JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 102, NO. D12, PAGES 13,457–13,464, JUNE 27, 1997

Observation of an ultraslow large-scale wave near the tropical tropopause

Kevin Hamilton

Geophysical Fluid Dynamics Laboratory/NOAA, Princeton University, Princeton, New Jersey

Abstract. An analysis is made of very high resolution radiosonde data taken at seven western Pacific island stations during TOGA-COARE (Tropical Ocean–Global Atmosphere and Coupled Ocean-Atmosphere Response Experiment). Evidence is found for a wave near the tropopause with periods ~30–40 days and with very slow (~3 m s^{-1}) eastward propagation. This oscillation appears quite coherent across the region considered (a 37° longitude spread). The oscillation has a short vertical wavelength (~3 km) and is strongly attenuated above the tropopause and thus would be very hard to observe in either satellite data or conventional meteorological analyses.

1. Introduction

The early papers of *Wallace and Kousky* [1968] and *Yanai et al.* [1968] showed that the much of the variance seen in radiosonde data in the tropical stratosphere can be reasonably interpreted as vertically propagating planetary-scale waves. These waves are presumably forced in the troposphere and appear to satisfy the dispersion relations for free equatorial waves above the tropopause. There are now observations of various vertically propagating, planetary-scale spectral components with periods from ~3 to 20 days that are prominent at different times and heights in the tropical middle atmosphere. In particular, there are indications of global-scale eastward propagating Kelvin waves with phase speeds of ~25–30 m s^{-1} [*Wallace and Kousky*, 1968], ~50–70 m s^{-1} [*Hirota*, 1978], and ~100 m s^{-1} [*Salby et al.*, 1984].

In contrast to the equatorial planetary waves with phase speeds >20 m s^{-1} that appear clearly in stratospheric observations, the most prominent very large scale coherent waves in the tropical troposphere have much longer periods and slower phase speeds. The tropical variability in the period range from ~30 to 60 days is dominated by the large-scale eastward propagating Madden-Julian oscillation (MJO) [e.g., *Madden and Julian*, 1972]. In the troposphere the MJO has a horizontal structure and polarization very similar to the linear equatorial Kelvin wave, but the vertical wavelengths and horizontal phase speeds associated with the MJO are not consistent with free Kelvin wave solutions (at least if the usual expression for vertical stability is used). The presumed explanation for this is that the MJO is continuously forced by convective heating, and indeed the observed MJO structure is consistent with the standard linear theory if a weaker "effective moist stability" is used in the dispersion relation.

The basic reason for the prominence of faster phase speed Kelvin waves in the stratosphere is well understood [e.g., *Holton*, 1972; *Garcia and Salby*, 1987; *Manzini and Hamilton*, 1993]. The key point seems to be that the deep vertical scale of convective heating favors the excitation of long vertical scale waves (with corresponding fast horizontal phase speeds). Thus the occurrence of a prominent fast wave in the stratosphere may not reflect a particular modulation of the tropospheric convection at the same phase speed and zonal scales, but can simply be a response to very broadband convective heating.

On the other hand, it seems plausible that the systematic, slowly propagating, large-scale modulation of the convective heating in the troposphere would force at least some free equatorial wave variance that could be seen in the middle atmosphere. Indeed, there have been reported some observations of Kelvin waves near the tropical tropopause with periods ~20 days or longer [*Parker*, 1973; *Tsuda et al.*, 1994; *Nishi and Sumi*, 1995]. However, it is useful to note there are some considerations that limit the observability of very slow waves. One important point is that slow stratospheric waves are expected to exhibit very short vertical wavelengths. For a hydrostatic Kelvin wave in constant mean flow and stratification (and assuming that the vertical phase variations occur on scales smaller than the density scale height) the vertical wavenumber is given as $m = N/\hat{c}$, where $\hat{c}$ is the Doppler-shifted phase speed and N is the Brunt-Vaisala frequency. For stratospheric values of $N \sim 0.025\ s^{-1}$ this means that the vertical wave-

