Evolution and characteristics of Madden-Julian Oscillation convection and clouds during DYNAMO

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Evolution and characteristics of Madden-Julian Oscillation convection and clouds during DYNAMO

by

Cora Virgei

A thesis submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Meteorology

Program of Study Committee:
Xiaoqing Wu, Major Professor
Tsing-Chang Chen
William Gutowski

Iowa State University
Ames, Iowa

2016

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ABSTRACT

Mechanisms behind the Madden-Julian Oscillation (MJO) initiation are poorly understood, although there are a few theories based on the cloud evolution. The purpose to this study is to use cloud resolving model output to observe MJO evolution by analyzing cloud top information and cloud types. Cloud top data will be used to divide MJOs into stages, and study cloud types and cloud characteristics for each stage during each MJO.

We use a two-dimensional version of the Clark-Hall Cloud Resolving Model (CRM) with large-scale forcing input over the Northern Sounding Array of the Dynamics of the Madden-Julian Oscillation (DYNAMO) field campaign to produce convective outputs such as cloud mass flux, heat and moisture budgets, precipitation, etc. Large-scale forcing data (provided by Colorado State University) showed two periods of stronger forcing, and one period of weaker forcing. This study focuses on the periods of two MJOs linked with the stronger forcing. Observational temperature, moisture, radiation and precipitation biases show comparisons to the two MJOs linked with these stronger forcing periods, and one weaker MJO. The largest biases occurred during periods of weaker large-scale forcing. During periods of enhanced precipitation, convective rain had higher rates, while stratiform rain dominated the domain.

Cloud top height and temperature frequencies were examined to determine the stages of the two MJOs evaluated in the 90-day time frame (October 1 to December 29). Vertical profiles of different variables show the evolution during each of the four stages of the MJO; suppressed, developing, mature, and decay. The suppressed stages show moisture in the lower atmosphere and convection that remained mostly lower than 0°C. Mostly low and
medium level stratiform clouds appear in the suppressed stages for both MJOs. The developing stage reaches into the higher atmosphere as ice water content increases and total cloud mass flux increases with height. Higher stratiform clouds form in this stage, and few convective towers start to form. The mature stage shows peaks in all variables, as convective towers and anvil clouds are dominant at this time and reach to the troposphere. Lower level variables tend to decrease first before higher levels in the decaying stages as notably fewer lower stratiform clouds are present. MJO1 (October MJO) lasts longer than the MJO2 (November MJO), but MJO2 shows greater quantities in all variables. MJO2 has higher clouds present in each stage except for the decaying stage. The connections between the stages can be made to convection and a moistening of the atmosphere. CRM sensitivity test was performed with a 500 m resolution to reproduce MJO convection and clouds on a finer scale. Evolution of the clouds show agreement with MJO initiation forming in a stepwise fashion, and with the 'recharge-discharge' theory.
CHAPTER 1
INTRODUCTION

The Madden-Julian Oscillation (MJO) is a tropical disturbance that starts in the Indian Ocean and propagates eastward at about 5 ms\(^{-1}\) (Madden and Julian 1971, 1972). It has an intraseasonal cycle of 30-60 days and plays important roles in weather and climate, such as precipitation, tropical cycles, monsoons, El Niño - Southern Oscillation, the North Atlantic Oscillation, and more (Zhang 2013). The active phase of the MJO, which includes strong deep convection and precipitation, starts in the Indian Ocean and travels to the western Pacific Ocean. Strong westerly winds occur within and to the west of the convection in the lower atmosphere while easterly winds take place to the east. These zonal winds reverse direction in the upper atmosphere (Zhang 2005). The MJO has two peak seasons, the primary of which is December-March; the secondary peak season is June-September (Zhang and Dong 2004).

The MJO is difficult to predict with models because of limiting factors such as the representation of cumulus convection in simulations, for example. GCMs poorly simulate MJOs because they cannot resolve small scale phenomenon such as cloud-related processes. Cloud resolving models (CRMs) can give a more in-depth understanding of these convective processes because they are at a high enough resolution to evaluate simulated cloud ice, cloud water, and water vapor, which are natural outcomes from cloud growth (Zeng et al. 2007). Cloud systems are a crucial part of the global climate system because they affect radiation, coupling of thermodynamical and large-scale dynamical processes, along with the surface energy budget. CRMs have been used to explore precipitating convection and their
dynamical features as well as cloud-mesoscale interactions. Because of their fine spatial resolutions, CRMS can portray cloud system structures such as radiation properties and cloud geometric (Liang and Wu 2004). CRMs can generate various types of cloud systems when large-scale forcing and evolving horizontal wind fields are applied (Grabowski et al. 1996; Xu and Randall 1996). For example, when strong large-scale forcing and weak wind shear is put into the model, non-squall clusters dominate the domain. When periods of strong or moderate forcing mix with strong wind shear, squall clusters form, and weak large-scale forcing with strong zonal wind shear create scattered convection. Although, two-dimensional models such as the one used in this study cannot simulate three-dimensional cloud systems such as scattered, random convection, or mesoscale convective complexes, but they can simulate two-dimension convection such as squall lines (Tompkins 2000).

When trying to understand the basic mechanisms and dynamics that create the MJO system, Hayashi and Sumi (1986) found that it can be excited spontaneously in an "aqua-planet", a general circulation model (GCM) that runs without land, and sea surface temperatures (SST) that have a latitudinal dependence. This reveals that topography does not play a significant role on the initiation of the oscillation, as well as land-sea interactions. Other MJO mechanisms suggest Kelvin waves and MJOs are not dynamically distinct modes; it is possible that the MJO is a planetary Kelvin wave modified by intense convection since planetary MJO events and synoptic scale Kelvin waves have comparable vertical and horizontal structures (Roundy 2012). A previous MJO system can create a Kelvin wave response that triggers another MJO event (Knutson and Weickmann 1987). Zhang (2005) explains that the Kelvin wave is the only equatorial mode with an eastward propagating, planetary scale zonal wind field similar to the MJO observations, although the Kelvin wave
propagates much faster than the MJO. Therefore, the Kelvin wave is understood to be the dynamical origin of the MJO.

