Modulation of radiative heating by the Madden-Julian Oscillation and convectively coupled Kelvin waves as observed by CloudSat

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[1] The vertical distribution of radiative heating affects the moist static energy budget and potentially the maintenance and propagation of the Madden-Julian Oscillation (MJO). This paper uses CloudSat data to examine the radiative heating climatology in the tropics and the vertical structure of its modulation by the MJO and convectively coupled Kelvin Waves (KWs). Composites of active regions of the MJO and KW both show positive radiative heating anomaly in the middle and lower troposphere and slightly negative radiative heating anomaly in upper troposphere. Such bottom-heavy profiles can help to strengthen the MJO while weaken the KWs. Another finding is that cloud condensate anomalies associated with the MJO are significantly more bottom-heavy than those of the KWs, while the radiative heating anomalies associated with the MJO are only very slightly more bottom-heavy. **Citation:** Ma, D., and Z. Kuang (2011), Modulation of radiative heating by the Madden-Julian Oscillation and convectively coupled Kelvin waves as observed by CloudSat, *Geophys. Res. Lett.*, *38*, L21813, doi:10.1029/2011GL049734.

1. Introduction

[2] Although the Madden-Julian Oscillation (MJO) was first identified 40 years ago [*Madden and Julian*, 1971] and has long been recognized as an important phenomenon, it is still not well understood. The MJO features planetary scale circulation and convection signals in the tropics that propagate eastward at a speed of around 5 m/s. The convective signals of the MJO are clearly seen in the Outgoing Long-wave Radiation (OLR) data, and its temperature, moisture and wind structures have been quite well documented [e.g., *Wheeler and Kiladis*, 1999; *Kiladis et al.*, 2005; *Zhang*, 2005]. Besides being the dominant intraseasonal variability in the tropics, the MJO also affects the El Nino-Southern Oscillation, tropical cyclones, Asian and Australian monsoons, and mid-latitude weather [e.g., *Zhang*, 2005]. The persistent difficulty in simulating the MJO with general circulation models highlights our insufficient knowledge of how the atmosphere operates in the tropics [e.g., *Lin et al.*, 2006; *Kim et al.*, 2009], and improved prediction and understanding of the MJO would also benefit weather and climate forecasts.

[3] A recently emerged view of the MJO is that, unlike the fundamentally buoyancy driven convectively coupled waves, processes that alter the column integrated moist static energy (MSE), are essential to the existence and the propagation characteristics of the MJO [e.g., *Raymond and Fuchs*, 2007; *Sobel et al.*, 2008; *Maloney*, 2009]. Radiative heating is known to be an important example of such a process. The extensive clouds in the active regions of the MJO, which have higher column-integrated MSE and enhanced convection, reduce the radiative cooling and help to amplify the original column MSE anomaly. Combining surface and top of the atmosphere radiative flux measurements, *Lin and Mapes* [2004] found that column integrated radiative heating anomaly is nearly in phase with the precipitation anomaly with a magnitude around 10–15% of the heating associated with the precipitation. Because column integrated radiative heating represents a net source of column integrated MSE, this amount is very significant, comparable to the amount of column MSE export associated with the divergent flow. Because of this importance, radiative feedback is invoked in a number of simple models of the MJO and the tropical mean circulation [e.g. *Raymond*, 2001; *Tian and Ramanathan*, 2003; *Bony and Emanuel*, 2005; *Sugiyama*, 2009].

[4] In addition to its column integral, the vertical distribution of radiative heating can also be important because it affects the efficacy of the circulation that arises in response to this radiative heating in importing or exporting column MSE. As briefly discussed by *Kuang* [2011] and confirmed by cloud-resolving model simulations, if the radiative heating is concentrated in the lower troposphere, the divergent circulation that arises to balance this heating results in more import of column MSE and further enhancement of convection. On the other hand, if the radiative heating is concentrated in the upper troposphere, the divergent circulation that arises results in more export of column MSE. Thus, for the same amount of column integrated radiative heating, a more bottom-heavy profile will result in a stronger response in the precipitation.

[5] The goal of this paper is to constrain the vertical distributions of radiative heating anomalies associated with the MJO using radiative heating profiles from CloudSat, which are derived from its multiyear global reflectivity measurements from the 94 GHz Cloud Profiling Radar (CPR) [*Stephens et al.*, 2002]. Previous studies have used CloudSat to examine cloud structures associated with the MJO and the boreal summer intraseasonal variabilities [*Masunaga et al.*, 2008; *Riley et al.*, 2011; *Jiang et al.*, 2011]. In addition to results for the MJO, we will also present the results for convectively coupled Kelvin waves (KWs). While radiative feedback is not believed to be essential for the existence of convectively coupled waves [e.g., *Mapes*, 2000; *Khouider*