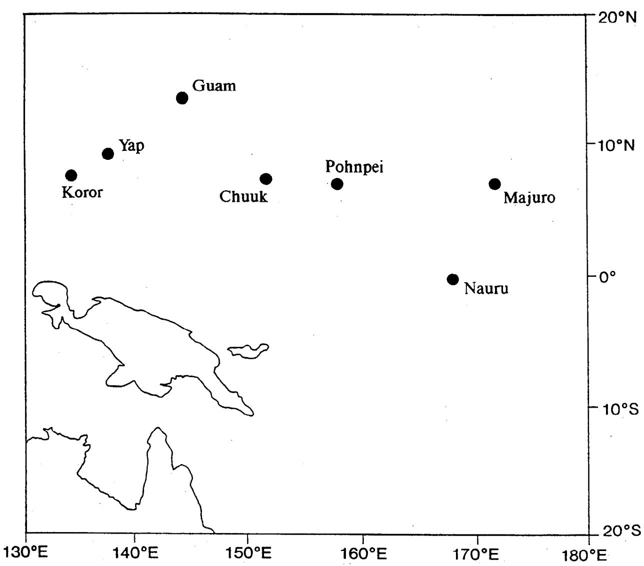

Figure 1. Map of the western Pacific region showing the location of the seven stations used in this study.

Paper number 97JD00486.

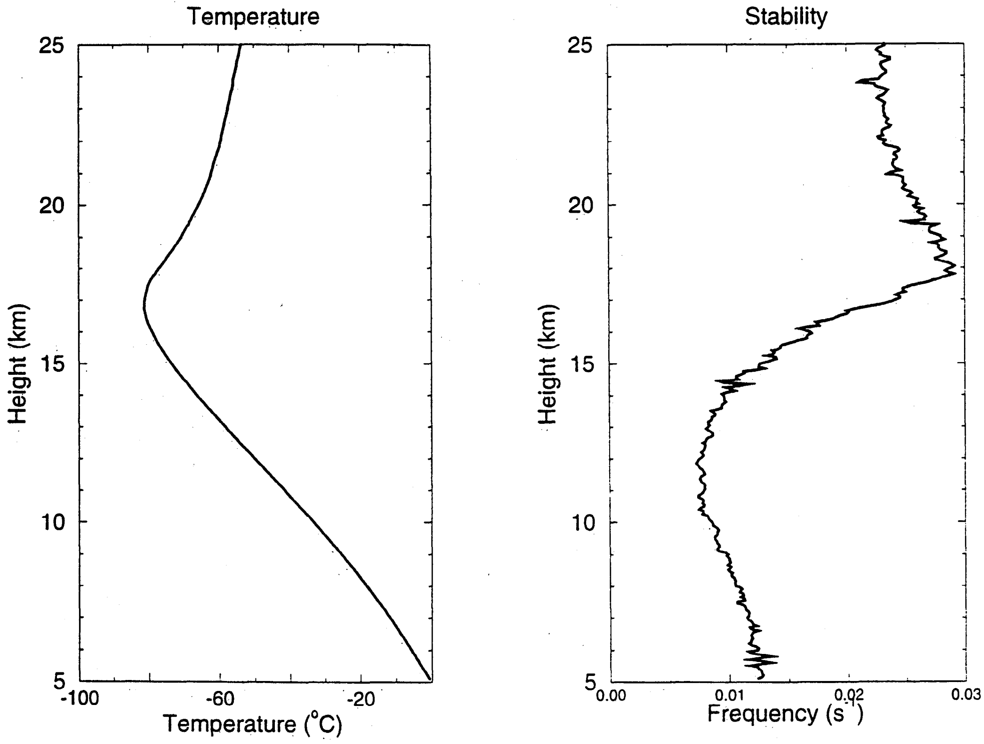

Figure 2. (left) Temperature as a function of height averaged over twice-daily soundings for 120 days at Majuro. (right) Brunt-Vaisala frequency computed from the mean temperature profile. The vertical derivative of temperature was estimated using centered differences on levels spaced 50 m apart.

length will be about 1 km for each 4 m s^{-1} in $\hat{c}$. Thus a very slow wave (say <15 m s^{-1}) can be expected to have a vertical wavelength that will certainly be too small to observe with satellite radiometer data and may even be too short to be found in conventional radiosonde data. The other problem that may limit the observability of slow stratospheric waves is the small vertical group velocity expected. For the simple case of a Kelvin wave in constant mean flow and stratification, the vertical group velocity is $V_g = (k/m)\hat{c}$, where k is the horizontal wavenumber. For a zonal wave, one $\hat{c}$ = 10 m s^{-1}, 2.5

