NASA-CR-192983

NAG5-1519

IN-45-CR

160266

p-10

ROSSBY-GRAVITY WAVES IN TROPICAL TOTAL OZONE DATA

J. L. Stanford and J. R. Ziemke

Department of Physics & Astronomy, Iowa State University
Ames, Iowa 50011

Abstract. Randel (1992) has recently reported evidence for Rossby-gravity waves in tropical data fields produced by the European Centre for Medium Range Weather Forecasts (ECMWF). The purpose of this paper is to show that similar features are observable in fields of total column ozone from the Total Ozone Mapping Spectrometer (TOMS) satellite instrument. The observed features are episodic, have zonal (east-west) wavelengths of ~ 6,000–10,000 km and oscillate with periods of 5–10 days. In accord with simple linear theory, the modes exhibit westward phase progression and eastward group velocity. The significance of finding Rossby-gravity waves in total ozone fields is that (1) the report of similar features in ECMWF tropical fields is corroborated with an independent data set and (2) the TOMS data set is demonstrated to possess surprising versatility and sensitivity to relatively smaller scale tropical phenomena.

Submitted to *Geophysical Research Letters*, March 1993

(NASA-CR-192983) ROSSBY-GRAVITY WAVES IN TROPICAL TOTAL OZONE DATA (Iowa State Univ. of Science and Technology) 10 p

N93-25432

Unclas

G3/45 0160266

Introduction

When one looks at small scale features found in tropical model output a question that comes to mind is the extent to which such features reflect the real atmosphere versus reflecting the dynamics built into the model. A recent study by Randel (1992) was motivated, in part, to obtain "truth" for validating tropical model results from the NCAR CCM (National Center for Atmospheric Research Community Climate Model). To do this, Randel used European Centre for Medium Range Weather Forecasts (ECMWF) tropical data. The ECMWF data themselves are global analyses resulting from a four-dimensional assimilation of available data using first-guess fields generated by the ECMWF forecast model, and later initialized to damp spurious fast gravity waves. Tropical data fields may be inaccurate due to sparse observational data and uncertainties in diabatic effects and mass-wind balance effects. Thus it is important to substantiate fields from tropical models and from combined model-observations (such as ECMWF). Randel (1992) found evidence for episodic Rossby-gravity wave signatures in the tropical ECMWF data, and was able to further corroborate the signals with tropical rawinsonde observations. The dynamical significance of Rossby-gravity waves is that they are believed to play a crucial role in the general circulation of the middle atmosphere through momentum transport and deposition, forcing the westerly phase of the well-known quasi-biennial oscillation.

In the present paper we show that features which compare closely with Randel's ECMWF Rossby-gravity signals also can be found in tropical total ozone measurements from the TOMS (Total Ozone Mapping Spectrometer) satellite instrument.

Randel (1990) used space and time spectral decomposition to demonstrate significant differences between data retrieval schemes used with LIMS (Limb Infrared Monitor of the Stratosphere). Such techniques can provide very sensitive tests of both model output and data retrieval schemes. Our investigation utilizes similar techniques with TOMS measurements representing total column ozone, integrated over a thick vertical column throughout the stratosphere; such data might be thought insensitive to waves with relatively short vertical wavelengths ($\sim$ 5 km) such as Rossby-gravity waves. The results presented here point to surprising utility of TOMS data sets: we find it is possible to observe several types of tropical wave signatures in total column ozone and in the next section show one such example, viz. Rossby-gravity waves.

Since TOMS is a totally independent instrument and data set from those used in producing ECMWF fields, the analyses presented here further corroborate the validity of the wave activity discussed by Randel (1992), and strengthen confidence in the ECMWF tropical data sets.

Data and analysis

The TOMS instrument aboard the Nimbus 7 sun-synchronous polar orbiting satellite has provided daily data since launch in October 1978. Bowman and Krueger (1985) analyzed the first four years of $5^\circ \times 5^\circ$gridded TOMS data from an earlier version and gave an account of missing data and global ozone characteristics. The long time series available for TOMS (we use 13 years of data, starting in 1979), plus its excellent horizontal resolution, make it useful for model validation studies.

