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Citation	Geophysical Research Letters, 30(9), 29-1-29-4 https://doi.org/10.1029/2002GL016685
Issue Date	2003-05-08
Doc URL	http://hdl.handle.net/2115/64844
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Type	article
File Information	Yamamoto_et_al-2003-Geophysical_Research_Letters.pdf

GEOPHYSICAL RESEARCH LETTERS, VOL. 30, NO. 9, 1476, doi:10.1029/2002GL016685, 2003

Correction published 12 July 2003

Kelvin-Helmholtz instability around the tropical tropopause observed with the Equatorial Atmosphere Radar

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Received 28 November 2002; revised 14 January 2003; accepted 18 January 2003; published 8 May 2003.

[1] In November 2001, the Equatorial Atmosphere Radar (0.20°S, 100.32°E) observed a continuous strong eastward wind shear (10–50 m s^{-1} km^{-1}), westward wind (2–27 m s^{-1}), and the radar echo layer tilted downward to the west in the region 0–1 km above the tropopause. During the same period, the Richardson number calculated with hourly-averaged horizontal wind and radiosonde temperature data was almost continuously <0.5 and sometimes <0.25, which seems to indicate that the Kelvin-Helmholtz instability (KHI) frequently occurs in that region. The existence of the tilted radar echo layer can be explained by KHI billows. A spurious updraft caused by the KHI-induced tilted echo layer and by the strong westward wind was also observed in the region. *INDEX TERMS:* 3360 Meteorology and Atmospheric Dynamics: Remote sensing; 3362 Meteorology and Atmospheric Dynamics: Stratosphere/troposphere interactions; 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology; 3379 Meteorology and Atmospheric Dynamics: Turbulence. **Citation:** Yamamoto, M. K., M. Fujiwara, T. Horinouchi, H. Hashiguchi, and S. Fukao, Kelvin-Helmholtz instability around the tropical tropopause observed with the Equatorial Atmosphere Radar, *Geophys. Res. Lett.*, *30*(9), 1476, doi:10.1029/2002GL016685, 2003.

1. Introduction

[2] Dynamical couplings between the stratosphere and the troposphere are the important processes that control the Earth's atmosphere. Especially, the tropical tropopause is the primary region for the airmass transport from the troposphere to the stratosphere [*Holton et al.*, 1995]. Nevertheless, there are still many controversies about the airmass motions in the tropical tropopause layer (TTL) [e.g., *Sherwood*, 2000], due to the scarcity of observation. VHF radar can directly observe three dimensional winds and turbulent motions with good time and height resolutions in the tropopause region [e.g., *Röttger*, 1980; *Gage*, 1990]. Some VHF radar observations have been already performed over the tropical Pacific with a typical height resolution of ~1000 m [e.g., *Gage et al.*, 1991a]. The thickness of the TTL is several kilometers, thus the observations of wind and turbulent motions with a height resolution of at least several hundred meters are indispensable to clarify the airmass motions in the TTL. The Equatorial Atmosphere Radar (EAR), recently installed at Bukit Kototabang (0.20°S, 100.32°E, 865 m above sea level), West Sumatra, Indonesia can observe winds and turbulence with a height resolution of 150 m in the troposphere and lower stratosphere (1.5–20 km in altitude) [*Fukao et al.*, 2003; hereafter F03]. In the present paper, we focus on the measurement around the tropopause region, and show evidence that the Kelvin-Helmholtz instability (KHI) frequently occurs in that region. We also discuss the effects of KHI on the vertical wind measurements by VHF radars in the tropics.

