). PI: Joshua Xiouhua Fu, Co-PI: Kazuyoshi Kikuchi, Period: 01/01/2016-12/31/2018, Amount: $501,501 (Person-month per year: 5 for Fu).

NASA-NNH15ZDA001N-PMM, Title: Three dimensional hydrometeor structure of the tropical intraseasonal oscillation: Satellite observations and global cloud system resolving model simulations. PI: Kazuyoshi Kikuchi, Co-PI: Joshua Xiouhua Fu, Period: 01/01/2016-12/31/2018, Amount: $459,100.72 (Person-month per year 2 for Fu).
F. BUDGET DETAILS


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Budget Explanation

Personnel
4-month/yr salary is requested for the PI. 1-month/yr salary is requested as partial support of institutional tech staff per IPRC institutional policy. PI, and tech staff salary is assumed to increase at a rate of 5% each year. Computation of fringe benefit is based on 42.45% for the PI and tech staff.

Travel
The travel is based on an estimate of two domestic trips per year ($5000) for the PI to attend scientific meetings essential to this research project. Estimated cost of each trip ($2500):

Meeting Place: e.g. Tallahassee; Round-trip airfare: $1000.00
Per diem/lodging: $200/day x 7days = $1400.00
Ground transportation: $100.00

Other direct costs
A post-doc researcher will receive training on this project for three years, whose stipends are projected to increase 5% per year.
The materials and supplies represent the costs of research supplies (e.g. data storage disks), copy charge, transparency, etc.
The publication cost is based on estimation of about 20 pages published in refereed journals at a page charge of $130, plus printing/copying charges of $400 per year.
Computer services include the charges for accessing SOEST Research Computing Facility and IPRC supercomputers and printers.
The ‘Others’ budget is for purchasing UH HPC computing and storage resources.

Indirect costs:
The University of Hawaii charges indirect costs at a rate of 41.5% of the total modified direct costs.

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3 The modified direct costs do not include post-doc stipends and computer service charges.
### G. TABLE OF PERSONNEL AND WORK EFFORT

<table>
<thead>
<tr>
<th>Name</th>
<th>Title</th>
<th>Mth/yr</th>
<th>Task</th>
</tr>
</thead>
</table>
| Joshua Xiouhua Fu | Associate Researcher | 4      | ● Oversee the progress of the project  
● Conduct data analysis and numerical experiments |
| Post-doc          |                    | 12     | ● Data processing  
● Run regional and global numerical experiments |
| Tech Staff        |                    | 1      | ● Support computing needs of the project |