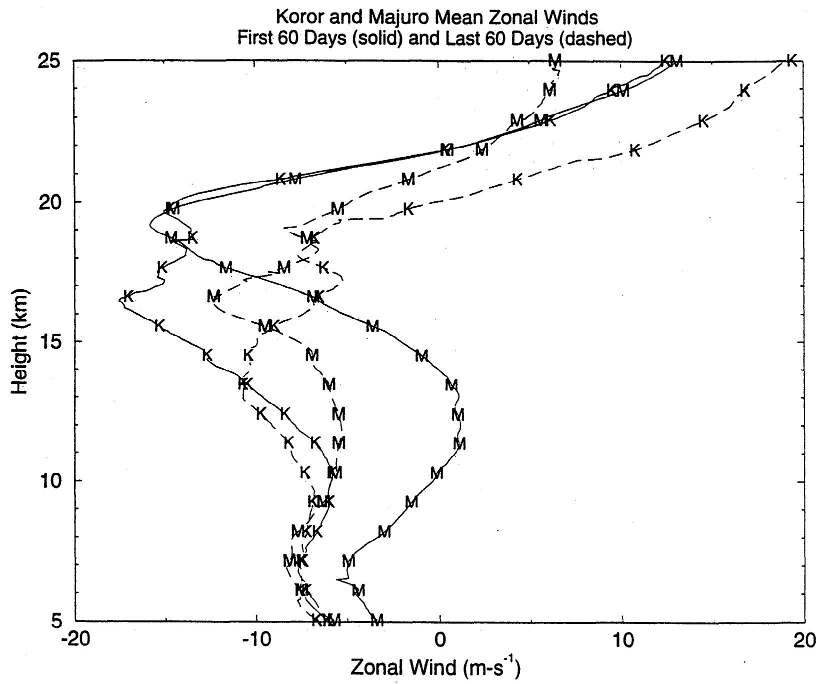

Figure 3. Zonal wind as a function of height averaged over the first 60 days (solid lines) and last 60 days (dashed lines). Results for Koror ("K") and Majuro ("M").

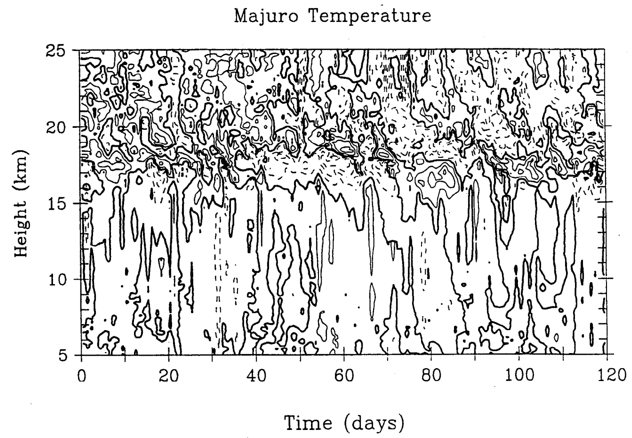

Figure 4. Height-time section of the temperature at Majuro with the 120-day mean removed at each level. The contour interval is 2°C, and dashed contours denote negative values.

km-vertical wavelength Kelvin wave, the expected vertical group velocity is only ~50 m d^{-1}. Obviously, shorter horizontal scales would have correspondingly faster group velocities, but the values obtained for any planetary scale wave is very slow. Even assuming very long dissipation timescales for the lower stratosphere, such waves can be expected to be attenuated quite strongly above their tropospheric forcing region. While somewhat more complicated formulae are needed for the other classes of equatorial waves, the same basic considerations concerning the small vertical wavelength and slow group velocity apply.

The purpose of the present paper is to describe a preliminary study of the large horizontal scale, short vertical wavelength variations in the tropical lower stratosphere. The data to be used are radiosonde profiles recorded at very high vertical resolution at a number of island stations in the western Pacific during part of the TOGA-COARE (Tropical Ocean–Global Atmosphere and Coupled Ocean-Atmosphere Response Ex-