2. Observation

[3] The EAR is a 47.0 MHz Doppler radar with a peak output power of 100 kW, with a quasi-circular antenna array of approximately 110 m in diameter, and with a time resolution of ~1 min. and with a time resolution of ~1.5 min. It has been continuously operated since July 2001, with some short-term data gaps (explained by F03). The EAR steers the antenna beam to the vertical, northward, eastward, southward, and westward on a pulse-to-pulse basis in a standard observation. The four oblique beams have a zenith angle of 10°. In this paper, all the data are averaged every hour and the height resolution is 150 m. In November 2001, Vaisala GPS radiosondes are launched every 3 or 6 hours from the Kototabang station of the Global Atmosphere Watch next to the radar site. Radiosonde data are averaged every 150 m to be matched to the height resolution of the EAR.

3. Results

[4] Figure 1 shows time-altitude cross-sections of vertical wind, zonal echo power imbalance (zonal EPI), zonal wind shear, and Richardson number (*Ri*). Zonal EPI is defined by the ratio of the echo power in the westward beam to that in the eastward beam. *Ri* is calculated from the radiosonde temperature data and the EAR horizontal wind data. A continuous updraft (>0.025 m s^{-1}) is clearly seen in the region 0–1 km above the cold-point tropopause determined by the radiosonde soundings (Figure 1a). The height of the tropopause almost always corresponds to the height of the maximum westward wind (not shown). Its time variation is affected by equatorial Kelvin waves [*Fujiwara et al.*, 2003]. The echo power in the westward beam is continuously stronger than that in the eastward beam in the updraft region (Figure 1b). The reason for this echo power imbalance will be discussed later. A strong eastward wind shear or westward wind which decreases with altitude from the tropopause (10–50 m s^{-1} km^{-1}) is also continuously observed in the same region (Figure 1c). Note that the meridional wind shear is negligible (not shown). *Ri* is almost continuously

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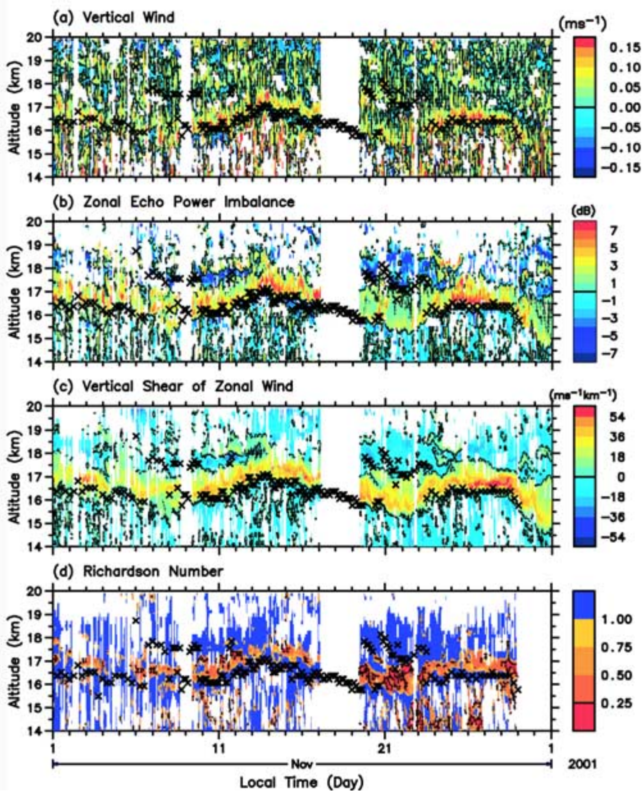

Figure 1. Time-altitude cross-sections of (a) vertical wind, (b) zonal echo power imbalance, (c) zonal wind shear, and (d) Richardson number in November 2001. Positive values in (b) denote that the echo power is stronger in the westward beam than in the eastward beam. Positive values in (c) denote the eastward wind shear. The tropopause defined by the temperature minimum is indicated by crosses.

<0.5 and sometimes <0.25. (Figure 1d). This small *Ri* is associated with the strong zonal wind shear, in spite of the strong increase of Brunt-Väisälä (buoyancy) frequency in this region (not shown).