There are multiple theories on MJO initiation based on convection. One theory is the "recharge-discharge" theory proposed first by Hendon and Liebmann (1990) for the Australian summer monsoon; Bladé and Hartmann (1993) suggested the same theory for the MJO. The "recharge phase" consists of the ocean temperature warming and the lower troposphere moistening to build up convective instability (Johnson and Ciesielski 2013). The discharge period then dries out and stabilizes the lower troposphere during the convective stage (Bladé and Hartmann 1993). This theory was then expanded to include the conditioning of the lower troposphere by cumulus convection through low-level heating and moistening and deepen into congestus clouds (Benedict and Randall 2007). A second MJO theory proposed by Mapes et al. (2006) explains how all cloud types occur to some extent at the same time in all phases, though the frequency at which they occur varies for each cloud type. This "building block" theory differs in that cloud populations don't evolve where one cloud type exists in each MJO phase. More studies show that cloud population sequence takes place in a stepwise fashion, where a phase is dominated by a specific cloud type (Kikushi and Takayabu 2004; Yoneyama et al. 2008; Virt and Wallace 2010; and Del Genio et al. 2012). Johnson and Ciesielski (2013) found patterns consistent with these results with relative humidity, divergence and vertical motion.

Since it has been shown that cloud type is an important component to modeling the MJO properly, multiple attempts at simulating the MJO have been made through field studies and CRMs. The Tropical Ocean-Global Atmosphere Coupled Ocean-Atmosphere Response Experiment (TOGA COARE) of 1992-1993 studied cloud populations over the western
Pacific Ocean and showed that shallow convection dominated during inactive MJO periods, while deep convection dominated during the active period (DeMott and Rutledge 1998). Wu et al. (1998) used large-scale observations to run a CRM for TOGA COARE to analyze the behavior of cloud systems of the MJO. The CRM generally reproduces the cloud-scale properties agreeably. TOGA COARE showed progress in observational features of the MJO, but the location over the Western Pacific Ocean has different surroundings and environment than the Indian Ocean. To understand the structure and evolution of cloud properties in the Indian Ocean during MJO phases, the Dynamics of the Madden-Julian Oscillation (DYNAMO) field campaign was conducted. The three main goals of DYNAMO were to discover how the troposphere is moistened during the initiation stages of the MJO, determine the role of cloud populations during MJO initiation, and to establish the role of air-sea exchanges during the development and evolution of the MJO (Johnson and Ciesielski 2013). The main DYNAMO time frame is from October 1 to December 29, 2011. Three MJO events occurred over the DYNAMO time frame; two strong and one weak (Xu and Rutledge 2014). According to Xu and Rutledge, the first MJO had a slower convective deepening, while the second MJO event had a very rapid convective deepening. This initiation timing is the most apparent variation between the first and second MJO events. These three MJO events had enhanced precipitation that lasted 1 to 2 weeks, and suppressed precipitation afterwards (Powell and Houze 2013). Given that convection during the third MJO event was significantly less than the first two MJO events, precipitation amounts were also smaller during the third MJO.

Mechanisms of the MJO initiation are still not understood, despite the increased amount of studies. More studies detailing the moistening processes, especially developing
cloud and precipitation fields are needed. CRMs can include details lacking in observational data that pertain to MJO evolution. This paper uses a CRM to reproduce cloud characteristics in the northern sounding array of DYNAMO. Observational data is used to influence the CRM while dependent variables are free to develop. This allows a secure agreement with most of the properties of the model but requires that the dependent variables be monitored (Grabowski et al. 1996). The major objective of this paper is to observe the evolution of the MJO using cloud resolving model output to help understand MJO initiation. A description of the CRM, including large-scale forcing inputs can be found in Chapter 2. Chapter 3 describes the basic thermodynamic features of temperature, moisture, radiation, and precipitation. Chapter 4 illustrates the MJO evolution and cloud characteristics through variables such as ice and liquid water content, and cloud mass flux. Chapter 5 presents results of a CRM simulation with a finer spatial resolutions, and Chapter 6 summarizes the results of this study.
CHAPTER 2
CLOUD RESOLVING MODEL AND OBSERVATIONS

Cloud Resolving Models provide the tools to generate cloud and radiation properties over climate sensitive regions, and help improve the understanding and representation of cloud systems in GCMs. There are many ways to use CRMs in studying large-scale functions of clouds. The CRM used in this study is forced by large-scale initial and boundary conditions. Ensembles of convection and clouds are simulated in response to the destabilized atmospheric environment.

2.1 Model and experimental design

The numerical design of this CRM is based on Clark (1977, 1979) and Clark and Hall (1991). The model is 2 dimensional, with x in the east-west component. The dimensions are 200 km horizontally by 40 km vertically, with a 3 km resolution, and time steps at every 15 seconds. Radiation calculations were made every 150 seconds. The vertical coordinate has 52 levels in a stretched grid. The Coriolis term is set to zero in this experiment, and simple periodic lateral boundary conditions are used. The effective radii of water droplets and ice crystals are 10 and 30 μm respectively, which is used for radiation calculations. Surface fluxes (sensible and latent heat) are prescribed to observational data. Free-slip, rigid bottom and top boundary conditions are applied together with a gravity wave absorber in the upper 14 km of the domain. A cloud-interactive radiation parameterization is necessary to study properties of cloud systems, so the radiation scheme that is used is the NCAR Community Climate Model 2 (CCM2) radiation model described in Kiehl et al. (1994). The Kessler
(1969) bulk warm rain parameterization and the Koenig and Murray (1976) bulk ice parameterization are used. The ice parameterization uses two types of ice; Type A is low density slow falling ice, and type B is high density fast falling ice such as graupel. This CRM generates cloud fields such as condensation, precipitation, radiation, etc. More details on the numerical design of this model can be found in Grabowski et al. (1996).

