Turbulence at the tropopause due to breaking Kelvin waves observed by the Equatorial Atmosphere Radar

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[1] The Equatorial Atmosphere Radar (EAR) installed in Sumatra Island, Indonesia, observed significant enhancement of turbulence in the tropopause region, 15–17 km, intermittently for ~5 days in November 2001. The turbulence intensity was estimated with the spectral width of the radar echo power spectrum, and the turbulence during the period was a factor of up to ~5 larger in kinetic energy than that in other periods. Further analyses confirm that the enhanced turbulence was convectively generated in the breaking phase of an equatorial Kelvin wave. Between July and December 2001, we observed at least three more prominent cases of the turbulence generation by breaking Kelvin waves in the tropopause region. *INDEX TERMS:* 3334 Meteorology and Atmospheric Dynamics: Middle atmosphere dynamics (0341, 0342); 3362 Meteorology and Atmospheric Dynamics: Stratosphere/troposphere interactions; 3379 Meteorology and Atmospheric Dynamics: Turbulence; 3384 Meteorology and Atmospheric Dynamics: Waves and tides; 6952 Radio Science: Radar atmospheric physics. **Citation:** Fujiwara, M., M. K. Yamamoto, H. Hashiguchi, T. Horinouchi, and S. Fukao, Turbulence at the tropopause due to breaking Kelvin waves observed by the Equatorial Atmosphere Radar, *Geophys. Res. Lett.*, *30*(4), 1171, doi:10.1029/2002GL016278, 2003.

1. Introduction

[2] Dynamical processes responsible for the cross-tropopause transport in the tropics have been studied for half a century [e.g., *Holton et al.*, 1995]. Determining the concentrations of minor constituents and particles in the tropopause region, they directly or indirectly control the stratospheric photochemistry and the Earth's radiative balance. Yet there still is active debate even on the conceptual framework suitable for the tropical tropopause region itself as well as the dominant processes there [*Haynes and Shepherd*, 2001]. This is in part due to relative scarcity of observations in this region. In this paper, we present one of the first results of the Equatorial Atmosphere Radar (EAR) which has been operated at Bukit Kototabang (0.20°S, 100.32°E, 865 m above sea level), West Sumatra, Indonesia since July 2001. Since then we have observed some events of the turbulence generation in the breaking phase of equatorial Kelvin waves in the tropopause region. The role of Kelvin waves in the tropical stratosphere-troposphere exchange (STE) has been recently discussed on the basis of balloon-borne measurements [*Fujiwara et al.*, 1998, 2001] and a numerical experiment [*Fujiwara and Takahashi*, 2001]. These studies suggested that the turbulence generation associated with Kelvin waves plays a role in transporting stratospheric ozone into the upper troposphere, but without direct turbulence observations. We first describe the radar system and then show a case in November 2001.

2. Observation

[3] The EAR is a 47.0 MHz Doppler radar with a peak output power of 100 kW and with a quasi-circular antenna array of approximately 110 m in diameter (S. Fukao et al., The Equatorial Atmosphere Radar (EAR): System description and first results, submitted to the Radio Science, 2002; hereinafter referred to as F02). The measuring principle is illustrated in Figure 2 of *Fukao et al.* [1994] [see also *Hocking*, 1983]: The radar pulse transmitted to oblique beam directions is scattered most effectively by isotropic turbulent eddies with half the beam wavelength (~3 m) in each sampling volume of ~150 m in the range (determined by the pulse length of 1 μs) and ~600 m in the horizontal at the altitude of 16 km (determined by the two-way half-power beam width of 2.4°). The echo received by the radar is Doppler-shifted due to airmass motions, with a finite "spectral width" (Figure 1). The velocity at the peak echo power corresponds to the mean wind velocity along the beam in the sampling volume, and the spectral width is due to turbulent motions of the 3-m eddies and some contamination effects (explained later). The beam direction is electrically changed to the vertical, northward, eastward, southward, and westward on a pulse-to-pulse basis using the active phased array method (explained by F02). The four oblique beams have the zenith angle of 10°, allowing horizontal wind measurements. It takes 85 s to obtain a complete set of vertical profiles after the data integration, and in this paper we use hourly averaged data. The maximum altitude of the atmospheric measurement is ~20 km, which is determined by the transmitting power and by the antenna aperture. The vertical resolution of the data is 150 m × cos 10° for the oblique beam measurements.