[5] The vertical wind, the zonal wind, and the zonal wind shear are composited based on the relative altitude with respect to the tropopause height during November 2001, and are shown in Figure 2. Data during days 6–9, 11, and 19–23 are excluded because the tropopause heights were displaced to higher altitudes. In the region 0–1 km above the tropopause, the updraft with the maximum of ~0.069 m s^{-1} at 300 m above the tropopause is clearly seen. The statistical uncertainties of the vertical wind are estimated as ~0.004 m s^{-1} above the tropopause and ~0.009 m s^{-1} below the tropopause, according to the method by *Balsley et al.* [1988].

4. Interpretation

[6] *Ri* is almost continuously <0.5 and sometimes <0.25 in the region 0–1 km above the tropopause (Figure 1d). However, KHI is considered to occur frequently even if observed *Ri* is >0.25. One reason is that *Ri* is not always <0.25 in all stages of KHI [*Fritts and Rastogi*, 1985]. Another reason is that the time stage of KHI occurrence and non-occurrence also appears during the averaging time of one hour. The representative horizontal scale of the KHI billow train (*D*) is ~6 km, if we apply Equation (7) of *Muschinski* [1996] (hereafter M96), with the representative vertical scale of ~1 km (i.e., the thickness where *Ri* is <0.5). Furthermore, if we regard the zonal wind at 300 m above the tropopause in Figure 2 (23 m s^{-1}) as the representative zonal wind in the region (*U*), the KHI billow train advection time scale is D/U ~260 s. It is small enough to explain the existence of time stages, both of KHI occurrence and non-occurrence within the averaging time of one hour. *Ri* computed with highest-time-resolution (~85 s) horizontal wind becomes <0.25 when wind shear is temporally strong, even when *Ri* calculated with hourly-averaged horizontal wind shows >0.25 (not shown).

[7] Gravity waves and KHI cause mis-estimation of the vertical wind measured with VHF radars [e.g., *Nastrom and VanZandt*, 1994; M96]. *Nastrom and VanZandt* [1994] show that vertically propagating gravity waves with downward phase propagation lead to a downward bias in the measured vertical wind velocity, especially in the troposphere. As for the effects of KHI, M96 suggests that mis-estimation of vertical wind occurs under the tilted echo layer produced by KHI billows. If the echo layer is tilted by KHI billows, the effective vertical beam direction is tilted toward the perpendicular axis of the refractivity surface, because the effective radar beam direction is determined by the convolution between the angle dependency of the echo

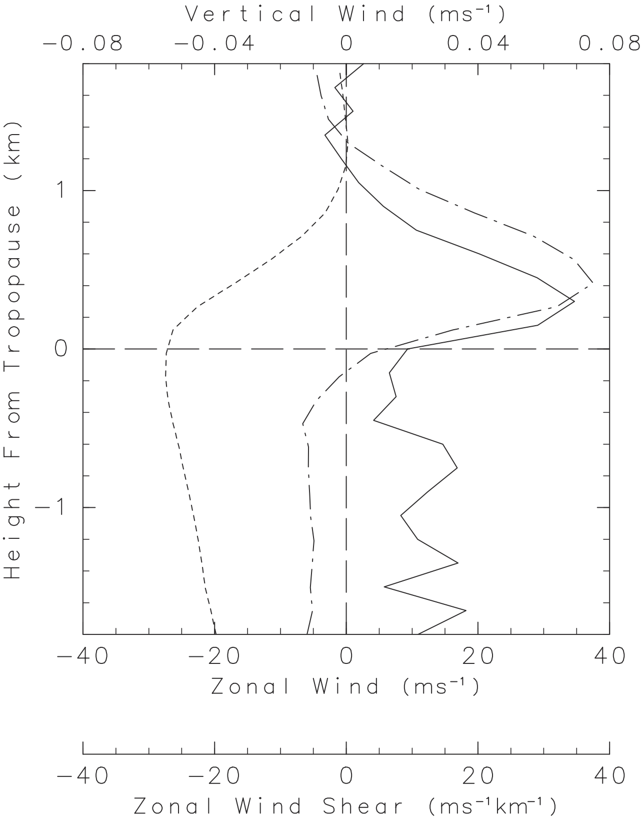

Figure 2. Tropopause-based average profiles of vertical wind (solid curve), zonal wind (dashed curve), and zonal wind shear (dot-dashed curve) in November 2001.