2.2 Large-scale forcing

The forcing data used in this experiment is provided by Paul Ciesielski and Richard Johnson from Colorado State University (Ciesielski et al. 2013; Johnson and Ciesielski 2013). The DYNAMO experimental data included are array-averaged basic fields of wind, temperature, moisture, divergence and vorticity. Additionally, advective tendencies of temperature and moisture, apparent heat source and moisture sink, surface fluxes, and rainfall are used. These observations are available in the Northern Sounding Array (NSA; Fig. 1), which has four boundary sites of Colombo (6.91˚N and 79.87˚E), Revelle (0.10˚N and 80.50˚E), Gan (0.69˚S and 73.15˚E), and Malé (4.19˚N and 73.53˚E). The experiment runs from 01 October to 29 December 2011 with a 6-hour resolution. The vertical resolution is 25-hPa. The data set was created objectively using multiquadric interpolation by analyzing upper-air dropsonde data onto a 1 degree, 25-hPa grid (Johnson and Ciesielski 2013).

The convective processes and their relationship to large-scale variables are complex over the Indian Ocean, partly because of the presence of organized convection and strong interaction between large-scale motion. Figure 2 shows the domain averaged large-scale forcing for temperature and water vapor mixing ratio over the NSA DYNAMO. Strong cooling and moistening starts October 14 and last until November 3. A period of weaker
forcing follows until November 23, when cooling and moistening rapidly intensify and last until December 1. Another period of weak forcing follows with few peaks in temperature forcing from December 7 to 17.

2.3 Wind and surface fluxes

Figure 3 illustrates the zonal wind speed and sea surface temperature over NSA during the time frame. The model domain-averaged wind is relaxed to follow the observations. When comparing zonal wind speed to larger-scale forcing, wind shear is stronger in areas with stronger cooling and moistening. A westerly wind burst gradually turned into easterlies just as large-scale forcing became strong during the first MJO (MJO1). As the large-scale forcing started to decay, westerly winds intensify again, and a period of weaker forcing followed, including weak easterly winds with very little shear. High levels of forcing protruded again for the second MJO (MJO2), and wind shear increases with westerly wind bursts shortly after this time of high convection and precipitation.

Figure 4 shows the surface flux time series of SST, sensible heat, and latent heat, averaged over the domain. SSTs start out low and rise gradually during MJO1 and peak during early MJO 2, before declining more rapidly towards the end of MJO3. The highest peak in SST is 10 days before large-scale forcing peaks in MJO2. Sensible heat flux values start low and rise just as large-scale forcing increases during the MJO1. Levels decrease between MJO1 and MJO2, and peak again with large-scale forcing during MJO2. Sensible heat then rises again towards the end of MJO3, when large-scale forcing has only increased vaguely. Latent heat flux values don't vary as strongly during MJO1, but increase significantly during the convective period of MJO2, when strong westerly wind bursts occur.
Sensible heat flux matches the SST for MJO2, but sensible heat has peaks during MJO1 that don't match with the SST. This suggests additional factors that affect sensible heat. The zonal wind figures show westerly wind bursts during this time, which can show the convergence during MJO1 can be the cause of high sensible heat values for MJO1.

2.4 Observational data during DYNAMO

Observational data used in this study included radiation, precipitation, heat source and moisture sink, sea surface temperatures and liquid and ice water content. Observational radiation data was obtained from CERES SYN1deg product, and can be found at http://ceres.larc.nasa.gov/order_data.php. Radiation temporal resolution was 3-hourly, and spatial resolution was 1° x 1° on a global grid. Radiation data used included top of atmosphere (TOA) longwave (LW) radiation upward, TOA shortwave (SW) radiation upward and downward, surface LW radiation upward and downward, and surface SW radiation upward and downward directions. Precipitation observations used were array-averaged analysis' of budget-derived precipitation based on the Q2 budget. Precipitation is also located through high-temporal-resolution infrared rain-rate satellites combined with microwave rainfall estimates, based on the Tropical Rainfall Measuring Mission (TRMM) 3B42v7 product. Heat source and moisture sink were array-averaged six-hourly data with 41 levels of data for each six-hour period. Heat source and moisture sink were computed as:

\[
\frac{Q_1}{c_p} = \left( \frac{p}{p_0} \right)^\kappa \left[ \frac{\partial \theta}{\partial t} + \mathbf{V} \cdot \nabla T + \omega \frac{\partial \theta}{\partial p} \right]
\]

\[
\frac{Q_2}{c_p} = -\frac{L_v}{c_p} \left[ \frac{\partial q}{\partial t} + \mathbf{V} \cdot \nabla q + \omega \frac{\partial q}{\partial p} \right]
\]

where the change in time (dt) is 12 hours, initial pressure (p_0) is 1000 hPa, the specific heat of dry air at constant pressure (c_p)=1004 J K^{-1} kg^{-1}, the latent heat of condensation
\(L_v = 2.5 \times 10^6 \text{ J kg}^{-1}\), the gravitational acceleration \((g) = 9.8 \text{ m s}^{-2}\), and \(\kappa = R/c_p\) where \(R\) is the gas constant. Sea surface temperature observations were acquired by two sources, from the NOAA/ESRL website, and the Woods Hole Oceanographic Institution. More information on precipitation, heat source and moisture sink, and sea surface temperature observations can be found in Ciesielski et al. (2013) and Johnson and Ciesielski (2013). Cloud observations used can be found in Feng et al. (2014). Cloud and observation properties are retrieved for all sky conditions at Gan Island, Maldives.
CHAPTER 3
BASIC THERMODYNAMIC FEATURES

3.1 Temperature and moisture

Figure 5 shows comparisons of observations to model output with temperature and moisture bias. The model output is averaged to 6-hour periods for constituency with the observations. The model temperature tends to be 2 to 4 degrees cooler on average, so differences between the fields are small. The biggest temperature and moisture differences occur in periods of weaker forcing, regularly in the upper atmosphere for temperature, and in the lower atmosphere for moisture. The model tends to be warmer in the upper levels and drier in the lower levels. MJO1 tended to have the larger cold temperature differences with the model than the others, especially in the early stages of the MJO before the large-scale forcing peaked. MJO1 also had higher moisture differences than MJO2 with model output, as well as drier biases.