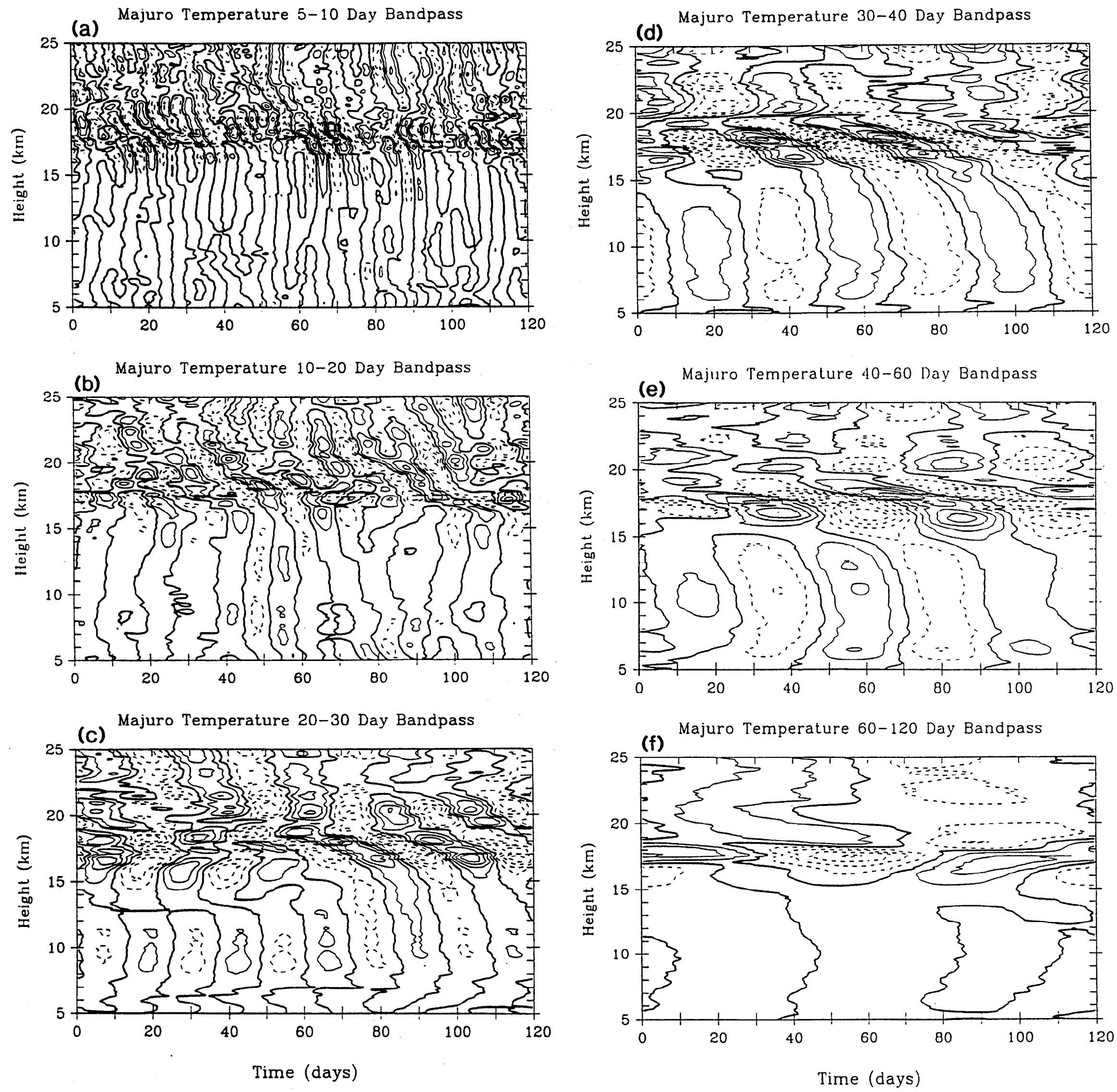

Figure 5. Height-time section of the temperature at Majuro band-passed over different period intervals: (a) 5–10 days, (b) 10–20 days, (c) 20–30 days, (d) 30–40 days, (e) 40–60 days, and (f) 60–120 days. The contour intervals are 1°C, 0.8°C, 0.5°C, 0.4°C, 0.5°C, and 1°C for Figures 5a–5f, respectively. In each case dashed contours denote negative values.