This study uses TOMS version 6 daily data from the NASA/Goddard Space Flight Center made available on CD-ROM disk in a format of 1°latitude by 1.25°longitude bins, covering 1 November 1978 to 31 January 1992. We regridded the data onto a 5°× 5°mesh extending from 85°N to 85°S in latitude and 180°to 175°W in longitude. Zonally averaged monthly mean percentages of missing 5°× 5°data were found to be less than about 2% at all latitudes (excluding polar night) and all months from June 1980 to January 1992. The worst month for missing data is June 1979 for which ~30–40% of data is missing at latitudes not in polar night. Similarly, July 1979 to May 1980 have roughly 5–10% missing data. All missing data were replaced using linear interpolation in time.

Space-time spectra were computed using either 180, 90, or 60-day window lengths. During each calculation, time series averages and possible low frequency trends were removed using the filtering technique discussed by Stanford et al. (1993); the chosen filter response had half-amplitude at a period of 250 days. This was followed by applying a 10%–10% cosine taper window to reduce leakage. These power spectra calculations also included a decomposition in space-time variables into eastward and westward components (see, for example, the Appendix of Ziemke and Stanford, 1990); no effort was made to remove standing-wave variability in the data. A 0.25–0.5–0.25 running mean was applied once to the raw power ordinates as a spectral estimator. Raw power spectra ordinates are defined in this study by $(2\Delta f)^{-1}[A^2(k,\omega)+B^2(k,\omega)]$, where Δf is the unit bandwidth (1 day^{-1} here). Spectral amplitude used in this study is the square root of twice the power. $A(k,\omega)$ and $B(k,\omega)$ are calculated via Fast Fourier Transform (FFT) in both time and space from the following zonal space-time harmonic definition for total column ozone Ω:

$$\Omega_{\pm}(x,t)=\sum_{k=0}^{\pi/\Delta x}\sum_{\omega=0}^{\pi/\Delta t}\Big[A_{\pm}(k,\omega)\cdot\cos(kx\pm\omega t)+B_{\pm}(k,\omega)\cdot\sin(kx\pm\omega t)\Big]. \qquad (1)$$

Here, t (x) denotes time (zonal distance), Δt (Δx) is the temporal (spatial) sampling interval, k is the zonal wavevector, ω is the circular frequency, and + (−) denotes the westward (eastward) propagating component of Ω. Spectra involving more than one zonal wavenumber were derived by combining the spectra for each individual wavenumber.

All plots in this study, other than spectra, do not incorporate an eastward/westward separation. The bandpass filter response function given by Murakami (1979) was applied in frequency space (using an inverse FFT) to reconstruct bandpass filtered time series.

Rossby-gravity waves in TOMS

The study by Randel (1992) used ECMWF tropical wind fields for 1980–1987. He found waves with 6–10 day periods in the meridional wind, propagating westward and concentrated primarily in zonal waves 4–7 (wavelengths of ~ 6,000–10,000 km). One lengthy episode extending from the latter half of July 1985 into October 1985 was particularly strong, with meridional wind amplitudes maximizing in the upper troposphere near 200 hPa pressure level (~ 10 km altitude). The wave signatures resembled Rossby-gravity waves trapped near the equator, although not exactly symmetric about the equator. The spectral characteristics for this 1985 episode in Randel's 200 hPa meridional wind at 2°S are captured by waves 3–8 with periods 4–15 days. To compare with his study, we searched for this episode in the tropical TOMS data after retaining only zonal waves 3–8 and employing a bandpass filter with half amplitudes at 4 and 15-day periods.

Figure 1 presents the TOMS spectra during July-October 1985, at the time of the Rossby-gravity waves found by Randel. The spectra are computed with a 90-day window beginning 16 July 1985. As highlighted by the arrows, there is a clear westward propagating disturbance in zonal waves 5–6 with a period near 6 days. Randel (1992) finds a similar 6-day wave in zonal waves 5–6 (his Fig. 11b). Figure 2 shows a Hofmöller (time vs longitude) diagram during the time covered by Fig. 1, for TOMS data evaluated at 5°N. Also shown for comparison is Randel's analysis (his Fig. 11a) of unfiltered ECMWF meridional winds. Figure 2 reveals clear evidence of westward phase propagation and eastward packet (group velocity) propagation. As discussed next, such behavior is consistent with linear tropical Rossby-gravity wave dynamics.