The reason for these differences can be explained by Grabowski et al. (1996). The model cannot represent the domain-averaged large-scale horizontal gradients and vertical velocities due to the use of periodic boundary conditions (Wu et al. 1998). This means that advective trends need to be found superficially. Sensitivity tests can be performed to further evaluate these explanations.

3.2 Radiation

Other comparisons to observations can be made to show characteristics of the MJO, such as radiation. Radiation at the top of the atmosphere includes incoming solar flux,
reflected solar flux, and outgoing longwave flux. Radiation at the surface includes downward solar flux, reflected upward solar flux, incoming longwave flux and outgoing longwave flux. Table 1 shows the comparisons of model output radiation to observational radiation data. The top of atmosphere (TOA) longwave (LW) and shortwave (SW) model data are larger than observations. Reasons for these differences could be that the models are producing too much water vapor or clouds. Model to observational comparisons are moderately smaller for these quantities.

Clear sky offline radiation tests compare model output radiation in normal convective simulations to simulations with no cloud output (clear sky simulations, Fig. 6), with directional LW and SW radiation at the surface and top of atmosphere. Figure 6 represents the clouds in the model as the differences between total radiation and clear-sky radiation. Clear-sky TOA LW radiation follows maximums of model output TOA LW radiation, and periods of the lower TOA LW radiation compare to periods of high large-scale forcing values when convection is dominant. For MJO1, the differences between clear-sky and normal TOA LW radiation are minimal, but as the large-scale forcing increases, normal TOA LW output decreases as more clouds and water vapor form in the atmosphere. Normal TOA LW output decreases even more for the periods of enhanced large-scale forcing in MJO2. Clear-sky SW radiation is minimal due to no SW radiation reflected off clouds. The biggest difference to model output SW radiation are during periods of higher large-scale forcing magnitudes and convection reflects the SW radiation. MJO2 has higher values of TOA SW radiation than MJO1. Clear-sky downward surface LW follows the same trend as model output but with lower quantities, since minimal LW would be reflected as well. Downward surface LW increases as large-scale forcing increases in MJO1, and decreases
towards the end of MJO1. It then increases again towards the peak large-scale forcing for MJO2, with larger values than the peak forcing of MJO1. Surface LW up radiation matches exactly, and tends to trend minimally but similar to SST.

3.3 Precipitation

Three periods of enhanced precipitation with 1 to 2 week durations were found during the DYNAMO observation period. Reduced precipitation periods followed each enhanced precipitation period. Each period was part of a MJO event. The model output precipitation was compared to two observational precipitation sets. First, budget precipitation derived from the $Q_2$-budget is compared to the model output, followed by a comparison to TRMM rainfall. Both sets of observations are averaged over the NSA DYNAMO region. Model output tends to follow the budget precipitation output better than the TRMM observational data. The TRMM data tends to have greater values, as seen in Fig.7. TRMM observational levels has higher levels of precipitation during periods of higher large-scale forcing in both MJO1 and MJO2, but peaks in MJO2. Observational budget precipitation values trended higher than model output during suppressed periods with low to no large-scale forcing in both MJO1 and MJO2.

Powell and Houze (2013) used cloud radars to observe vertical profiles of wind, temperature, and moisture content every three hours at the Gan Island site on Addu Atoll during DYNAMO. The reflectivity data from this site was used to determine convective versus stratiform rain in the radar echo. Areas of strong vertical motion, heavy rain, and a low-level to mid-level maximum in diabatic heating were defined as convective precipitation
regions. Stratiform precipitation was defined with less intense vertical motion, lighter precipitation, and a radar bright band near the 0°C level.

For the CRM output in this study, all precipitation is assumed stratiform precipitation, unless the maximum vertical velocity is greater than 10 hPa hr$^{-1}$ or the precipitation rate is greater than 25 mm hr$^{-1}$. Figure 8 shows total precipitation rate averaged over the NSA for 90 days, averaged every 6 hours, and percent of the domain covered by stratiform rain versus convective rain. The black line shows total precipitation, the blue line illustrates convective precipitation, and the blue line is stratiform precipitation. Similar to observational data, three periods of enhanced precipitation occur, comparable to each MJO in the time period. The first large-scale convective event lasts more days than the second large-scale convective event, but the second event has greater magnitudes of precipitation rate. The third event is very weak compared to the first two events. During the periods of high large-scale forcing, convective rain rates exceed stratiform rain rates, but stratiform rain takes up a higher percentage of the domain.

Convective precipitation starts out minimally in the first few days of the period, with three small peaks under 0.2 mm hr$^{-1}$. An increase occurs around October 16 when large-scale forcing increases. Convective precipitation peaks above 0.5 mm hr$^{-1}$ every other day, reaching greater than 1 mm hr$^{-1}$ once or twice during the convective event during MJO1. After November 4, the minimal convective rain reaches zero again with a few peak points until November 10, when precipitation is minimal. Another significant convective event starts November 16 when large-scale forcing starts to increase again for MJO2, and intensifies substantially with peaks above 1.5 mm hr$^{-1}$ starting November 24. The event ends when convective rain becomes minimal again around November 30, when large-scale forcing
becomes negligible again. Stratiform precipitation follows the same patterns as convective precipitation, reaching peaks and minimums on the same days, but usually reaching about half the rain rate as convective precipitation during peak periods. During times when rain is minimal, stratiform rain rate can be equal to or greater than the convective rain rate. The differences in precipitation rates for MJO1 and MJO2 could be caused by differences in cloud characteristics.
CHAPTER 4
CHARACTERISTICS OF MJO CONVECTION AND CLOUDS

4.1 Cloud top temperature/height frequency

Figure 9 shows the simulated cloud top height (km) and temperature (Celsius) frequency during the 90 days of DYNAMO. Each height level where the liquid water mixing ratio is greater than 0.05 g kg$^{-1}$ is considered part of a cloud. The base is found at the first level that the mixing ratio reaches this value, and a cloud top is at the next level when mixing ratio is below the value. A new layer is added each time a new base and top is found at each grid point, but only the highest cloud top is used. Temperature profiles are produced for each grid point and the temperature at the level of the cloud top is used. Cloud top temperature frequencies were also binned to 5 °C intervals with the units being % (frequency a top hit a temperature bin / 200 grid points).