layer and the antenna beam pattern (see and Figure 2 of M96). Under this condition, the horizontal wind component, which is significantly greater than the vertical wind component, contaminates the Doppler shift in the vertical beam. *Fukao et al.* [1991] (hereafter F91) show that a reversal of the vertical wind direction around the jet maximum (updraft above the jet maximum and downdraft below it) occurs when the peak horizontal wind speed exceeds 60 m s^{-1}. M96 suggests that the critical value shown in F91, 60 m s^{-1}, may be related to a critical *Ri* (0.25), and that a reversal of the vertical wind direction occurs due to a reversal of tilting direction of the echo layer produced by KHI billows.

[8] Here we estimate the magnitude of the effect of spurious vertical wind ($\overline{\Delta w}$) using the model suggested by M96. For the calculation, we use the values at 300 m above the tropopause, which are composited based on the relative altitude with respect to the tropopause height as shown in Figure 2. Furthermore, we presume the angle (Θ_c) at which the echo intensity due to quasi-specular backscatter equals the echo intensity due to isotropic backscatter (see M96). The results are (Θ_c, $\overline{\Delta w}$) = ($\leq$10°, 0.031 m s^{-1}), (11°, 0.038 m s^{-1}), (12°, 0.045 m s^{-1}), (13°, 0.053 m s^{-1}), and (14.3°, 0.064 m s^{-1}) respectively. Θ_c = 14.3° corresponds to the maximum value of Θ_c presumed in the model of M96. The magnitude of the estimated spurious updraft varies 45–93% of the observed maximum updraft according to the presumed Θ_c. Therefore, the observed updraft is mostly spurious. Downdrafts below the tropopause (below the maximum of westward wind) as shown in F91 are not clearly seen in Figure 2, because the horizontal shear is not strong enough to generate KHI in the region.

[9] KHI has several stages within its life cycle [e.g., *Browning and Watkins*, 1970]. The tilt angle of the echo layers in the mature stage of KHI billows is typically ~10° (see M96). Thus the tilt angle can vary between zero and ~10° downward to the west in almost all stages of KHI. The refractivity surface nearly perpendicular to the vertical beam was tilted downward to the west, and caused the spurious vertical wind contaminated by the horizontal wind component. Furthermore, the typical tilting angle of 10° downward to the west apparently caused the stronger echo power in the westward beam than that in the eastward beam in that region (see Figures 1b and 4; note that the zenith angle of the oblique beams is 10° in our case). Figure 4 Therefore, the existence of both the spurious vertical wind and zonal EPI can be explained by the effects of KHI billows.

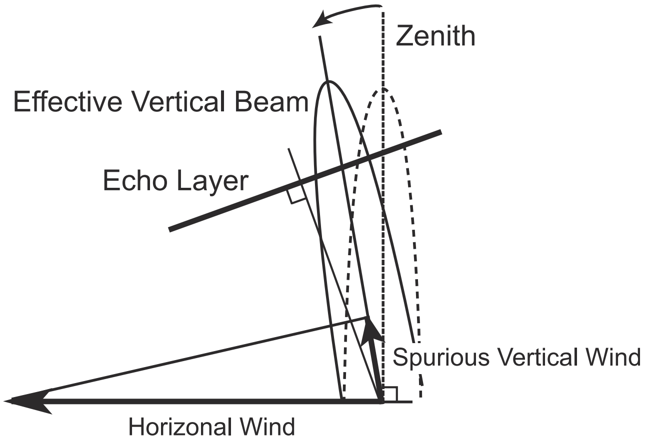

Figure 3. Schematic diagram showing the contamination of the Doppler shift by the horizontal wind component in the vertical beam.