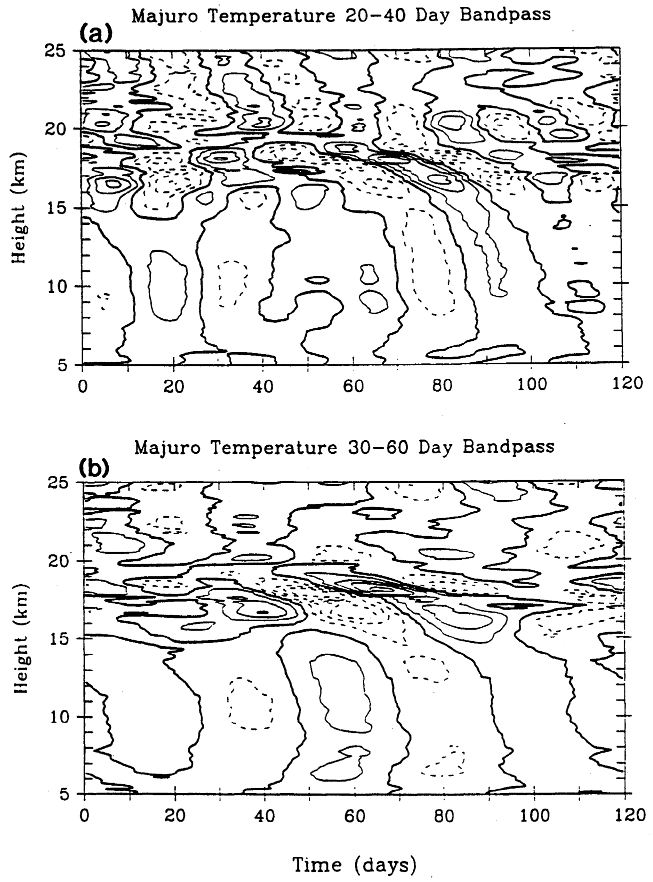

Figure 6. As in Figure 5 but for period intervals of (a) 20–40 days and (b) 30–60 days. The contour interval in each case is 0.5°C.

periment) experiment. These data are described in section 2, below. Section 3 discusses the results of an analysis designed to isolate low-frequency components with zonal coherence over the western Pacific region. Conclusions are summarized in section 4.

2. Data and Large-Scale Environment

The data employed here were obtained from the TOGA-COARE World Wide Web site (http://www.ofps.ucar.edu/codiac) and are provided by the University Corporation for Atmospheric Research (UCAR) Office of Field Program Support (UCAR is funded by the National Science Foundation). They consist of soundings from the seven stations shown in Figure 1 during the 120 day period November 1, 1992, to February 28, 1993. Six of the stations were operated by the U.S. National Weather Service (NWS): Koror (134.5°E, 7.3°N), Yap (138.1°E, 9.5°N), Guam (144.8°E, 13.6°N), Chuuk (151.8°E, 7.4°N), Pohnpei (158.2°E, 7.0°N), and Majuro (171.4°E, 7.1°N). These stations provide twice-daily soundings of wind and temperature at a nominal 6-s resolution. There are a small number of missing soundings at these stations, but the great majority of soundings provide complete data coverage in the 5- to 25-km height range of present interest. The station at Nauru (166.9°E, 0.5°S) was operated by the Taiwan Weather Bureau and provided data at a 10-s nominal resolution. Unfortunately, the majority of soundings at Nauru stop at heights around 18 km, and none reaches 25 km.

The nominal 6-s resolution for the U.S. NWS stations amounts to roughly 30 m height resolution. Of course, the actual effective resolution depends on the instrument characteristics and the data processing applied. For the temperature observations the situation is fairly well understood. The reported 6-s data are just the raw output from the temperature sensors on the Vaisala RS80-15 radiosondes employed. *Allen and Vincent* [1995] have examined the effects of the temperature sensor lag on the effective resolution of the data from this type of sonde. They conclude that the sensor lag noticeably suppresses variance only for wavelengths less than 0.5 km.

The wind data are much more problematical. When the raw 6-s position data for the sondes are used to derive winds in a straightforward manner, the results are apparently very noisy. The actual data provided are smoothed in a complicated way (see http://www.ofps.ucar.edu/codiac) and have perhaps ~1-km effective resolution. The wind data as finally processed also seem to have some small, but noticeable, discontinuities at certain heights (see Figure 3, below).

Only the soundings for nominal launch times of 0000 and 1200 UT were employed in this study. The first step in the analysis of the data was the interpolation of the wind and temperature data onto a regular 50-m grid in geopotential height. Missing data were then filled in from previous and successive profiles. Limiting interest to the 5- to 25-km height region, this results in an array of winds and temperatures at 240 times and 800 heights. Adjacent heights and times were then averaged to produce a 120×400 array (1 day by 100 m), which is then the basis for the plots shown in this paper. A similar procedure was adopted at Nauru, but only data up to 21 km were considered, and a large number of points at levels above ~17 km had to be filled in by interpolating from results at nearby launch times.

Figure 2 shows the 120-day mean temperature as a function of geopotential height at Majuro and the Brunt-Vaisala frequency calculated from this mean temperature. The strong increase in stability above about 15 km is evident. Results for the other stations are similar. Figure 3 shows the zonal wind averaged over the first 60 days and over the last 60 days for Koror and Majuro. The strong (magnitude >10 m s^{-1}) easterlies seen near the tropopause at both stations are in accord with the seasonal climatology for this area [e.g., *Oort*, 1983]. However, the western Pacific is unusual in having such strong climatological tropopause easterlies. The region of strong easterlies actually coincides rather closely with the area covered by the stations used in the present study. At some heights the curves in Figure 3 display some rather odd bumps of small vertical scale (but generally less than 1 m s^{-1} in amplitude). These are presumably a consequence of limitations associated with either the observation of balloon positions or the processing of the position data to deduce the winds.