Kikuchi and Takayabu (2004) used cloud top frequency histograms to define stages of the MJO from January 6 to February 5 1993 with the TOGA COARE. Infrared equivalent blackbody temperature data from Japanese Geostationary Meteorological Satellite (GMS/IR T$_{bb}$) were binned to 5 K intervals in each 1°x1° grid.

Stages are defined subjectively by Kikuchi and Takayabu (2004). The "suppressed stage" is the time period where almost all clouds are warmer than 300 K (27 °C). The "developing stage" follows the "suppressed stage", where clouds mature but most cloud temperatures are above 270 K (-3 °C). The 'mature stage' is where cloud top temperatures are below 250 K (-27 °C). The "decaying stage" is a shift of peaks from the "mature stage" of higher cloud tops and lower cloud top temperatures to lower cloud tops.
The MJO stages in this study are defined subjectively by the cloud top temperature frequency. The "suppressed" stage is when most clouds are below 10°C. The "developing" stage is defined by the cloud top temperature frequency reaching heights higher (colder) than -10°C, but the frequency doesn't reach past 15% of the domain. The MJO reaches the "mature" stage when the cloud top temperature frequency is above 15% and around -30°C. The decaying stage is a transitioning stage where there is less variety in cloud top temperature heights, but still cloud top temperatures colder than the suppressed stage.

Cloud top height frequencies compares with cloud top temperature frequency very closely. The "suppressed" stage of the MJO1 has lower cloud tops with warmer temperatures from October 5 to 9, when higher cloud tops start to develop. A peak in cloud top height as well as a low in cloud top temperatures appears at October 14. The "developing" stage is from October 9 to 14, and the "mature" stage starts October 15. The decaying stage is November 4 to 10. For MJO2, the stages are as follow; suppressed is November 11 to 16, developing is November 17 to 22, mature is November 23 to 28, and decaying is November 29 to 30.

These stages could also be compared with precipitation. When compared to 15 minute increments, the mature stage begins when the precipitation rate is greater than 1 mm hr⁻¹. The mature stage continues while the precipitation rate hits above 1 mm hr⁻¹ at least once every 2 days. The suppressed and developing stages are not as apparent for MJO1, but the decaying stage is more evident. MJO2 shows a clearer difference between the suppressed and developing stages, but not a palpable decaying stage.
4.2 Ice and liquid water

Figure 10 shows the 90-day evolution of liquid and ice water path from the CRM (top). The model liquid and ice water path have peaks correlating to peak periods of large-scale forcing. During the suppressed stages of the MJO, liquid water path is greater than the ice water path, which is mostly zero at these times. During maxed forcing periods, ice water path maximizes and is greater than the liquid water path. A possible explanation for this is that clouds aren't high enough to contain ice water in the periods when forcing is minimal, so it is understandable that liquid water path is greater during these periods. The ice water path increases greater than the liquid water path due to higher clouds in this time frame, as will be talked about in the cloud top height frequency section.

Figure 11 shows the 90-day simulated total water content (liquid and ice) over the NSA DYNAMO domain. Water content follows the cloud top height and temperature frequency, where the beginning shows water content in the lower levels of the atmosphere, which few spikes into the upper atmosphere. Water content increases into the upper atmosphere from the developing stage to the mature stage. Two periods of enhance water content occur throughout the atmosphere, relative to the two MJOs during this period. When compared to observations, ice and liquid water path did not match magnitudes due to spatial constraints and resolution, but patterns in the time series matched very closely.

In Fig. 12, vertical profiles are made of ice and liquid water content of each stage during the first two MJOs. In both the October and November MJO, liquid water content peaks lower in the atmosphere during the suppressed stage, but the MJO2 had a larger peak in liquid water content. The ice water content appears more in the developing stage, showing that ice is more present in the developing stage than in the suppressed stage. The peak in the
liquid water content starts to rise in the developing stage for both MJOs as well. As the
mature stage begins, the ice water content maxes out beyond the peak of the liquid water
content, indicating more ice is present in the atmosphere during the mature stage than in the
developing stage. The decaying stage shows liquid and ice water content both having maxed
values at similar strengths, but in different heights of the atmosphere. Both October and
November MJOs show similar shapes in the ice/water liquid content profiles, but the
November profiles consistently have bigger values of both ice and liquid water content.

4.3 Heat and moisture budget

Yanai et al. (1973) introduced heat and moisture budget as measures of apparent heat
source ($Q_1$) and apparent moisture sink ($Q_2$), which can infer the character of precipitation.
These values can be derived observationally through temperature and moisture conservation
equations ($Q_{1o}$, $Q_{2o}$) and explicitly through CRMs ($Q_{1m}$, $Q_{2m}$). Grabowski et al. (1996)
presents precise equations for $Q_{1o}$, $Q_{2o}$, $Q_{1m}$, and $Q_{2m}$. Estimates of $Q_1$ and $Q_2$ through CRMs are:

$$Q_1 = Q_{1e} + Q_{1c} + Q_{1r} + Q_{1d}$$

$$Q_2 = Q_{2e} + Q_{2c} + Q_{2d}$$

where

$$Q_{1e} \equiv -\pi \frac{\rho_0}{\rho_0} \frac{\partial \rho_0 (w' \theta')}{\partial z}$$

$$Q_{1c} \equiv \frac{L_v}{c_p} (c - e) + \frac{L_f}{c_p} (f - m) + \frac{L_s}{c_p} (d - s)$$

$$Q_{1d} \equiv \pi (D_\theta)$$

$$Q_{2e} \equiv \frac{L_v}{c_p \rho_0} \frac{\partial \rho_0 (w' q'_v)}{\partial z}$$
\[ Q_{2c} \equiv \frac{L_v}{c_p} [(c - e) + (d - s)] \]  
\[ Q_{2d} \equiv -\frac{L_v}{c_p} (D_{q_v}) \]

