論文内容の要旨

論文題目　Madden-Julian 振動における降雨バンドに伴う
運動量の輸送効果に関する研究

(A Study on the Effects of Convective Momentum Transport
Associated with Rain Bands within the Madden-Julian Oscillation)

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Madden-Julian Oscillation (MJO) is the most significant atmospheric variation in the tropics, and its reproduction is one of the major issues for current General Circulation Models (GCMs). Using the output data of the MJO 2006 experiment conducted by *Miura et al.* (2007) in a global cloud resolving Non-hydrostatic Icosahedral Atmospheric Model (NICAM, *Satoh et al.* 2008), the author analyzed the Convective Momentum Transport (CMT) in relation with the phase of a successfully reproduced MJO. It was found that, at the altitude of 2km-6.5km, CMT in ensemble worked effectively to slow down the eastward propagation of the westerly wind involved with the MJO convection.

Convective momentum transport of subgrid-scale cloud systems are a well known source of uncertainty in current GCMs. In GCMs, CMT are usually, if at all, parameterized as a mixing component which operates to reduce environmental wind shear (down gradient). However, it has long been known that organized Meso-scale Convective Systems (MCSs) often involve CMT that produce or intensify environmental wind shear (up gradient); squall line type MCSs are typically up gradient in the direction perpendicular to the line alignment. By directly calculating the clouds without using cumulus parameterization, NICAM permits such up gradient CMT, and has possibly overcome this uncertainty due to inaccurate representation of CMT effects. Since NICAM succeeded in reproducing the MJO, it is worth examining what roles CMT has played in the achievement.

Despite a successful reproduction of the MJO with NICAM, accurate parameterization of CMT effects remains to be a major issue, since the state-of-the-art super computer resources are not sufficient to perform long term integrations using global cloud resolving models, while satisfactory MJO reproduction is necessary in meeting social expectations such as long-range weather forecast or prediction of global climate change.

Setting the long term goal on the development of a cumulus scheme relevant to up gradient CMT, the objectives of this study were (I) to clarify the distribution structure of CMT acceleration involved in rainbands within the MJO convection, (II) to quantify their ensemble impacts on the environmental zonal wind, and (III) to analyze what components account for the ensemble. The results of analysis aimed on (I), (II), and (III) are respectively shown in the 4th, 5th, and 6th chapter of this paper, succeeding preliminary results shown in chapter 3.

In chapter 3, center of the MJO convection was located; meso-scale rainbands produced by NICAM and those retrieved from the Tropical Rainfall Measurement Mission Microwave Imager (TRMM/TMI) were compared; MJO wind structures produced by NICAM and re-analysis were compared. The average propagation speed of the MJO center between 100° - 170° E was 1.08° / (6hours) ≈ 4.8m/s. In the output data of NICAM, 162542 rainbands were identified, and the frequency distributions of the rainbands were in good agreement with those observed by TMI. Area within 100° - 170° E, 12° S-12° N was selected for further analysis due to the large number of rainband cases identified in it and their relatively homogeneous distribution. In this analysis region, 60997 cases were found, 15221 cases of which came along with complete 3-d dataset necessary to calculate CMT. The axis alignment of NICAM rainbands showed an overall preference to the east-west direction, but for those having large area and located between -20° to 0° from the MJO center tended to be closer to southeast-northwest direction. Similar preferences were observed in TMI rainbands, but the data amount of TMI was not enough to show the significance of the latter tendency. Average wind structure of MJO produced in NICAM and that of JCDAS agreed reasonably.

In chapter 4, an MJO-relative composite structure of the acceleration due to CMT is displayed, after a check on temporal representability of 6-hourly CMT data. Six-hourly snapshot data proved to be sufficient to represent the characteristics of CMT and its upscale effect on the environmental horizontal wind. Equatorial rainbands that involve strong upscale acceleration to the environment were most frequently found between -20° to 0° from the MJO center. Their upscale zonal acceleration ensemble formed a three-storied structure: positive at lower levels (below 1.6km); negative at mid levels (2km-6.5km); postive at upper levels (above 11km). At 7km-10km, both negative and positive acceleration were found and the inclination was unclear.

In chapter 5, the impact of upscale acceleration of the CMT ensemble on the environmental zonal wind $\bar{u}$ was quantified, and under an assumption that the MJO structure does not change, the author estimated the expected modification in phase speed of the MJO when the CMT effects were ignored. The upscale acceleration due to CMT accounted for -160% on the 2km-6.5km averaged wind difference between +20° and -30° from the MJO center. In the absence of CMT effects, $\partial\bar{u}/\partial t$ would increase to 260% of its original value; provided that the MJO structure does not change, the eastward propagation of the westerly wind at 2km-6.5km would become 2.6 times faster. The accelerated eastward propagation of the westerly wind (2km-6.5km) is likely to lead to earlier triggering of new convection to the east of the MJO, and in a view that the wind structure of the MJO is a response to convective heating, it is suggested that the eastward propagation speed of the entire MJO may also increase by 2-3 times of the original speed.

In chapter 6, the CMT components that account for the three-storied structure were explored; rainbands were sliced into height-longitude sections, each 2-d structure of up/down drafts in the height-longitude sections were identified, and the 2-d structures were further divided and classified into groups according to the types of CMT they involve. While more than half of the negative acceleration of 2.5km-6km were due to the contribution from updrafts involving up gradient CMT, the contribution from updrafts that mix the mid-level (2.5km-6km) with the upper levels (above 7km) and contribution from rear-inflow type down drafts were also relatively large.

It is concluded in correspondence with the objectives of this study (I) - (III) that:

(1) CMT involved with rainbands within the MJO has a clear preference to construct into a three-storied structure which positively/negatively/positively accelerate environmental zonal wind at the lower/middle/upper levels.

(2) The acceleration due to CMT has large impact on the change of environmental zonal wind (up to -160% at mid-levels), possibly having strong control over the phase speed of the MJO.

(3) Both up/down gradient CMT largely account for such strong impacts.

It is strongly suggested that cumulus parameterization relevant to the effects of up gradient CMT is necessary for GCMs in order to reproduce the MJO in satisfactory. According to the past works done by others and to the preference for the southeast-northwest direction found in the axis alignment of large rainbands located between -20° to 0° relative to the MJO center, it is speculated that the up gradeint CMT were involved with rainbands having north-south component in their alignment; they are likely to evolve under conditions in which a low-level (1000hPa-800hPa) zonal wind shear exist. However, such relationships of environment and CMT cannot yet be discussed quantitatively enough, and the direct connection between the environmental condition and CMT ensemble effects remains as a major issue to be clarified.