Influence of QBO-MJO connection on the turbulence variation in the TTL observed with equatorial atmosphere radar

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Abstract. Atmospheric turbulence triggers vertical transport of heat and material exchange within troposphere and the stratosphere known as Stratosphere-Troposphere Exchange (STE). This phenomenon occurs in Tropical Tropopause Layer (TTL), a transition layer within 14-18.5 km. The state of TTL is the key to understand how phenomena in the troposphere and stratosphere interact. The interaction between Quasi-Biennial Oscillation (QBO), a zonal wind oscillation in stratosphere, and Madden-Julian Oscillation (MJO) defined as an eastward moving disturbance of convective system in the previous study is closely linked in boreal winter. This study presents the variation of turbulence intensity toward QBO-MJO interaction in TTL calculated from spectral width observed with Equatorial Atmosphere Radar (EAR) located in Agam, West Sumatra (0.2°S, 100.32°E). Analysis is focused on the extended boreal winter period. Turbulence intensity (σ_turb) in TTL tends to have an inversely proportional value toward zonal wind in 50 hPa. Generally, enhancement of turbulence intensity is observed on active phase MJO. Zonal wind and vertical wind are stronger in active phase MJO occurred in QBOE than QBOW that can lead to increase turbulence intensity in TTL. These parameters intensification is associated with stronger convective and precipitation system during QBOE-MJO that is caused by more unstable atmosphere.

Keywords: EAR, turbulence, TTL, QBO-MJO connection.

1. Introduction

Madden Julian Oscillation (MJO) is an eastward moving large convective system that recurs every 30 to 100 days in equator [1]. As major fluctuation in tropical weather on weekly to monthly timescales, the MJO convective system may associate with extreme precipitation and lead to environmental hazards [2]. A stratospheric phenomenon that was recently observed to have connection with MJO is Quasi Biennial Oscillation (QBO). QBO is an alternating zonal wind in the stratosphere with 24-28 months period due to interaction of gravity wave and background wind [3]. Previous study found that around...
40% of MJO activities is related to QBO in boreal winter [4]. MJO activities is significantly stronger during QBO easterly phases (QBOE) as the tropopause is higher and colder that can lead to lower static stability and the vertical wind shear is weaker, hence the convective system is stronger than in QBO westerly phases (QBOW) [3][5]. Martin et al. [6] conducted a set of simulations that combined change in tropopause temperature and wind shear to describe the interaction between QBO-MJO and found that temperature change in the tropical tropopause layer (TTL) has more significant effect towards convective intensity than change in wind shear. The TTL tend to have lower temperature in QBOE than QBOW. This evidence shows that the state of TTL is the key to understand stratosphere-troposphere interaction.

TTL is the transition layer between troposphere and stratosphere spanning from 14 – 18.5 km [7]. The TTL acts as a gate to the stratosphere and understanding all relevant processes are essential for better prediction in the future climate. The turbulence phenomenon in the TTL is responsible for vertical transport of heat and materials between the troposphere and stratosphere [8]. However, the variation of turbulence toward QBO-MJO interaction remains unknown due to the scarcity of data observation. This study presents a turbulence variation in TTL associated with MJO in different QBO phases using high vertical resolution Equatorial Atmosphere Radar (EAR) data. The data used and methodology are explained in the following section.

2. Data and Methods
This study is mainly based on observational data analyses from EAR located in Agam, Sumatra Barat, Indonesia (0.2°S, 100.32°E, 865 m) starting from June 2001 to December 2019. Additional analysis of the convective system has done using precipitation data from Tropical Rainfall Measuring Mission (TRMM) 3B42 product and Outgoing Longwave Radiation from European Centre for Medium-Range Weather Forecast (ECMWF).

2.1. Equatorial Atmosphere Radar
EAR is a circular antenna array radar approximately 110 m in diameter that incorporate 560 three-element Yagi antennas. Each EAR antenna is driven by a solid-state transmitter-receiver module with 180 W peak output power to produce total peak output power of 100 kW. The active phased-array antenna system enables the EAR to steer radar beams on a pulse-to-pulse basis [9]. EAR is high-resolution Doppler radar in spatial and time, up to 150 m and 10 minutes. The radar has five output variables: echo power, spectral width (σ_νobs), and 3D wind calculated from Doppler velocity received in five beam directions (vertical, north, south, west, east). This study used northward beam to minimize the shear broadening effect following Fujiwara et al. [10]. The observed spectral width (σ_νobs) consists of four components: turbulence motion (σ_νturb), beam broadening effect (σ_νbroad) that caused by the difference in doppler velocity in a finite radar beam width, shear broadening effect occur due to the background wind change in a volume atmosphere and the last is transience of air motions during the data integration time (85 s), mainly caused by the Brunt–Väisälä oscillation. The value of transience and shear broadening effect are negligible that is concluded from the scale analysis [10]. Thus, turbulence intensity can be expressed with equation (1)

\[ σ_νturb^2 \approx σ_νobs^2 - σ_νbroad^2 \]  