[4] The observed spectral width (half-power half width), σ_{obs}, consists of three factors [*Hocking*, 1983; *Fukao et al.*, 1994]: Turbulent motions of the 3-m eddies, σ_{turb}; the broadening effects, σ_{broad}, consisting of the beam broadening effect caused by the finite radar beam width and by the background wind and the shear broadening effect caused by the changes in background wind within the sampling volume; and the contamination due to transience of air motions during the data integration (85 s), σ_{trans}, mainly caused by the Brunt-Väisälä oscillation. We use Equation 16 of *Nastrom* [1997] to estimate σ_{broad}. (Its term (I), the beam

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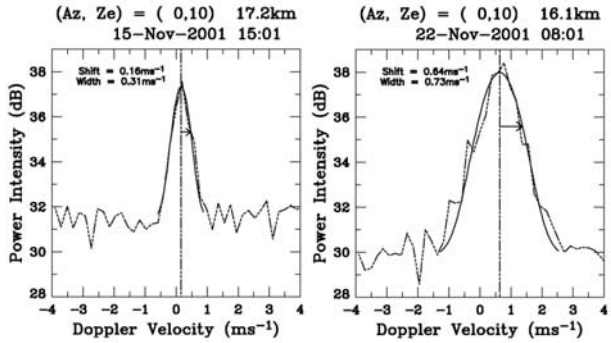

Figure 1. Hourly averaged echo power spectrum for the northward beam obtained at 17.2 km on 15 November 2001 (15:01LT) (left) and obtained at 16.1 km on 22 November 2001 (08:01LT) (right). The unit of the ordinate is arbitrary. The solid curves are the Gaussian fit to the spectrum. Note that the spectral width here includes all the three factors. See text for details.

broadening effect by the background wind, was generally found to dominate σ_{broad}.) We also confirmed that σ_{trans} estimated with Equation 6 of *Fukao et al.* [1994] is negligibly small ($\simeq 0.1 \times \sigma_{broad}$). Thus, we derive σ_{turb} as $(\sigma_{turb})^2 = (\sigma_{obs})^2 - (\sigma_{broad})^2$.

3. Results and Discussion

[5] Figure 1 shows two examples of the hourly averaged echo power spectrum in the northward beam on 15 and 22 November 2001. The σ_{obs} is 0.31 m s^{-1} on 15 November and 0.73 m s^{-1} on 22 November. The estimated (σ_{turb}, σ_{broad}) is (0.27, 0.16) m s^{-1} for the 15-November case and (0.66, 0.31) m s^{-1} for the 22-November case. The kinetic energy of the turbulence is approximately proportional to $(\sigma_{turb})^2$ if the 3-m eddies are the dominant agent of the turbulence, and this assumption is valid in the first order [e.g., *Hocking*, 1983]. In this case, the kinetic energy of the turbulence of the latter is a factor of 6.0 larger than that of the former.

[6] Figure 2 shows the time-altitude distribution of the turbulence component of the spectral width, σ_{turb}, for the northward beam from 10 to 30 November 2002. Note that in this paper, we only use the northward beam measurement for the turbulence analysis, so that the effect of the strong zonal wind shear [*Yamamoto et al.*, 2003] is minimized. The tropopause is defined by the temperature minimum measured by radiosondes launched at the Kototabang Global Atmosphere Watch (GAW) station next to the radar site. On 19–20 November, the tropopause jumped up by ~2 km, and the enhancement of turbulence suddenly appeared in the 15–17 km region. The enhancement continued until 23 November intermittently with a period of half a day to a day in this altitude region. Finally, around 23 November, the enhanced turbulence seems to have mixed with the turbulence below 15 km. The two examples in Figure 1 characterize the contrast between the relatively quiet period (left) and the turbulent period (right) in the tropopause region. For 12–16 November, the σ_{turb} in the 15.5–17-km region is on average 0.46 ± 0.12 m s^{-1}, and for 19–23 November, it is 0.55 ± 0.19 m s^{-1} with seven peaks of 0.8–1.2 m s^{-1}. The peak turbulence intensities are, therefore, a factor of ~5 larger in kinetic energy than those in the quiet periods.