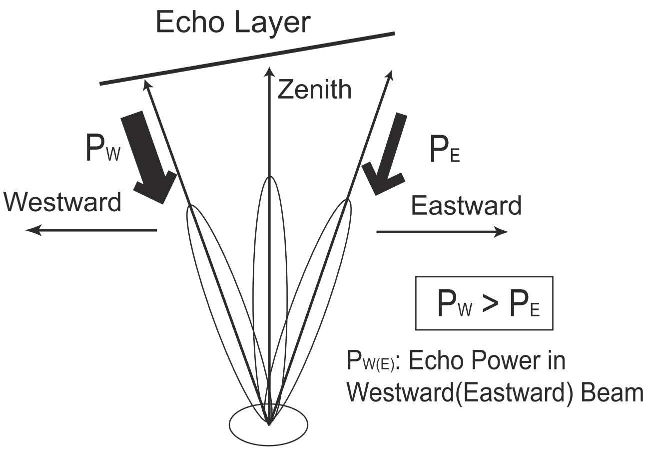

Figure 4. Schematic diagram showing the relation between the tilted echo layer and the echo power imbalance.

5. Discussion

[10] *Balsley et al.* [1988] discussed errors of the vertical wind obtained by VHF radar due to the tilt of the vertical beam under the condition of the tilted echo layer or tilted isentropic surfaces (see Appendix 4 in their paper). They concluded that the effect of the tilted echo layer is essentially averaged out, because they assumed that the tilted echo layer is generated by the lee waves and that the tilt angles of the vertical beams are distributed over all azimuths and over all phases of the lee waves. However, our observation shows that a spurious updraft continuously appears due to KHI billows. This effect is not averaged out because the off-vertical tilts of the vertical beam have a nearly constant azimuth. The previous vertical wind measurements in the tropics [e.g., *Balsley et al.*, 1988; *Gage et al.*, 1991b] may include the contamination of the horizontal wind component. However, the influence may be smaller than our measurements because of the coarse height resolution (~1 km) of their measurements. In any case, vertical wind measurements by VHF radar must be treated with caution when and where the strong wind shear seems to be associated with the generation of KHI also in the tropics. The radar beam steering to plural zenith angles that enables the estimation of Θ_c may be useful for the removal of $\overline{\Delta w}$ to obtain the true vertical wind component.

[11] We also see the correlation between the sign of the zonal wind shear and that of the zonal EPI above the 1-km KHI region up to ~20 km in Figures 1b and 1c. For example, during November 7–12, the zonal EPI and the zonal wind shear are both positive at 16–17.2 km and above 18 km, while they are both negative at 17.2–18 km. This correlation occurs even if *Ri* > 0.25. *Tsuda et al.* [1997a, 1997b] and *Worthington et al.* [1999] showed a similar correlation from mid-latitude measurements, and suggested that inertia-gravity waves can also produce tilted echo layers.

[12] In this paper, we have shown the first observational evidence that KHI associated with strong wind shear frequently occurs around the tropical tropopause. Both the spurious vertical wind and zonal EPI can be explained by the existence of KHI billows. KHI around the tropopause may play a role in the tropical stratosphere-troposphere exchange.

[13] **Acknowledgments.** The operation of the EAR is based upon the agreement between the Radio Science Center for Space and Atmosphere of Kyoto University (RASC) and the National Institute of Aeronautics and Space (LAPAN) of Indonesia signed on September 8, 2000. The radiosonde observations were conducted by the Frontier Observation Research System for Global Change (FORSGC), Japan, the Indonesian Agency for the Assessment and Application of Technology (BPPT), and the Indonesian Meteorological and Geophysical Agency (BMG). The authors also thank M. Oyamatsu for helping in data analysis, and Gernot Hassenpflug for careful reading of the manuscript. Figure 2 was produced with the GFD-DENNOU Library. The present study was partially supported by Grant-in-Aid for Scientific Research on Priority Area - 764 of the Ministry of Education, Culture, Sports, Science, and Technology (MEXT) of Japan.