Comparison with theory

The usual quasi-geostrophic approximation is invalid for wave dynamics in low latitudes because the apparent Coriolis force is small near the equator. Starting instead with the primitive equations, in the form of an equatorial beta plane model linearized about a state of rest, the equations of motion yield solutions of the form (Andrews *et al.*, 1987):

$$(u', v', w', \Phi') = e^{z/2H} Re\left[\left\{\hat{u}(y), \hat{v}(y), \hat{w}(y), \hat{\Phi}(y)\right\} \exp[i(kx + mz - \omega t)]\right]. \qquad (2)$$

Here x, y, z are eastward, northward, and vertical coordinates; u, v and w are zonal, meridional and vertical winds; Φ is geopotential; ω is angular frequency and H is scale height (about 7 km for the lower stratosphere). The wavenumbers in the x and z directions are k and m. Primes are perturbation quantities and carets $(\hat{})$ refer to their amplitudes as a function of y. The solutions are those which occur in quantum harmonic oscillator theory, having the form of a Gaussian times Hermite polynomials. The gravest solution contains the Rossby-gravity mode, for which the zonal, meridional and vertical wind perturbation components are

$$(\hat{u}, \hat{v}, \hat{\Phi}) = \hat{v}_o \cdot [i|m|\omega y N^{-1}, 1, i\omega y]\exp(-\beta|m|(2N)^{-1}y^2). \qquad (3)$$

The vertical wavenumber is given by $m = -\text{sgn}(\omega)N\omega^{-2}(\beta + \omega k)$, where β is the Coriolis parameter $2\Omega a^{-1}\cos(y/a)$, a is the earth's radius, and N is a measure of the static stability, $\sim 2 \times 10^{-2}$ for the stratosphere. In the absence of a background wind, the Rossby-gravity wave zonal phase speed is given by

$$v_p = \omega/k = (2m)^{-1}\left\{N \pm [N^2 + 4N\beta m k^{-2}]^{1/2}\right\}. \qquad (4)$$

For Rossby-gravity waves whose zonal phase speed is westward (as observed in Fig. 2), ω is negative and the negative sign must be chosen in (4). For this case, the zonal group velocity is given by

$$v_g = \partial\omega/\partial k = (2m)^{-1}\left\{N - N^2 k[N^2 k^2 + 4N\beta m]^{-1/2}\right\} \qquad (5)$$

which is positive, viz. eastward, opposite to the direction of phase movement in (4). These v_p and v_g are speeds with respect to mean background winds. The winds in the lower stratosphere over Singapore during this time are ~ 10 ms^{-1} (B. Naujokat, Free University of Berlin, personal communication), but this is considerably to the west of the maximum Rossby-gravity wave amplitudes in the eastern Pacific (Fig. 2). For the latter region, Randel's Fig. 12b shows that the 200 hPa mean wind is near zero. The observed phase speed of wave 6, 6-day period waves is ~ 12 ms^{-1} westward with respect to the earth. With respect to the mean background wind, the phase of the waves in Fig. 2 is thus likely moving slowly westward, while that of the packet envelope (v_g) is eastward, opposite that of the mean wind. These observations are thus consistent with Rossby-gravity wave dynamics.

Expression (3), for zero background wind, predicts perturbations localized in the vicinity of the equator ($y = 0$), decaying in amplitude by $1/e$ in distance $L = \sqrt{2N/\beta m}$. Randel (1992) estimated $m = 7.9 \times 10^{-4}$ meter^{-1}, so that $L \simeq 13°$ latitude. For variance, the $1/e$ distance is half this value. Figure 3 shows both Randel's meridional ECMWF wind (variance) and our TOMS (amplitude) analyses near the equator. The horizontal phase structure of the waves is shown in Fig. 4. The ozone perturbations were examined by calculating covariances, $N^{-1} \cdot \sum_{t=1}^{t=N} \Omega_{ref}(t) \cdot \Omega(t)$, after filtering and removing all time means. For this two-month case study, $N = 60$. Figure 4b shows the results. Note that the observed perturbations indeed are trapped near the equator, although the $1/e$ distance may be larger than the zero background wind prediction. The presence of near-by midlatitude disturbances makes it difficult to accurately estimate the $1/e$ distance. As noted by Randel, the background zonal wind field exhibits latitudinal asymmetry about the equator for this case study and a marked reduction in meridional trapping can occur with wind shear (Zhang and Webster, 1989). The fact that the disturbances are not symmetric about the equator is perhaps also related to background wind shear.