[7] Figure 3 shows the time-altitude distributions of potential temperature measured by radiosondes and of zonal wind anomaly by the EAR. The potential temperature plot indicates that before November 19, the isentropes near and just above the tropopause were moving downward and that after the tropopause jump, their downward motion continued and extended into the region where the turbulence was enhanced. Also, we see that the static stability in the turbulent region at 15–17 km during 19–23 November was weaker than other periods. At the same time, a significant zonal wind oscillation was observed in the 15.5–18.5-km region, with the period of ~13 days (e.g., at 17 km from 11 to 24 November), and the turbulent region corresponded to the maximum eastward wind phase of the oscillation. Its vertical wavelength, λ_z, is estimated as ~5 km (e.g., the region from 16 km to 18.5 km on 21 November corresponds to half the wavelength). The background zonal wind,, during the period was −20 to 0 m s^{-1} at 16–17.5 km with an eastward wind shear, and the amplitude, U, was ~20 m s^{-1} at 17 km. No substantial meridional-wind component (not shown) was observed in this oscillation. These characteristics suggest that the disturbance is an equatorial Kelvin wave, one of the eastward-moving large-scale equatorial gravity waves [e.g., *Andrews et al.*, 1987]. From the linear wave theory, the zonal phase speed, $c^{(x)}$, is roughly estimated as ~6 m s^{-1} and the zonal wavelength, λ_x, is roughly estimated as ~7 × 10^3 km using the values, λ_z = 5 km, $\bar{u}$ = −10 m s^{-1}, $N = 2 \times 10^{-2}$ s^{-1}, where N is the Brunt-Väisälä (buoyancy) frequency, and the period of 13 days.

[8] These estimations show that the amplitude of the wave, $U \sim 20$ m s^{-1}, is comparable to or even greater than the intrinsic zonal phase speed, $(c^{(x)} - \bar{u}) \sim 16$ m s^{-1}, so that the wave should be breaking at least around the

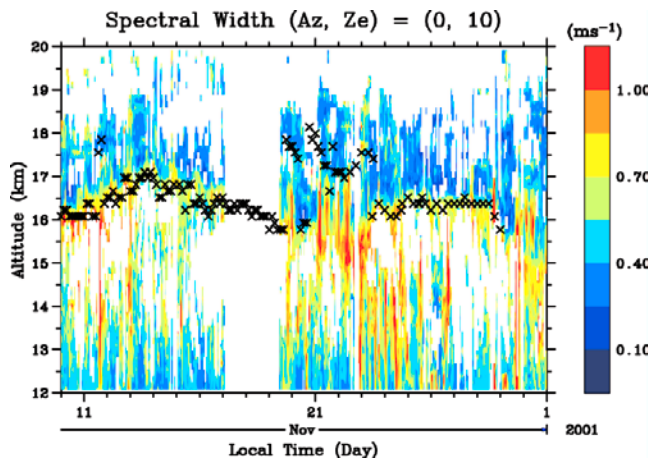

Figure 2. Time-altitude distribution of the turbulence component of the spectral width, σ_{turb}, for the northward beam in the altitudes from 12 to 20 km and from 10 to 30 November 2001. There was no EAR observation on 17, 18, and the former half of 19 November. Other white regions indicate no σ_{turb} estimation due to low signal-to-noise ratio of the measurement. The location of the tropopause defined by the temperature minimum measured by the radiosondes is indicated by crosses.