(1)

The beam broadening effect calculated from half-power half-width EAR (Δν; 1.7°) and horizontal wind shown in equation (2) [11]. Thereafter turbulence intensity obtained from equation (1) rescaled to daily time resolution.

\[ σ_νbroad \approx \frac{Δν}{2} |U_h| \]  

(2)

Previously, data quality control was carried out by eliminating data values that is more than three standard deviation, so that error in the equipment or data recording does not interfere accuracy of the results.
2.2. MJO index
The MJO phase and amplitude determined by Real-Time Multivariate MJO index (RMMI) [12] and centralized on phase 4, following EAR location. We define Lag-0 as the first day MJO convective passing through EAR. This research focused on the QBO-MJO connection during extended boreal winter (November to March) to obtain larger sample sizes that those from traditional definition of winter season (December to February) [13]. We identified a total of 46 MJO events from the analysis period of 2001–2019.

2.3. QBO index
In this study, the QBO is defined by zonal-mean zonal wind data at 50 hPa averaged over 10°S–10°N (U50) provided by National Oceanic and Atmospheric Administration (NOAA). When the seasonal-mean U50 smaller than 0.5 standard deviation, it is set to the QBOE phase. Likewise, the opposite is set to the QBOW. We grouped all identified MJO events into QBOE and QBOW. A given MJO event considered to be in QBOE (QBOW) if its mid-date, defined as the midpoint between its starting and ending dates, falls within QBOE (QBOW) month or when the zonal wind is less than -3.8 (greater than 3.8). By these definitions, there are total 17 MJO events during QBOE, 16 events during QBOW, and 13 events during QBO transition.

2.4. OLR and precipitation
MJO can be identified by eastward propagating negative anomaly of outgoing longwave radiation (OLR). This study used OLR data from ERA5 ECMWF. Precipitation events are identified using the daily Tropical Rainfall Measuring Mission (TRMM) 3B42 version 7 (3B42v7) Multi-satellite Precipitation Analysis [14]. Both datasets cover a period of 2001–2019 with 0.25° spatial resolution. The datasets then rescaled into daily temporal resolution. After that, datasets classification was carried to identified QBO phases and averaged between 5°N-5°S and 97.5°E-102.5°E to represent EAR region.

3. Results
Section 3.1 will discuss the interaction between turbulence and zonal wind at 50 hPa considered as QBO phenomena. The evolution of turbulence and wind velocity through MJO events is in the following section. Section 3.3 explains turbulence and wind variation by MJO-QBO link. The possible source of turbulence will show later in the discussion part.

3.1. Turbulence intensity and zonal wind
We will first discuss about how turbulence intensity is associated with zonal wind in 50 hPa. Figure 1.a shows turbulence profile and the region between red lines define the TTL region. Turbulence has low intensity in the lower troposphere region, then the intensity builds up after 10 km and reaches its peak near the TTL. This growing intensity mainly caused by wind shear enhancement after approaching TTL, considering that \( \sigma_{\text{turb}} \) is proportional to wind shear [10].

Time series of mean monthly \( \sigma_{\text{turb}} \) in TTL region (blue line) and U50 (magenta line) is presented in figure 1.b. Qualitatively, the value of \( \sigma_{\text{turb}} \) tends to be inversely proportional with U50. For example, in 2003, zonal wind is in peak of positive phase and associated with low turbulence intensity. Zonal wind phase is in negative during 2006 while turbulence intensity is high. The possible explanation following previous study is when the zonal wind is in negative phase, the atmospheric stability will be lower than positive phase of zonal wind so that the turbulence intensity tends to increase [5].
Figure 1. a) Turbulence vertical profile. TTL is defined by region between red lines, b) Time series of turbulence ($\sigma_{turb}$; black) and 50 hPa zonal wind (magenta) from NOAA.