Finally, we note that the TOMS perturbation envelope (lower stratosphere) is somewhat to the east of the upper tropospheric ECMWF signal in Fig. 2. This eastward packet displacement with height is consistent with Holton's (1972) modeling of Rossby-gravity wave excitation from upper tropospheric sources: Holton's perturbations propagated upward and eastward into the lower stratosphere.

Summary

1. The features described here in TOMS total ozone, an independent data set, corroborate the Rossby-gravity waves found recently by Randel (1992) in ECMWF tropical analysis fields.

2. The original TOMS design objective was to measure ozone integrated throughout the depth of the stratosphere. The total ozone analyses presented here demonstrate that TOMS data are considerably more versatile and can be utilized for investigations of relative short-vertical-scale tropical features such as Rossby-gravity waves.

The long time series (~ 15 years), near global coverage and high quality characteristics of TOMS data suggest that they are suitable for validating model results and other data sets. They may be particularly valuable in the relatively data poor and dynamically difficult tropical region.

Acknowledgments. We thank Ms. Patricia T. Guimaraes, Dr. Richard D. McPeters, Dr. Arlin J. Krueger, and the members of the NASA TOMS NIMBUS Experiment and Information Processing Teams, and the National Space Science Data Center for providing the TOMS data on CD-ROM disc. We have enjoyed several helpful conversations with Dr. W. J. Randel. This work was supported by National Aeronautics and Space Administration Grant NAG 5-1519.

References

Andrews, D. G., J. R. Holton, and C. B. Leovy, 1987: *Middle Atmosphere Dynamics*, Academic Press, Inc., New York. pp. 489.

Bowman, K. P., and A. J. Krueger, 1985: A global climatology of total ozone from the Nimbus 7 Total Ozone Mapping Spectrometer. *J. Geophys. Res., 90*, 7967–7976.

Holton, J. R., 1972: Waves in the equatorial stratosphere generated by tropospheric heat sources. *J. Atmos. Sci., 29*, 368–375.

Murakami, M., 1979: Large-scale aspects of deep convective activity over the GATE area. *Mon. Wea. Rev., 107*, 994–1013.

Randel, W. J., 1990: Kelvin wave-induced trace constituent oscillations in the equatorial stratosphere. *J. Geophys. Res., 95*, 18641–18652.

Randel, W. J., 1992: Upper tropospheric equatorial waves in ECMWF analyses. *Q. J. Roy. Meteor. Soc., 118*, 365–394.

Stanford, J. L., J. R. Ziemke, and S. Y. Gao, 1993: Stratospheric circulation features deduced from SAMS constituent data. *J. Atmos. Sci., 50*, 226–246.

Zhang, C. D., and P. J. Webster, 1989: Effects of zonal flow on equatorially trapped waves, *J. Atmos. Sci., 46*, 3632–3652.

Ziemke, J. R., and J. L. Stanford, 1990: One-to-two month oscillations in the stratosphere during Southern winter. *J. Atmos. Sci., 47*, 1778–1793.