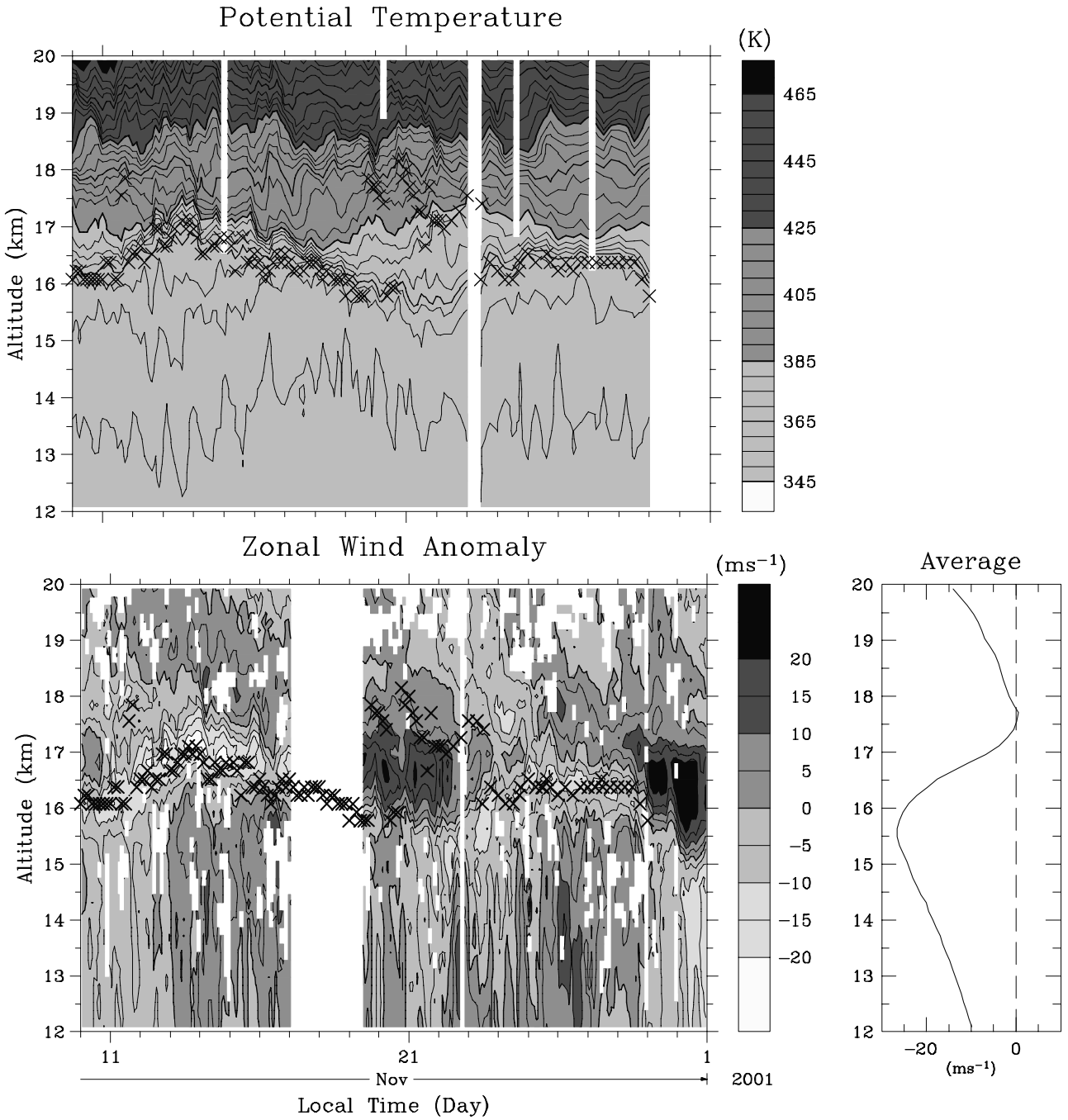

Figure 3. Same as Figure 2 but for potential temperature measured by the radiosondes (top) and zonal wind anomaly measured by the EAR (eastward positive; bottom left) with the average profile (bottom right).

maximum eastward wind phase of the wave [e.g., *Andrews et al.*, 1987]. Therefore, it is concluded that the turbulence observed in the 15–17-km region during 19–23 November was convectively generated in the breaking phase of an equatorial Kelvin wave. The thickness of the turbulent region, ~2 km, is comparable with the observations by *Fujiwara et al.* [1998, 2001] which showed >1-km thick region with nearly constant ozone mixing ratios in the breaking phase of the Kelvin waves. It should be noted that the intermittent nature of the turbulent generation may indicate some interplay between the Kelvin wave and shorter-period gravity waves.

[9] The turbulence came right after the maximum downward displacement phase of the wave in the tropopause region (Figure 3), and was located over different isentropes. Furthermore, the turbulence in the tropopause region has merged into the turbulence in the 12–15 km region around 23 November (Figure 2); this would have resulted in much wider range of the turbulent transport. Therefore, the turbulence associated with the Kelvin wave may have caused effective and irreversible transport of lower stratospheric airmass deeply into the troposphere. This process would affect the ozone budget [*Fujiwara et al.*, 1998] and water vapor budget [*Fujiwara et al.*, 2001] in the tropopause region.