Under normal conditions, a low value of $\sigma_{turb}$ coincides with the positive zonal wind phase. However, a special case was found in 2010, 2016, 2019. The phenomena occur after strong El Nino in the previous year. Previous study by Kawatani [15] showed that El Nino phenomena have impact on QBO period. El Nino produce more convective activities that lead to greater gravity waves released and finally accelerate the QBO phase change.

3.2. Turbulence and wind evolution during MJO

A Composite of turbulence and related parameters during MJO event was carried out to examine the relationship between MJO and turbulence intensity. Figure 2 a) shows composite time series of $\sigma_{turb}$ from 15 days before and after MJO to show the evolution of each parameters. Turbulence intensity at 12-16 km before active MJO is 0.7 – 0.8 m s$^{-1}$. After MJO event, the value increases to 0.8-1.1 m s$^{-1}$. Furthermore, the turbulence intensity of 0.8-0.9 m s$^{-1}$ is in 16 km and tends to rise at 17 km in Lag-0.
Figure 2. Time height section of a) Turbulence ($\sigma_{turb}$), b) Zonal wind, and c) Vertical wind. Lag-0 is the first day when MJO in phase 4.

Figure 2.b shows a zonal wind composite for all MJO events. According to the composite, we observed strengthening of zonal winds reaching $-20 \text{ m s}^{-1}$ at 15-17 km and $4 \text{ m s}^{-1}$ in 18 km after MJO. This pattern is consistent with the strengthening of the turbulence intensity after the MJO, which indicates the influence of wind shear.

The vertical wind strengthens slightly before Lag-0 and continues after 15 days (figure 2c). Significant vertical flow reinforcement is seen at an altitude of 13-15 km with value $4-8 \text{ cm s}^{-1}$. This strengthening is caused by updraft (vertical upward motion) of water vapor which is closely related to the convective system. When MJO passes through EAR (Lag-0), a mass of moist air is lifted and promote the formation of convective system.

3.3. Turbulence and wind evolution during MJO

According to figure 2, the MJO phenomena are related to the turbulence intensity fluctuation measured by the EAR. Meanwhile, recent research found that MJO in the troposphere is related to stratospheric phenomena, Quasi Biennial Oscillation [4][13][16]. This section discusses the influence of the QBO-MJO interaction on turbulence and wind intensity.
Figure 3. a) Turbulence and b) Vertical wind difference between QBOE and QBOW (QBOE – QBOW).

The difference in vertical wind activity between QBOE and QBOW is shown in figure 3. The significant enhancement of vertical wind is seen in QBOE. The vertical motion intensifies around Lag-2 and continues until Lag+15, which is consistent with the pattern of turbulence intensity in 16-18 km (figure 3). These intensification variables concentrated at 12-15 km. The updraft only seemed to strengthen on Lag-0 day in QBOW. Similar pattern is also shown in QBON with lower intensity.

During the QBOE phase, the upper troposphere tends to be more unstable indicated by a small $N^2$ value. Unstable atmospheric conditions will support updraft and produce higher vertical wind activity in the QBOE phase [17]. Unstable atmospheric conditions also indicate turbulence activity.

4. Discussion
Figure 4 shows time-height section of turbulence and zonal wind and time series of OLR along with precipitation in different phase of QBO. Before MJO passes phase 4 (Lag-0), precipitation increase along with decreased OLR, especially in QBOE, as shown in figure 4 c) and f) for QBOE and QBOW, respectively. Thus, we can conclude that the higher precipitation can cause turbulence intensity to be higher due to lower atmospheric instability.
In general, turbulence intensification at TTL is more visible at QBOE and consistent with zonal wind reinforcement. An interesting pattern of turbulence intensity occurs during QBOW, the value is higher at 12-14 km and 16 km than other region along with intensification of precipitation. The area coincides with the height of the convective outflow that makes possible explanation of turbulence reinforcement is due to the local diurnal convective system which will indeed strengthen during QBOW.

5. Conclusion
Recent study found QBO-MJO has strong connection in boreal winter. The key concept on how these phenomena interact is in the TTL. The TTL turbulence is responsible for vertical transport of heat and materials between the troposphere and stratosphere. Therefore, the urge of turbulence research is essential to understand troposphere stratosphere interaction. This study highlights the variation of turbulence intensity that associated with MJO in different QBO phases. We estimated turbulence intensity using spectral width data obtained by EAR throughout 2001-2019. The turbulence tends to be higher in QBOE along with enhancement of vertical wind activity. The possible reason for this higher intensity turbulence is greater activity of convective system in QBOE. The enhancement of turbulence intensity was observed during MJO in QBOE phase, along with enhancement of zonal wind and updraft that showed in strengthening of vertical wind. This enhancement is presumed to be associated with stronger convective and precipitation system before Lag-0, that lead to more unstable atmosphere in QBOE.