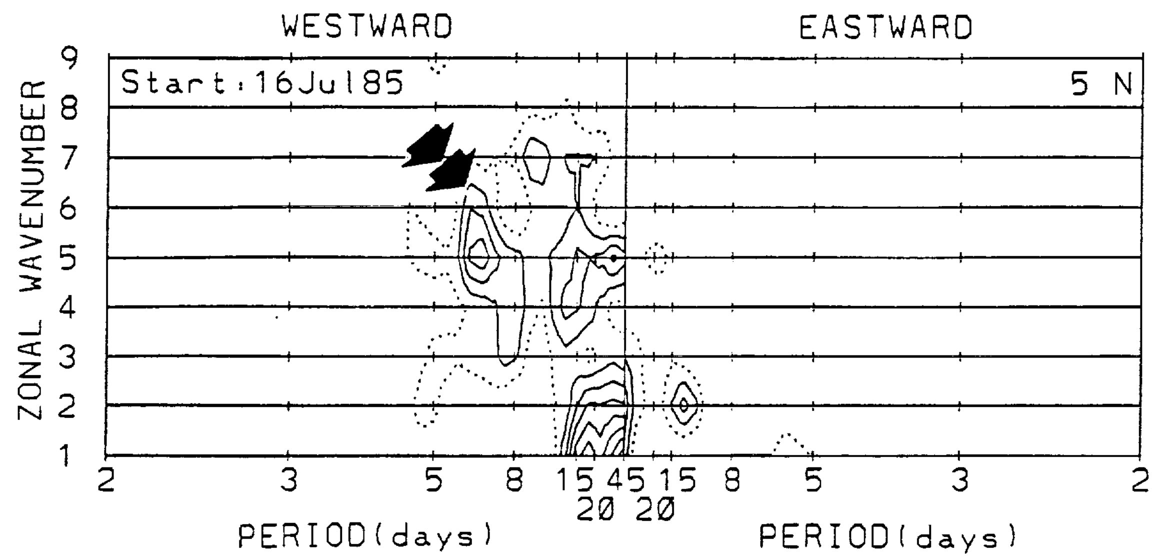

FIGURE 1. Zonal wavenumber vs. frequency westward/eastward spectral amplitudes for TOMS version 6 data at 5°N. Dates: 90 days beginning 16 July 1985. Units: DU. Dashed contours are 0.15. Solid contours begin at 0.3 and increment by 0.15. Periods in days shown. Arrows point to 6-day feature discussed in text.