[10] Between July and December 2001, we observed at least three more prominent cases in which breaking Kelvin waves caused significant enhancement of turbulence in the tropopause region, i.e., in August, in October, and around the end of November (see Figures 2 and 3 (bottom)), although we always observed vertically-propagating Kelvin waves in the lower stratosphere. This suggests that the tropopause-level Kelvin waves may be an accompanying structure at the top of the large-scale organized convection in the troposphere, the so-called Madden-Julian or Intra-Seasonal oscillation, especially in the eastern hemisphere [e.g., *Madden and Julian*, 1994; *Fujiwara and Takahashi*, 2001].

4. Conclusion

[11] We observed convectively generated turbulence in the breaking phase of an equatorial Kelvin wave in the tropopause region in November 2001 by the newly installed atmospheric radar, the EAR. Breaking Kelvin waves are considered to play an important role in STE, and this study is the first to confirm the turbulence generation associated with the Kelvin waves propagating in the tropopause region. The favorable phase relation between the downward displacement and turbulence associated with the wave and the downward extension of turbulent region both contributed to irreversible transport of the stratospheric airmass into the upper troposphere. This report has briefly illustrated the potential of the EAR in studying the tropical tropopause region over Indonesia.

[12] **Acknowledgments.** The EAR was established and has been operated by Radio Science Center for Space and Atmosphere of the Kyoto University, Japan, and the Indonesian National Institute of Aeronautics and Space (LAPAN). The radiosonde observation was conducted by the Frontier Observation Research System for Global Change, Japan, the Indonesian Agency for the Assessment and Application of Technology (BPPT), and the Indonesian Meteorological and Geophysical Agency (BMG). This study was supported in part by the Grant-in-Aid for Scientific Research on Priority Area (No. 764), MEXT, Japan. The first author was supported by Research Fellowships of the Japan Society for the Promotion of Science for Young Scientists. We thank two anonymous reviewers and A. Gettelman for comments.

References

Andrews, D. G., J. R. Holton, and C. B. Leovy, *Middle Atmosphere Dynamics*, 489 pp., Academic, San Diego, Calif., 1987.

Fujiwara, M., and M. Takahashi, Role of the equatorial Kelvin wave in stratosphere-troposphere exchange in a general circulation model, *J. Geophys. Res.*, *106*, 22,763–22,780, 2001.

Fujiwara, M., K. Kita, and T. Ogawa, Stratosphere-troposphere exchange of ozone associated with the equatorial Kelvin wave as observed with ozonesondes and rawinsondes, *J. Geophys. Res.*, *103*, 19,173–19,182, 1998.

Fujiwara, M., F. Hasebe, M. Shiotani, N. Nishi, H. Vömel, and S. J. Oltmans, Water vapor control at the tropopause by equatorial Kelvin waves observed over the Galápagos, *Geophys. Res. Lett.*, *28*, 3143–3146, 2001.

Fukao, S., M. D. Yamanaka, N. Ao, W. K. Hocking, T. Sato, M. Yamamoto, T. Nakamura, T. Tsuda, and S. Kato, Seasonal variability of vertical eddy diffusivity in the middle atmosphere, 1, Three-year observations by the middle and upper atmosphere radar, *J. Geophys. Res.*, *99*, 18,973–18,987, 1994.

Haynes, P., and T. Shepherd, Report on the SPARC tropopause workshop, *SPARC Newsl.*, *17*, 3–10, 2001. (Available at http://www.aero.jussieu.fr/~sparc/)

Hocking, W. K., On the extraction of atmospheric turbulence parameters from radar backscatter Doppler spectra, I, Theory, *J. Atmos. Terr. Phys.*, *45*, 89–102, 1983.

Holton, J. R., P. H. Haynes, M. E. McIntyre, A. R. Douglass, R. B. Rood, and L. Pfister, Stratosphere-troposphere exchange, *Rev. Geophys*, *33*, 403–439, 1995.

Madden, R. A., and P. R. Julian, Observations of the 40–50-day tropical oscillation—A review, *Mon. Weather Rev.*, *122*, 814–837, 1994.

Nastrom, G. D., Doppler radar spectral width broadening due to beamwidth and wind shear, *Ann. Geophys.*, *15*, 786–796, 1997.

Yamamoto, M. K., M. Fujiwara, T. Horinouchi, H. Hashiguchi, and S. Fukao, Kelvin-Helmholtz instability around the tropical tropopause observed with Equatorial Atmosphere Radar, *Geophys. Res. Lett.*, accepted for publication, 2003.

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