In these equations, \( \rho_0 \) is air density, \( L_s \) and \( L_f \) are latent heat of sublimation and fusion, \( c, e, d, s, f, \) and \( m \) are rates of condensation, evaporation, deposition, sublimation, freezing and melting, respectively. The right hand side of the model \( Q_1 \) equation contains the eddy transport \( (Q_{1e}) \); radiation \( (Q_{1r}) \), which includes both shortwave \( (Q_{rs}) \) and longwave \( (Q_{rl}) \) tendencies; and subgrid-scale diffusion \( (Q_{1d}) \), which includes the divergence of the parameterized vertical flux linked with the surface sensible heat flux. Also, the right hand side of the model \( Q_2 \) equation contains the eddy transport \( (Q_{2e}) \), the phase change \( (Q_{2c}) \), and subgrid-scale diffusion \( (Q_{2d}) \), which also includes divergence of the parameterized vertical flux linked with the surface latent heat flux.

Figure 13 is the 90-day mean profiles of observational and CRM-produced heat source and moisture sink, averaged over the domain, and Fig. 14 shows the vertical profile of the heating effects due to different phase change processes. The horizontal lines in Fig. 13 represent the standard deviations of the time series model-produced heat and moisture budgets. The difference between the observations and model output are very small compared to the standard deviations, except for the very top of the atmosphere. These results are similar to those found in TOGA COARE (Wu et al. 1998) and GATE (Grabowski et al. 1996). The shape \( Q_1 \) vertical structure is reliant on the latent heat released by the phase changes. Condensation has a large role in transferring moisture, which can cause disparity for \( Q_1 \) and \( Q_2 \) (Yanai et al. 1973). The heating and cooling effects shown in Fig. 14 are condensation, evaporation, deposition, sublimation, and fusion.
Figure 15 shows the domain-averaged 90-day time series of simulated heat and moisture budgets to compare the evolution of heat and moisture budget to the evolution of the MJO. Heat source and moisture sink are dominant at times when large-scale forcing is strong. Vertical profiles are then taken of each MJO stage of $Q_1$ and $Q_2$ in Fig. 16 to compare development. The suppressed stage for each MJO has anti-peaks of moisture sink in the very lower levels, although values are less for MJO1. The developing stages in each MJO matches the suppressed stage closely, but is increased in value. The mature stage has very well-defined peaks in both heat source and moisture sink, but the MJO2 has values almost twice the size than MJO1. The decaying stages have small peaks in the higher atmosphere, but have smaller magnitudes with uneven values for MJO2.

4.4 Cloud mass flux

CRMs can provide cloud mass flux since observational data cannot provide it accurately. Figure 17 shows the simulated cloud mass flux time series averaged over the area. During periods of higher forcing and convection, the downdraft mass flux is about half the updraft mass flux. This coincides with other CRM studies such as TOGA COARE (Wu et al. 1997) and GATE (Grabowski et al. 1996). This is also apparent in the lower to mid troposphere in Fig. 18, which shows the simulated 90-day average profile of the updraft mass flux, downdraft mass flux, and total cloud mass flux. Both updraft mass flux and downdraft mass flux peak between 1 and 2 km in height, but the updraft mass flux shows a secondary peak around 3 km.

When the profiles are separated into averages for each stage as in Fig. 19, updraft mass flux shows greater numbers than downdraft mass flux, and cloud mass flux stays low in
the atmosphere for the suppressed stage. Both updraft and downdraft mass flux slightly increase in the developing stage, while traveling higher in the atmosphere. The mature stage shows greater values of mass flux throughout the atmosphere, peaking at 3 km, higher levels than the suppressed and developing stages. The decaying stage shows a decrease in mass flux in the lower atmosphere, illustrating equal levels of mass flux with no peak at a specific height. MJO2 has cloud mass flux values that extend higher into the atmosphere during the early stages. The mature stage has the same shape as MJO2, but twice the values of downdraft mass flux and updraft mass flux.

4.5 Cloud frequency distribution

Liang and Wu (2005) used a modified version of the same CRM of the Atmosphere Radiation Measurement (ARM) to evaluate GCMs. Based on a cloud water path threshold, they defined certain cloud types within their grid. Convective clouds are described as having lower bases (around 4.5 km) and higher tops (9.5 km) and extend over great heights, anvil have higher bases and tops (>9.5 km), and the remaining clouds are stratiform clouds which are shallow clouds with small differences.

Figure 20 presents the simulated cloud distribution frequency as a function of cloud top and cloud base height. The deep convective towers have lower cloud base heights (<5 km) but higher cloud top heights (between 7 to 15 km). Anvil clouds represent higher tops and higher bases again (<10 km). The stratiform clouds appear to have equal cloud bases to cloud tops, and show in three different clusters. The first cluster is the lower stratiform clouds that peak at 2 km, the second peak between 4 and 6 km, and the third highest cluster peaks between 10 and 12 km.
The cloud distribution graphs are split into the MJO stages for the two MJOs in Fig. 21 and 22. Figure 21 shows the cloud distribution of each stage during MJO1. The suppressed stage shows thin stratiform clouds purely in the lower levels. Stratiform clouds are produced higher in the atmosphere for the developing stage of MJO1. Anvil clouds and convective towers have developed in the mature stage, but decrease in the decaying stage. The majority of the cloud distribution in the decaying stage are upper level stratiform clouds.