3. Results

Figure 4 shows a time-height representation of the unfiltered (1 day by 100 m) temperature data at Majuro. The pattern is complicated but does show a dominant downward phase progression, which is consistent with the expected upward energy propagation of equatorial planetary and gravity waves. The amplitude of the temperature fluctuations also grows rapidly with height near the tropopause. This seems reasonable if the effective forcing for the waves is in the upper troposphere (see the analysis for gravity waves by *Allen and Vincent* [1995]).

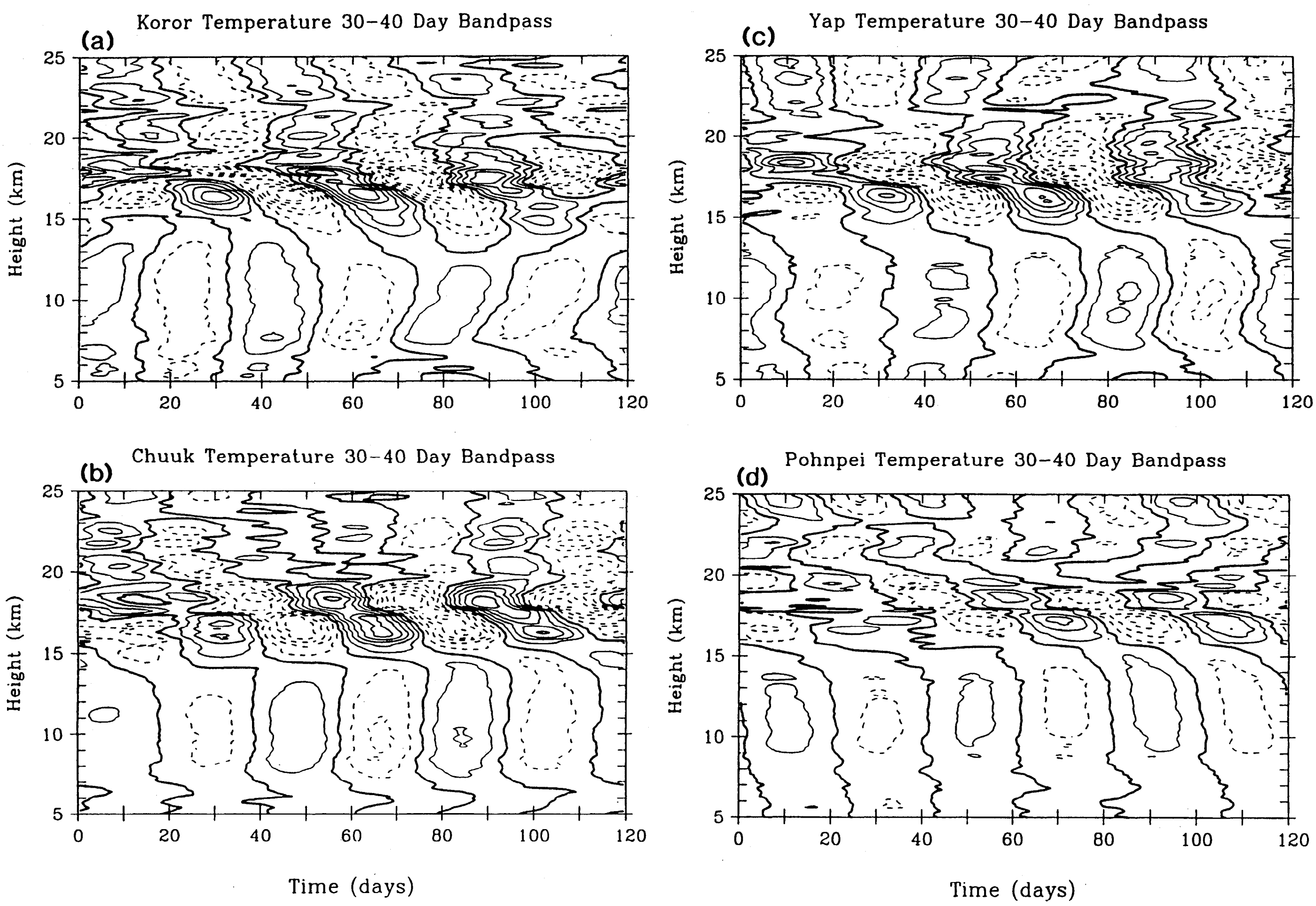

Figure 7. Height-time section of the temperature band-passed between 30 and 40 days for four stations: (a) Koror, (b) Yap, (c) Chuuk, and (d) Pohnpei. The contour interval in each case is 0.4°C.

