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RELEVANCE OF LARGE-SCALE SUBSIDENCE AND CUMULIFORM BUOYANCY TO MJO CONVECTIVE ONSET

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1. INTRODUCTION

Observations, reanalysis, and regional modeling simulations support a dynamic mechanism that explains onset of convectively active periods of the Madden-Julian Oscillation (MJO) over the Indian Ocean. Observations made during DYNAMO (Yoneyama et al. 2013) confirm that clouds moistened the middle troposphere prior to MJO onset over the Indian Ocean (Powell and Houze 2015a; Ruppert and Johnson 2015). Ground- and space-borne observations (Powell and Houze 2013, 2015b) indicate that the clouds responsible for the moistening existed within a 3–7 day long "transition" period during which the cloud population was dominated by "congestus"-like cumuliform elements that grow vertically above the boundary layer and often to around 500 hPa. Figure 1 illustrates a schematic from Powell and Houze (2013) that outlines the transition from suppressed convection to convective active MJO conditions. The red and blue curve at the top of the figure illustrates an idealized time series of the magnitude of wavenumber 1 anomaly in vertical motion at 500 hPa. Figure 2, adapted from Powell and Houze (2015a), indicates the change in the clear-sky adiabatic and radiative heating rates caused by the reduction of large-scale subsidence (like that seen in Fig. 1) between a time late during the suppressed MJO period to 4 days later, during the transition period. The reduction of subsidence caused by the wavenumber 1 feature apparently cools the lower troposphere, causing a steepening in the lapse rate below 500 hPa that made the environment more conducive to development of moderately deep convection.

2. MODEL

Version 3.5.1 of the Weather Research and Forecsting (WRF) model was used to replicate the development of two MJO events observed during DYNAMO. Each simulation was started several days before the observed transition periods began and was intergrated past the beginning of each convectively active MJO event. Grid spacing was 2 km, and 38 vertical levels were included. The domain extended from

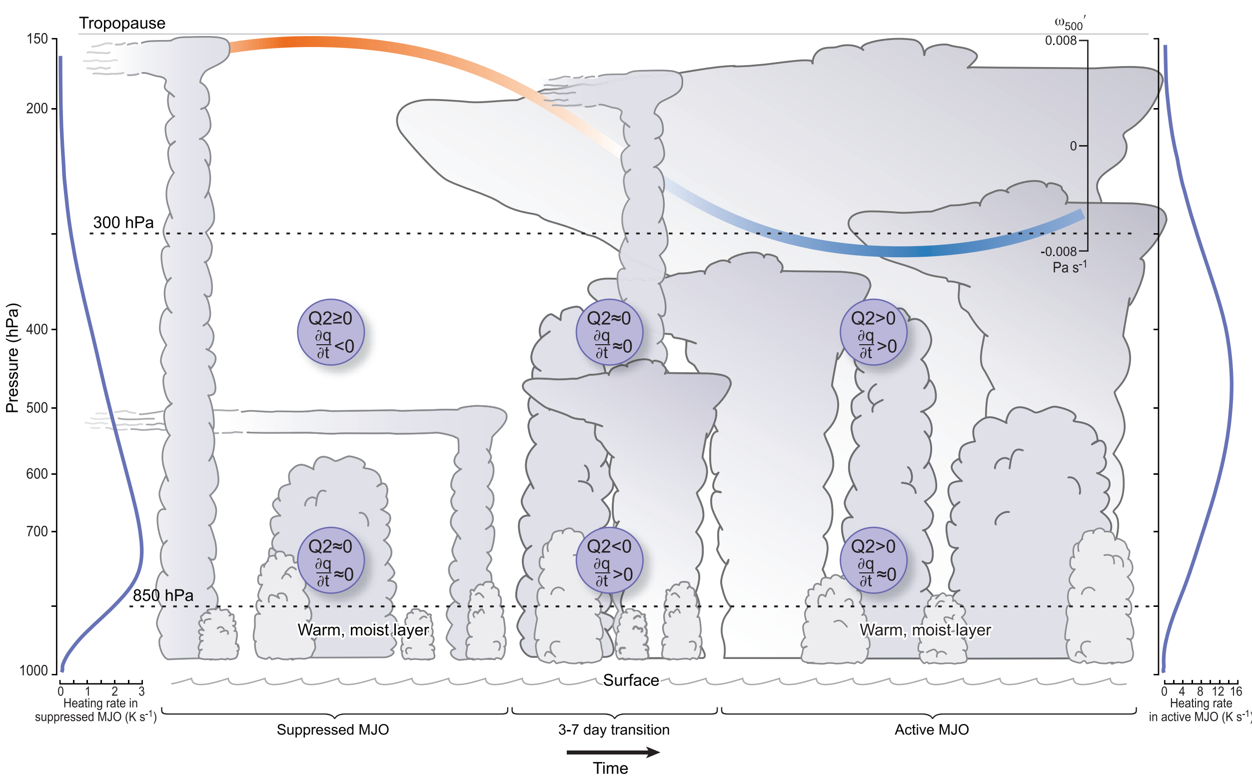

***Figure 1**: Schematic of the vertical growth of the cloud population over the Indian Ocean during suppressed and active MJO conditions, and during the 3–7 day long transition periods between them.*