Figure 22 shows the cloud distribution by stage for MJO2. Since MJO2 forms quicker than MJO1, stages are slightly more developed. The suppressed stage has only stratiform clouds again, but the clouds are extended into higher levels of the atmosphere. Stratiform clouds are more uniformly distributed with height in the developing stage, as well as a small amount of convective towers appear. The mature stage has a higher distribution of all clouds, especially convective towers, during MJO2 mature stage. The decaying stage has the majority of cloud top distribution remain around 10 km, with a few lower stratiform clouds.
CHAPTER 5

PRELIMINARY RESULTS OF A FINER CRM SIMULATION

Sensitivity tests can be run with model changes to evaluate cloud convection under different circumstances. The CRM was executed with a 500-m resolution. CMRs with fine spatial resolutions can portray the in-depth organization of cloud systems more easily, therefore the 500 m resolution run should illustrate more distinct cloud formations. Precipitation showed similar total rain rates, but convective rain was notably higher than stratiform rain during periods of enhanced convection and large-scale forcing. Cloud top information shows less low clouds in the suppressed stages but more clouds in general in the mature periods. Ice and liquid water path levels were consistent for both MJO1 and MJO2. When looking at cloud types for the 500-m resolution run, convective towers and shallow convection had higher frequencies than in the 3-km resolution run (Fig. 23). The cloud types most dominant in the area were mid and upper stratospheric clouds. The 500-m output had a higher frequency of both higher and lower clouds than the 3-km output, and also had higher clouds with tops reaching to 15 km higher, where the 3-km run had cloud top heights reaching to 14 km or lower. Cloud base height reached a peak of 14 km, slightly higher than peaks for the lower resolution run. The shapes of the distribution figures also vary between each resolution run. The higher resolution shows a steeper climb along the convective tower plume. This means that the lower resolution run has thicker lower stratiform clouds. The higher convective towers in the higher resolution also tends to have higher bases. The finer resolution output shows more frequent convective activity. These cloud types show structure differences and the main properties of the cloud geometric relationship. Reasons for a higher
frequency of clouds is that grid spacing is lower and can explicitly simulate more clouds in the system. Larger values of cloud mass flux tend to occur with higher resolutions since they can resolve larger vertical motion. This higher resolution has slightly larger values of cloud mass flux than the lower resolution run.

When comparing heat source and moisture sink, the finer resolution run had larger values of both $Q_1$ and $Q_2$ than the lower resolution run in most of the vertical profile of the domain. While still within the standard deviations for most of the profile, the finer resolution run did not match the observations as well as the original 3-km resolution run. More analysis will have to be done in the future to determine reasons behind this. Future work for this research includes more analysis based on the 500-m resolution run, and other possible sensitivity test for the cloud resolving model in this study. This includes redefining the MJO stages using cloud top temperature and height figures, and using the redefined stages to analyze types of clouds in each stage. The different shapes of the distribution figures for each stage could better explain the MJO evolution.
The Madden Julian Oscillation is an eastward propagating system of enhanced convection cycling every 30-90 days. Theories of MJO initiation based on convection are the "recharge-discharge" theory and the "building block" theory. The "recharge-discharge" theory explains how convective instability recharges the lower troposphere, and then discharges it through stabilization. The "building block" theory describes how all cloud types transpire in each phase of the MJO in varying frequencies. Other studies explain that cloud populations build up in a stepwise fashion, and each stage is dominated by a specific cloud. The results from this study can help understand MJO initiation through analysis of cloud evolution with comparisons to these theories.

In this study, a CRM was used to examine evolving cloud characteristics of the MJO. This CRM is forced by large-scale initial and boundary conditions to simulate clouds and convection. Output from the CRM is used to evaluate the basic MJO features of temperature, moisture, radiation and precipitation. The basic thermodynamic features show the evolution of two MJOs compared to the large-scale forcing.

Cloud top features showed four distinct stages of the MJO, similar to stages defined by Kikuchi and Takayabu (2004). Cloud top height and cloud top temperature evolve during the time period to show two periods of convection identified as the two MJOs, and each MJO has four distinct stages for DYNAMO. These stages are suppressed, developing, mature, and decay. The two periods of convection coincide with periods of strong larger-scale forcing and enhanced precipitation. These two periods are MJO1 (October MJO) and MJO2 (November
MJO). The enhanced precipitation period and the defined mature stages begin simultaneously. Convective and stratiform rain rates increase considerably, with convective rain rate dominating, but stratiform rain taking up a larger percent of the domain. Ice and liquid water path trends peak during the MJO periods, but ice water path is dominant during the mature stage, while liquid water path is dominant during all other stages.

Variables from the CRM output were put into vertical profiles based on the stages defined by the cloud top features to observe MJO evolution. Cloud mass flux, heat and moisture budget, and ice and liquid water content showed vertical profiles averaged during these defined stages for each MJO. Liquid water content dominates in the lower atmosphere of the suppressed stages, with almost no ice water content. Heat source and moisture sink show very low values throughout the atmosphere in the suppressed stages, and cloud mass flux also shows lower values with small peaks in the lower atmosphere. For all three variables, MJO1 has slightly higher magnitudes in the upper atmosphere. The developing stage of the heat and moisture budget tends to have values that increase uniformly throughout the atmosphere, while cloud mass flux and ice and liquid water content values stay the same in the lower height levels but increase in the upper height levels. The mature stage has a reoccurring trends with MJO2 having close to double the magnitude of MJO2. Decaying stages show numbers decreasing in the lower atmosphere first before decreasing in the atmosphere. These results are agreeable to the "recharge-discharge" theory, showing that the lower clouds moisten the atmosphere and recharge it. After intense periods of precipitation and convection, the lower atmosphere then discharges and stabilizes, as seen through the decaying stages.
Liang and Wu (2004) used the same CRM for the Atmospheric Radiation Measurement (ARM) to compare structure differences between cloud types. The cloud base and top height distribution figure (Fig. 20) was found using the same methods, and shows similar results with types of clouds during DYNAMO, convective clouds, anvil clouds, and stratiform clouds at varying heights. This distribution is split into the four MJO stages to see which cloud types would be most present during each stage. While the suppressed stages included mostly lower stratiform clouds, MJO2 included very few higher convective towers. All cloud types are present in the other stages to varying degrees, which supports the "building block" theory. The way the cloud tops build up in specific levels suggest that the MJO initiates in a stepwise fashion. Other indications of this are seen in the cloud top and base distribution figures (Figs. 20, 21, and 22). Instead of initiating stages having all cloud heights at varying frequencies, the transition from suppressed to developing stage shows cloud tops and base increasing with height. This can help better understand MJO initiation through cloud evolution.