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References

[1] Zhang C 2005 Madden-Julian Oscillation. Rev. Geophys., 43, RG2003.
[2] Zhang C and Ling, J 2017 Barrier effect of the Indo-Pacific Maritime Continent on the MJO: Perspectives from tracking MJO precipitation. Journal of Climate, 30(9), 3439-3459.
[3] Baldwin M P, Gray L J, Dunkerton T J, Hamilton K, Haynes P H, Randel W J, Holton J R, Alexander M J, Hirota I, Horinouchi T, Jones D B A, Kinnersley J S, Marquardt C, Sato K., and Takahashi M 2001 The quasi-biennial oscillation. Rev. Geophys., 39(2), 179–229.
[4] Son S W, Lim Y, Yoo C, Hendon H H, and Kim J 2017 Stratospheric control of the madden-julian oscillation. Journal of Climate, 30(6), 1909-1922.
[5] Collimore C C, Martin D W, Hitchman M H, Huesmann A and Waliser D E 2003 On the relationship between the QBO and tropical deep convection. Journal of Climate, 16(15), 2552-2568.
[6] Martin Z, Wang S, Nie, J, dan Sobel A 2019 The impact of the QBO on MJO convection in cloud-resolving simulations. Journal of the Atmospheric Sciences. Journal of the Atmospheric Sciences, 76(3), 669-688.
[7] Fueglistaler S, Dessler A E, Dunkerton T J, Folkins, I, Fu Q, and Mote P W 2009 Tropical tropopause layer. Rev. Geophys., 47, RG1004.
[8] Mega T, Yamamoto M K, Luce H, Tabata Y, Hashiguchi H, Yamamoto M, Yamanaka M D, and Fukao S 2010 Turbulence generation by Kelvin-Helmholtz instability in the tropical tropopause layer observed with a 47 MHz range imaging radar. J. Geophys. Res., 115, D18115.
[9] Fukao S, Hashiguchi H, Yamamoto M, Tsuda T, Nakamura T, Yamamoto M K, Sato T, Hagio M, and Yabugaki Y 2003. Equatorial atmosphere radar (EAR): System description and first results. Radio Sci., 38, 1053.
[10] Fujiwara M, Yamamoto M K, Hashiguchi H, Horinouchi T and Fukao S 2003 Turbulence at the tropopause due to breaking Kelvin waves observed by the Equatorial Atmosphere Radar. Geophys. Res. Lett., 30, 1171.
[11] Fukao S, Yamanaka M D, Ao N, Hocking W K, Sato T, Yamamoto M, Nakamura T, Tsuda T and Kato S 1994. Seasonal variability of vertical eddy diffusivity in the middle atmosphere 1. Three-year observations by the middle and upper atmosphere radar. Geophys. Res. Lett. 99, 18973-18987.
[12] Wheeler M C and Hendon H H 2004 An all-season real-time multivariate MJO index: Development of an index for monitoring and prediction. Monthly Weather Review, 132(8), 1917-1932.
[13] Zhang C and Zhang B 2018 QBO-MJO Connection. Journal of Geophysical Research: Atmospheres. Journal of Geophysical Research: Atmospheres, 123, 2957–2967.
[14] Huffman G J, Bolvin D T, Nelkin E J, Wolff D B, Adler R F, Gu G, Hong Y, Bowman K P and Stocker E F 2007 The TRMM Multisatellite Precipitation Analysis (TMPA): Quasi-Global, Multiyear, Combined-Sensor Precipitation Estimates at Fine Scales, Journal of Hydrometeorology, 8(1), 38-55.
[15] Kawatani Y, Hamilton K, Sato K, Dunkerton T J, Watanabe S, and Kikuchi K 2019 ENSO modulation of the QBO: Results from MIROC models with and without nonorographic gravity wave parameterization. Journal of the Atmospheric Sciences, 76(12), 3893-3917.
[16] Son S W, Lim Y, Yoo C, Hendon, H H, dan Kim J 2017 Stratospheric control of the madden-julian oscillation. Journal of Climate, 30(6), 1909-1922.
[17] Nishimoto E, and Yoden S 2017 Influence of the stratospheric quasi-biennial oscillation on the Madden-Julian oscillation during austral summer. Journal of the Atmospheric Sciences, 74(4), 1105-1125