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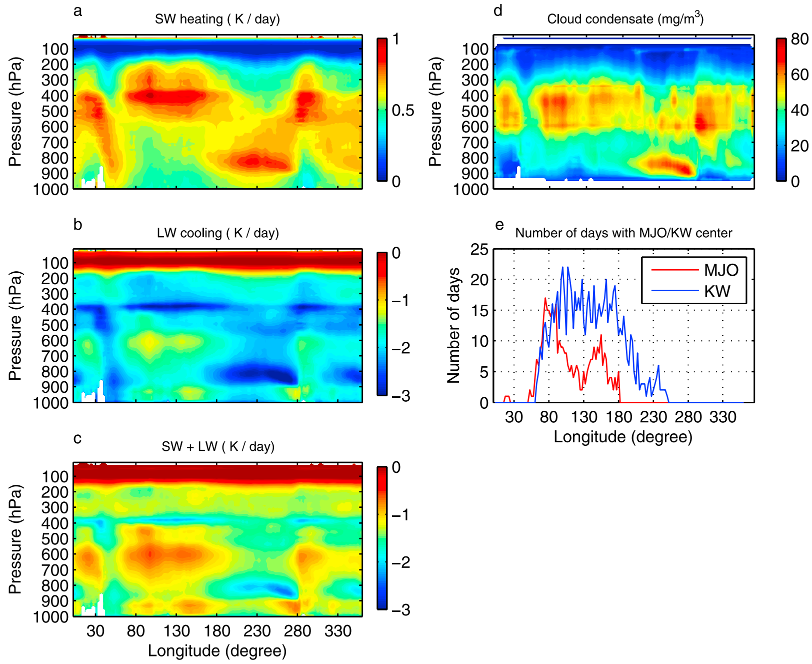

Figure 1. The 4-year climatology of radiative heating averaged between 10°S and 10°N (a) SW, (b) LW, (c) total radiative heating, (d) total cloud water content, and (e) the number of days for which the identified active centers of the MJO/KWs fall in a particular 2.5° longitude bin.

and Majda, 2006; *Kuang*, 2008a, 2008b; *Andersen and Kuang*, 2008], how radiative heating is distributed vertically could still modify the characteristics of these waves.

2. Data and Method

[6] We use radiative heating, cloud water/ice, water vapor and temperature data from CloudSat. The level 2 radiative fluxes and heating rates algorithm (2B-FLXHR) of CloudSat produces vertically resolved radiative heating data set based on the results from CloudSat's CPR. Cloud water/ice content data is provided by the level 2 radar-visible optical depth cloud water content product (2B-CWC-RVOD), using a combination of measured radar reflectivity factor and estimates of visible optical depth. Radiation and cloud data from Sep. 1, 2006 to Aug. 31, 2010 are used. We also analyzed temperature and water vapor data contained in the ECMWF-AUX product of CloudSat, which is derived from the European Center for Medium-Range Weather Forecasts reanalysis. Temperature and moisture structures associated with the MJO have been extensively documented before [e.g., *Kiladis et al.*, 2005; *Tian et al.*, 2006] and are included here only for reference. Only one year of the temperature and water vapor data (from Sep. 1, 2006 to Aug. 31, 2007) was used, which already yielded clear signals for our purpose. We shall use the 2.5° latitude × 2.5° longitude global NOAA Interpolated daily mean outgoing Longwave Radiation (OLR) dataset to identify the MJO and Kelvin wave events.

[7] A major limitation of this work is that radiative heating and cloud condensate are derived products instead of raw measurements such as the radar reflectivity. The cloud condensate products are retrieval results based on a priori lognormal size distributions constrained by the measured radar reflectivity. The products also have issues in heavily precipitating scenes because of radar attenuation and deviations from log-normality. The radiation fields are results from further radiative transfer calculations based on the cloud condensate values and reanalyzed temperature and moisture data. Despite these uncertainties, the CloudSat data represent our best current estimates of global cloud condensate and radiative heating rate distributions and it is worthwhile to have a first look at the modulations of these fields by the MJO and the KWs. Furthermore, atmospheric layers with heavy precipitation are in general already optically opaque so that radiative heating rates there are not sensitive to changes/errors in the cloud condensate retrievals, as we have verified in offline radiative transfer calculations. One might also reasonably expect differences seen between the composite structures of the MJO and the KWs to be less sensitive to the aforementioned uncertainties.

[8] To construct the MJO composite, we first average OLR data along the equator (between 10°S and 10°N), and then filter the data according to the space-time spectral window of the MJO (zonal wavenumber 0.5–9.5, frequency 0.01–0.05), following the approach of *Wheeler and Kiladis* [1999]. For each day, the local minima of the filtered OLR with values less than −20 W/m^2 are identified, and labeled as the "active convective centers". CloudSat data within 10°N/S are then binned according to their relative position to the active convective center of the MJO on the day they were collected to produce a composite structure. KWs composites are constructed similarly. With this simple procedure, we have neglected regional differences in MJO and KW structures.

3. Results

[9] To provide a context for the anomalies to be discussed, we present in Figure 1 the 4-year (Sep. 1, 2006–Aug 31, 2010) averages of (a) shortwave (SW), (b) longwave