MJO1 lasts longer than the MJO2, but MJO2 is more intense than MJO1. The suppressed period for MJO1 is longer and has fewer moisture in the upper atmosphere than MJO2. Both MJO1 and MJO2 seem to build up in a stepwise fashion. Hence, evolution of these MJOs vary as a more intense MJO has a more rapid development. A higher resolution version of the model shows higher frequencies of clouds due to lower grid spacing and larger vertical motion.

Kikuchi and Takayabu (2004) found that the developing stage has two quasi-levels of stable layers. The cloud top temperature and height figure showed similar results. Brown and Zhang (1997) showed that relative humidity above the freezing level (0°C) had dry and moist
bimodal structure. In the dry structure, parcel buoyancy is depleted through entrainment, which causes deep convection to be discouraged. This is why the low-level moisture building up in the suppressed stages and developing stages are so important in MJO evolution. The atmospheric moistening, represented in ice and liquid water content, increasing into the upper atmosphere provides the moistening necessary for the mature stage of the MJO, and the heavy convective precipitation events. The cloud top and base distribution figures show MJO2 has higher clouds moistening the atmosphere, and therefore could be the cause of MJO2 being significantly stronger than MJO1. Future work with a finer resolution model can show convection more clearly in these stages.
Figure 1. Area of DYNAMO Northern Sounding Array and Southern Sounding Array

Figure 2. Large-scale temperature forcing (left) and moisture forcing (right) for 90 days from October 1 to December 29, averaged over Northern Sounding Array Dynamo.
Figure 3. The zonal wind (top) in meters per second, contoured at 3 m s$^{-1}$ and averaged over the NSA for 90 days.
Figure 4. Observational surface fluxes of zonal mean sea surface temperature (top), sensible heat flux (middle) and latent heat flux (bottom) time series of 90 days over NSA DYNAMO.
**Figure 5.** The temperature (left) and moisture (right) bias for 90 days averaged over NSA DYNAMO. The bias shows the temperature (°C) and moisture (g kg⁻¹) model output minus the temperature and moisture observations.
Figure 6. Comparisons of offline clear-sky radiation values (red) to regular CRM radiation output (blue) for longwave and shortwave radiation at the top of atmosphere and surface.
Figure 7. Model output (blue) and observational precipitation (red) for budget precipitation derived from the $Q_2$ budget (top) and TRMM precipitation (bottom).
Figure 8. Six hourly averaged precipitation for 90 days averaged over NSA DYNAMO. The precipitation rate in mm hour$^{-1}$ (top) includes stratiform precipitation (red), convective precipitation (blue) and total precipitation (black). The percent of precipitation over the domain (bottom) includes stratiform (red) and convective (blue) cover.
Figure 9. Cloud top height (top) and cloud top temperature (bottom) frequency averaged over the domain for 90 days. Height is measured in kilometers, and temperature is measured in degrees Celsius.
Figure 10. Cloud Resolving Model liquid water path (top) and ice water path (bottom) averaged over the domain for 90 days during DYNAMO.
Figure 11. Total water content (ice water content and liquid water content) profiles averaged over the domain for 90 days during DYNAMO.
Figure 12. Ice water content (blue) and liquid water content (red) profiles averaged during each MJO stage over the domain during MJO1 (top) and MJO2 (bottom).
Figure 13. The 90-day mean profiles of heat source (top) and moisture sink (bottom). The solid red line is model output, the red dotted lines are observations and the horizontal black lines are the standard deviations.
Figure 14. The 90-day mean vertical profiles of heating effects of condensation (red solid line), evaporation (red dotted line), deposition (blue solid line), sublimation (blue dotted line), and fusion (green line), with height.
Figure 15. Heat source (top) and moisture sink (bottom) time series model data averaged over NSA DYNAMO for 90 days.
Figure 16. Vertical profiles of $Q_1$ (red) and $Q_2$ (blue) averaged over each MJO stage during MJO1 (top) and MJO2 (bottom)
Figure 17. Updraft (left) and Downdraft (right) mass flux during 90 days of NSA DYNAMO. Downdraft mass flux is about half of the Updraft mass flux during periods of convection and higher forcing in lower and middle troposphere.
Figure 18. The 90 day averaged vertical profile of the cloud mass flux with updraft mass flux (red), downdraft mass flux (blue) and total cloud mass flux (green).
Figure 19. The updraft mass flux (red), downdraft mass flux (blue) and total cloud mass flux (green) vertical profiles averaged during each MJO stage for MJO1 (top) and MJO2 (bottom).
Figure 20. Frequency of clouds by cloud top and cloud base over the period of NSA DYNAMO. Threshold for clouds are 0.05 g kg\(^{-1}\). Three cloud types present; deep convective towers, stratiform clouds, and anvil cirrus.
Figure 21. Cloud distribution frequency based on produced MJO stages for MJO1 in October. Stages are suppressed (top left), developing (top right), mature (bottom left) and decay (bottom right).
Figure 22. Same as Figure 16 but for MJO2 in November
Figure 23. Cloud top and base height frequency distribution for 500 m resolution model output for 90 days over NSA DYNAMO.
Table 1. The 90-day mean values of domain-averaged model radiation compared to observational radiation, including top of atmosphere longwave up, shortwave down, and surface longwave up and down and shortwave up and down. Measured in Watts per meter squared.

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