The results are considerably clarified when the data are band-passed in frequency. Figure 5 shows the time-height sections for various period ranges. The band pass was simply performed by reconstructing the series including just the appropriate Fourier frequencies. Except for the very lowest period range shown, the filtered time series display a clear tendency for downward phase propagation near and above the tropopause. The typical vertical wavelengths in Figure 5 vary strongly with the period range, with longer wavelengths at the shorter periods. The higher-frequency fluctuations also are seen to be less attenuated in the region above the tropopause. The variations at the longest period range shown (60–120 days) do not display downward phase propagation and may largely reflect the seasonal progression rather than the presence of transient waves.

The oscillations that appear in the 30- to 40-day band are particularly regular and coherent in height, at least within the 16- to 20-km height range and during the ~100 days in the middle of the record. The dominant vertical wavelength appears to be slightly greater than 3 km. Figure 6 shows the result of choosing somewhat wider limits for the band pass (20–40 days and 30–60 days). It seems that the 30- to 40-day band displays the most regular vertical phase progression near the tropopause. The oscillations in this band also turn out to be quite coherent among the stations considered here. Figure 7 displays the 30- to 40-day band-passed temperatures at each of Koror, Yap, Chuuk, and Pohnpei. In the 16- to 20-km height range the results for each station show a fairly regular oscillation with downward phase propagation and ~3- to 4-km vertical wavelength very similar to that seen at Majuro. There are also phase shifts which vary systematically with longitude. This is apparent in Figure 8, which shows the 17-km level 30- to 40-day band-passed temperatures at Koror, Yap, Chuuk, Pohnpei, and Majuro. The temperature variations in this period range propagate very regularly towards the east with a phase speed of about 3° longitude per day (roughly 3 m s^{-1}). The disturbance is roughly out of phase between Koror and Majuro, corresponding to a zonal wavelength of ~8000 km (zonal wavenumber 5). The eastward propagation is most regular in the 16- to 20-km height range, but can be seen to some extent in the troposphere. One point that is clear from Figures 7 and 8 is that while the 30- to 40-day temperature fluctuations at Pohnpei agree well in phase with the other stations, the amplitude is somewhat suppressed. It is not clear why the Pohnpei results differ in this respect (even from those at the nearby Chuuk station). Figure 9 shows the 10-km level 30- to 40-day band-passed temperatures at the same five stations. An eastward propagation is evident, but this is not as regular as that seen at 17 km. Examination of Figure 7 shows that above the 20-km level the regular slow eastward propagation is not observed.

Figure 10 shows the 30- to 40-day band-passed temperature at Guam and Nauru. The Nauru data reveal a short vertical wavelength wave near the tropopause similar to that seen in the stations near 8°N, but it is somewhat more intense, particularly near ~19 km, than the corresponding fluctuations at the