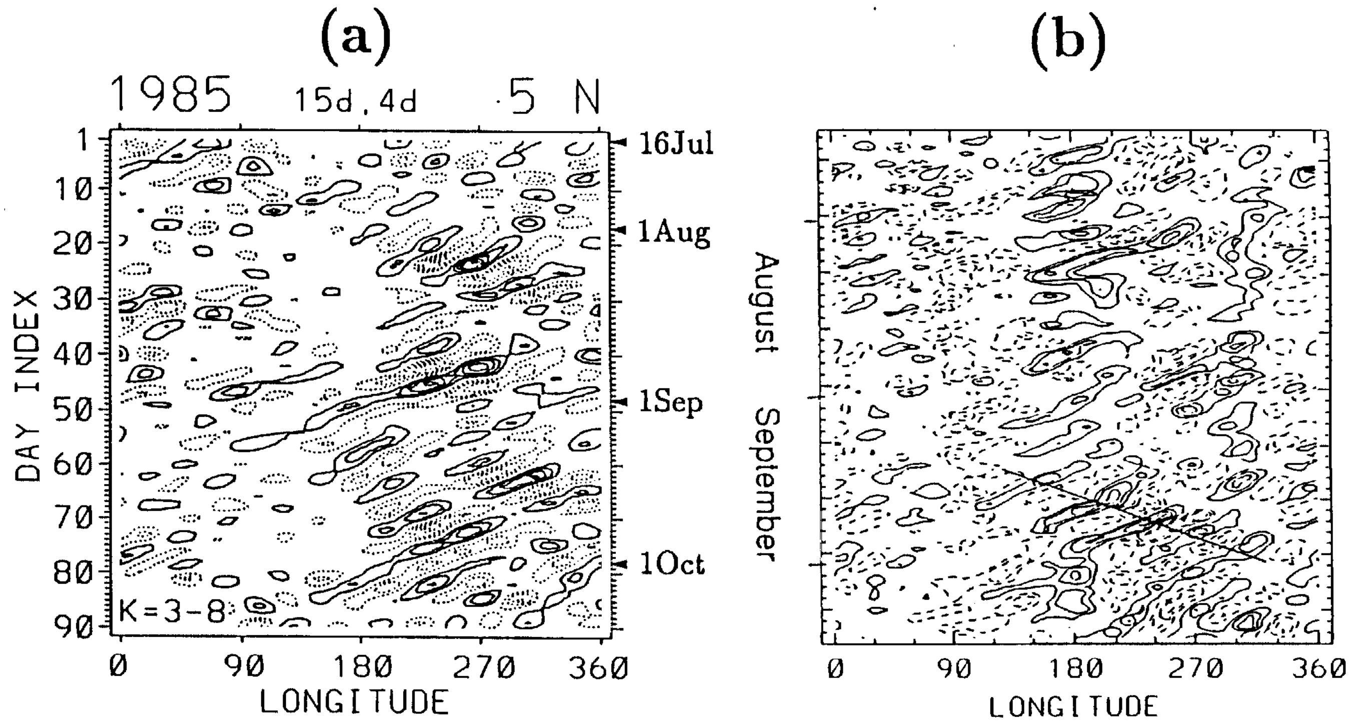

FIGURE 2. (a) Time vs. longitude Hofmöller diagram of data plotted in Fig.1, further truncated for zonal wavenumbers 3–8 and bandpass filtered with half-amplitude response at 15 and 4-day periods. One day per tick. Units: DU. Dashed (solid) contours begin at -1 (1) and increment (decrement) by 1. (b) Hofmöller diagram of the meridional wind at 200 hPa, 2°S over 90 days centered on August-September 1985; no space or time filtering has been applied. Straight dark line denotes Randel's estimate of possible group velocity direction. Contour interval is $4ms^{-1}$, with zero contours omitted. [This is Fig.11a of Randel, 1992]