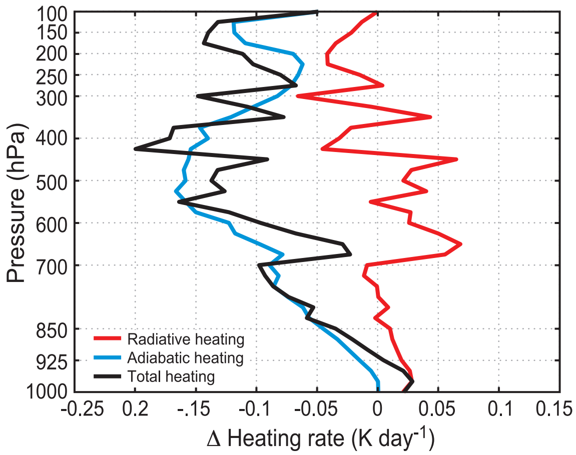

***Figure 2**: Changes in adiabatic (blue) and radiative (red) heating rates directly associated with the reduction in wavenumber 1 large-scale subsidence that occurs between suppressed and transition periods.*

roughly 58–88°E and 10°S–10°N, thus including much of the central equatorial Indian Ocean, the region where MJO convective onset occurred during DYNAMO. Simulated time series of precipitation, echo top heights, and vertical profiles of relative humidity closely matched fields derived from ERA-Interim or Tropical Rainfall Measuring Mission (TRMM) data. The simulations serve as an extended, high-resolution reanalysis of the MJO convective onset region and allow for analysis of how an ensemble of individual cloud elements grows within a changing large-scale environment.

3. RESULTS FROM WRF SIMULATIONS

Each model simulation developed distinct transition periods in the cloud population prior to MJO convective onset. During such periods, results confirm that moderately deep (above the boundary layer and up to about 500 hPa) cumulonimbus clouds moistened the troposphere. Vertical flux of moisture within precipitating elements and horizontal flux of moisture away from cloudy regions in the clear-air environment were the largest contributors to moistening. Because deep convection formation is sensitive to lower tropospheric humidity, it is presumed that moistening the lower and middle troposphere is a necessary process that must occur before widespread deep convection (i.e. a convectively active MJO) can develop. Observational and modeling results now indicate that clouds moistened the environment during DYNAMO. However, modeling results can also address what caused transition periods to develop.

Most tropical cumuliform convection is rooted in the boundary layer, and the distribution of the depth of such convection has three modes (Johnson et al. 1999): One in the boundary layer, one near the 0°C level, and one near the tropopause. This likely occurs because climatologically stable layers in the tropics occur above the boundary layer between 600–800 mb (Zuidema 1998) and near the 0°C level. Convection can only penetrate the 600–800 hPa stable layer if it possesses large buoyancy as it exits the boundary layer or if it penetrates into a region that is locally favorable for the convective updraft to continue moving upward. Over the Indian Ocean, shallow cumulus clouds are nearly ubiquitous, even during convectively suppressed conditions. However, if the properties of the boundary layer convection—or the environment above the boundary layer into which such convection penetrates—changes, then a larger amount of such convection can grow into moderately deep cumulus/cumulonimbus clouds.

Buoyancy can be approximated as the following:

$$B \approx g\left(\underbrace{\frac{T^*}{T_e}}_{Temperature} - \frac{\overbrace{p^*}^{Pressure}}{p_e} + \underbrace{0.608\left(q^*\right)}_{Vapor} - \overbrace{q_H}^{Hydrometeor} \right) \quad (1)$$

in which subscript *e* represents a value in the environment surrounding a cloud updraft, and superscript * represents the difference between the in-cloud updraft value and the environmental value. The buoyancy is affected by four variables, which are shown respectively in Eq. (1): temperature, pressure (geopotential), specific humidity, and hydrometeor mixing ratio. Figure 3 shows the impacts of each term on the mean buoyancy in the 700–850 hPa level during the simulation for the October MJO event observed during DYNAMO. During 8–9 October, the mean buoyancy (black) rapidly becomes less negative and nears zero. The temperature term (green) is the major contributor to the increase in mean buoyancy in the

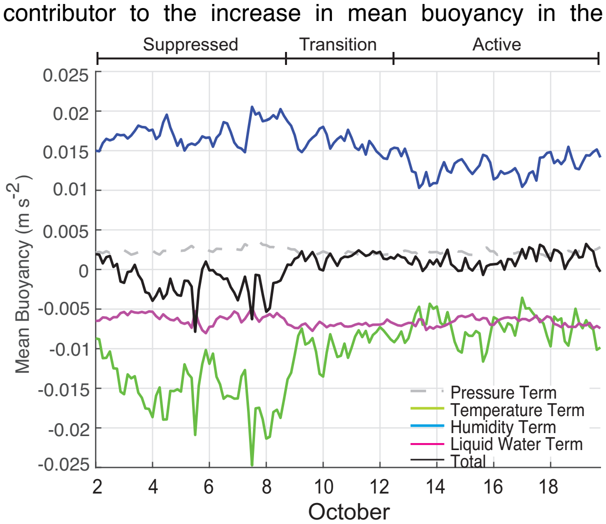

***Figure 3**: Mean buoyancy of simulated convective updrafts between 700–850 hPa. The buoyancy is separated into four terms as described in the text.*

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layer. As indicated at the top of the figure, the reduction in negative mean updraft buoyancy corresponds with the start of a transition period. Additional results indicate that the cooling of the environmental temperature on order of 0.1K is the apparent cause of the onset of transition periods in the model. Environmental cooling is caused by reduction in subsidence, although, horizontal advection of lower temperature in the clear-air environment may also play an important role.

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