References

Balsley, B. B., W. L. Ecklund, D. A. Carter, A. C. Riddle, and K. S. Gage, Average vertical motions in the tropical atmosphere observed by a radar wind profiler on Pohnpei (7°N latitude, 157°E longitude), *J. Atmos. Sci.*, *45*, 396–405, 1988.

Browning, K. A., and C. D. Watkins, Observation of clear air turbulence by high power radar, *Nature*, *227*, 260–263, 1970.

Fritts, D. C., and P. K. Rastogi, Convective and dynamical instabilities due to gravity wave motions in the lower and middle atmosphere: Theory and observations, *Radio Sci.*, *20*, 1247–1277, 1985.

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.*, in press, 2003.

Fukao, S., M. F. Larsen, M. D. Yamanaka, H. Furukawa, T. Tsuda, and S. Kato, Observation of a reversal in long-term average vertical velocities near the jet stream wind maximum, *Mon. Weather Rev.*, *119*, 1479–1489, 1991.

Fukao, S., H. Hashiguchi, M. Yamamoto, T. Tsuda, T. Nakamura, M. K. Yamamoto, T. Sato, M. Hagio, and Y. Yabugaki, The Equatorial Atmosphere Radar (EAR): System description and first results, in press, 2003.

Gage, K. S., The structure and dynamics of the free atmosphere as observed by VHF/UHF radar, in *Radar in Meteorology*, edited by D. Atlas, pp. 534–565, American Meteorological Society, Boston, Mass., 1990.

Gage, K. S., B. B. Balsley, W. L. Ecklund, D. A. Carter, and J. R. McAfee, Wind profiler-related research in the tropical Pacific, *J. Geophys. Res.*, *96*, 3209–3220, 1991a.

Gage, K. S., J. R. McAfee, D. A. Carter, W. L. Ecklund, A. C. Riddle, G. C. Reid, and B. B. Balsley, Long-term mean vertical motion over the tropical Pacific: Wind-profiling Doppler radar measurements, *Science*, *254*, 1771–1773, 1991b.

Holton, J. R., P. H. Haynes, M. E. McIntyre, A. R. Douglass, R. B. Rood, and L. Pfister, Stratosphere-troposphere exchange, *Rev. Geophys*, *33*(4), 403–439, 1995.

Muschinski, A., Possible effect of Kelvin-Helmholtz instability on VHF radar observations of the mean vertical wind, *J. Appl. Meteorol.*, *35*, 2210–2217, 1996.

Nastrom, G. D., and T. E. VanZandt, Mean vertical motions seen by wind profilers, *J. Appl. Meteorol.*, *33*, 984–995, 1994.

Röttger, J., Structure and dynamics of the stratosphere and mesosphere revealed by the VHF radar investigation, *Pure Appl. Geophys.*, *118*, 494–527, 1980.

Sherwood, S. C., A stratospheric “drain” over the maritime continent, *Geophys. Res. Lett.*, *27*, 677–680, 2000.

Tsuda, T., T. E. VanZandt, and H. Saito, Zenith-angle dependence of VHF specular reflection echoes in the lower atmosphere, *J. Atmos. Sol.-Terr. Phys.*, *59*, 761–775, 1997a.

Tsuda, T., W. E. Gordon, and H. Saito, Azimuth angle variations of specular reflection echoes in the lower atmosphere observed with the MU radar, *J. Atmos. Sol.-Terr. Phys.*, *59*, 777–784, 1997b.

Worthington, R. M., R. D. Palmer, and S. Fukao, An investigation of tilted aspect-sensitive scatters in the lower atmosphere using the MU and Aberystwyth VHF radars, *Radio Sci.*, *34*, 413–426, 1999.

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