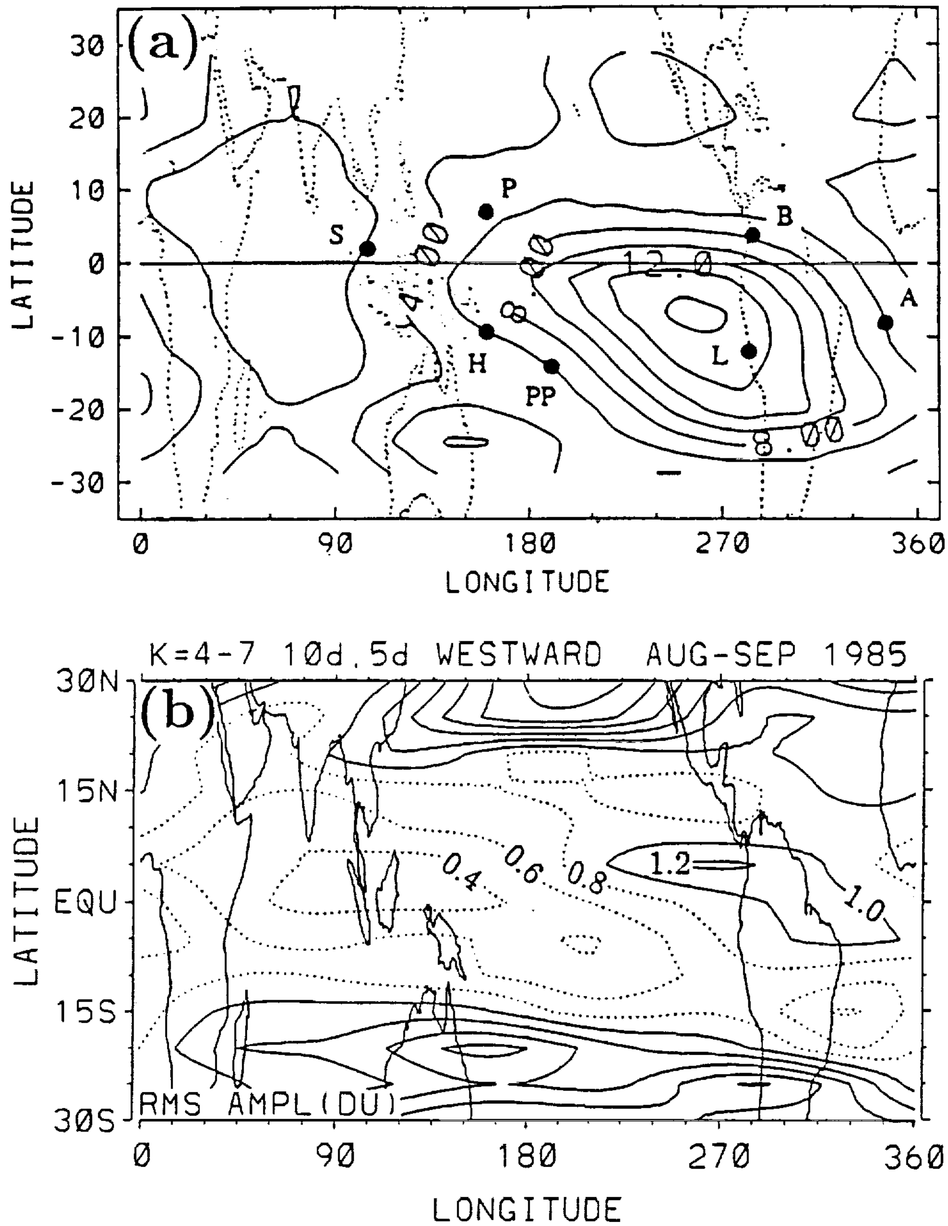

FIGURE 3. (a) Latitude-longitude map of the meridional wind variance for westward-propagating zonal waves 4–7 with periods 5–10 days, calculated from data over August-September 1985. Contour interval is 2 m^2s^{-2}. Dots denote rawinsonde stations. [This is Fig.12a of Randel, 1992] (b) Similar to (a), but for RMS amplitudes of westward propagating components in TOMS total column ozone. Calculation is over August-September 1985 for zonal waves 4–7, including bandpass filtering for periods 5–10 days (filter response one-half at 5 and 10 days). Units: DU. Solid (dashed) contours begin at 1.0 (0.8) and increment (decrement) by 0.2.

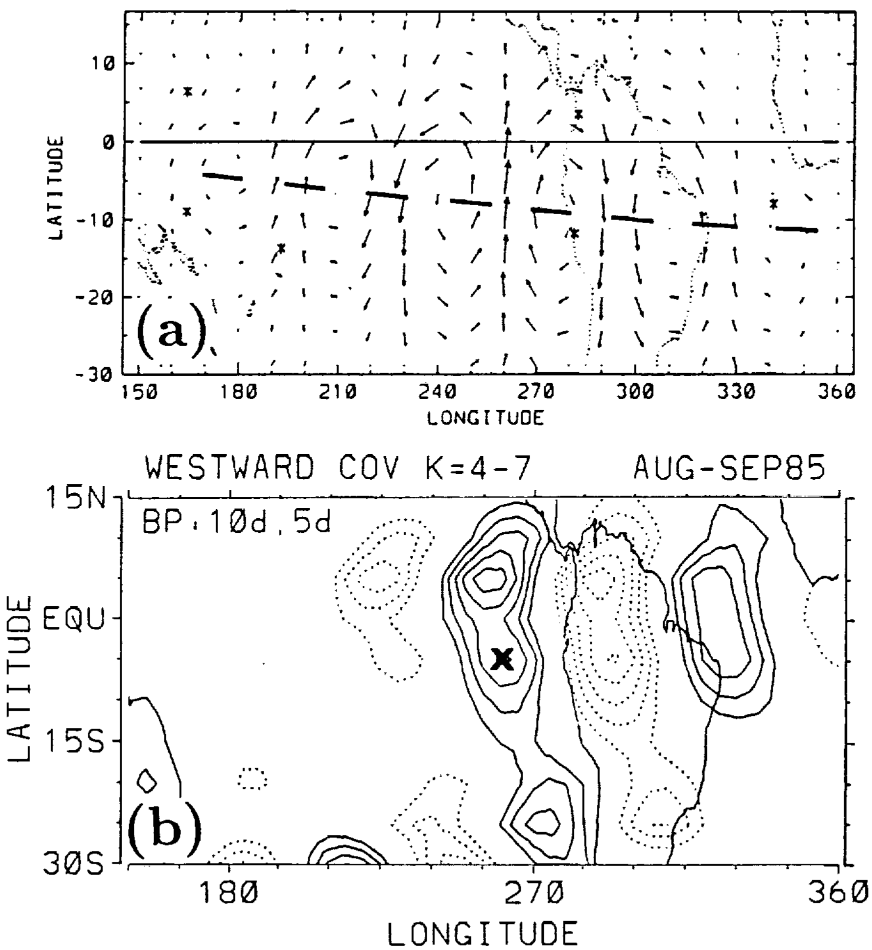

FIGURE 4. (a) Latitude-longitude diagram of the horizontal structure of westward-propagating fluctuations in 200 hPa filtered ECMWF meridional wind data used in Fig. 3a. Components of each vector are calculated as regressions upon the reference time series of meridional wind at 260°E, 7°S. The longest vector represents 4.5 ms^{-1}. The heavy dashed line indicates the approximate axis of symmetry for these waves. [This is Fig.13 of Randel, 1992] (b) Similar to (a), but for calculated covariance of the ozone data in Fig.3b. Reference point used is 260°E, 5°S (marked by "X"). Units: DU^2. Solid (dashed) contours begin at 0.3 (-0.3) and increment (decrement) by 0.1.