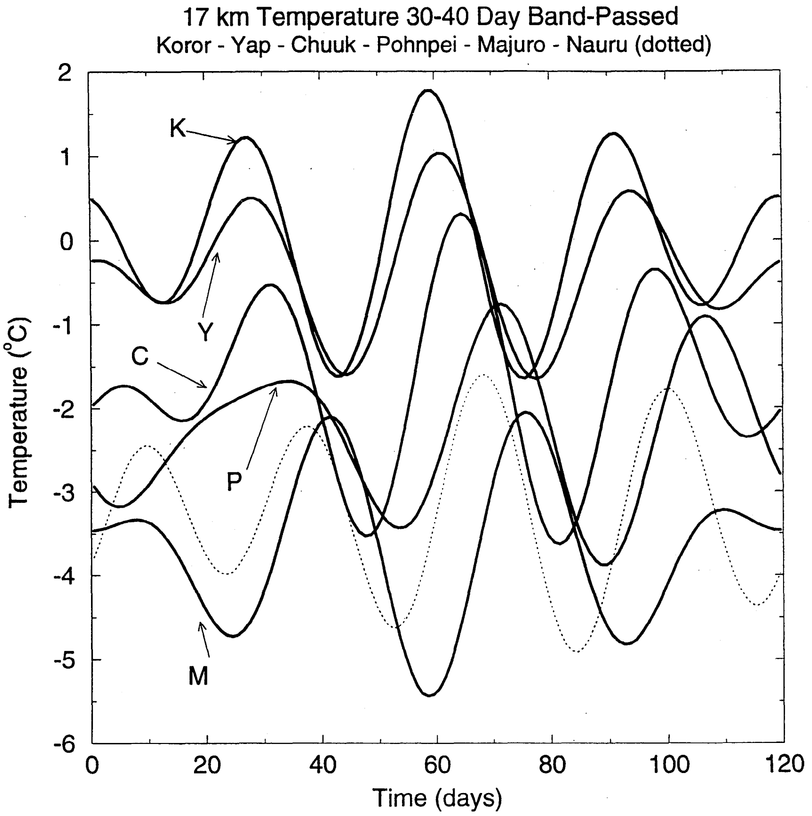

Figure 8. The 30- to 40-day band-passed temperature variations at the 17-km level for five stations near 8°N (solid curves) and for Nauru (dotted curve). The solid curves are labelled with "K" (Koror), "Y" (Yap), "C" (Chuuk), "P" (Pohnpei), and "M" (Majuro). Results are shifted downward by 0.1°C per degree of eastward displacement of the station relative to Koror.

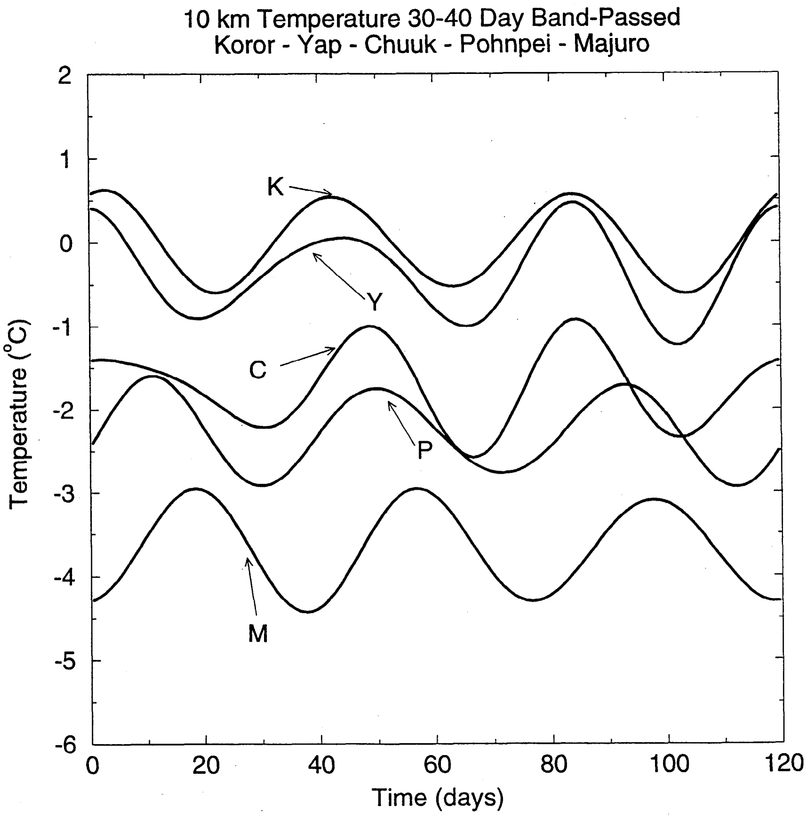

Figure 9. As in Figure 8, but for the 10-km level.

other stations (note the difference in contour interval between Figures 9b and 7). The dotted curve on Figure 8 shows the 30- to 40-day band-passed Nauru temperatures at 17 km. The phase of the Nauru curve is between that of Pohnpei and Majuro, consistent with the notion that the 30- to 40-day temperature variations reflect the presence of an eastward propagating mode with little meridional phase variation (at least between the equator and ~8°N). At Guam (13.6°N) there is some indication of an oscillation near the tropopause, but the continuous downward phase propagation is less evident than at the other stations.

From Figures 2 and 3 one can very roughly estimate for the 16- to 20-km range that $N \sim 0.025\ \mathrm{s}^{-1}$ and the mean flow is between -6 and $-15\ \mathrm{m\ s}^{-1}$. This leads to an estimated range for Doppler-shifted phase speed of ~9–18 $\mathrm{m\ s}^{-1}$. The standard dispersion relation for an equatorial Kelvin wave would then predict a range between about 2 and 4 km for the vertical wavelength. Such a wave would have a predicted meridional temperature modulation proportional to $\exp(-y^2/\Delta^2)$, where $\Delta = (2\hat{c}/\beta)^{1/2}$ and y is the distance from the equator. The width Δ is ~900–1200 km for $\hat{c} \sim$ 9–18 $\mathrm{m\ s}^{-1}$. This is consistent with the oscillation having significant amplitude at the 8°N stations. However, firm conclusions concerning the nature of the wave seen in the temperature data are not possible in light of the limited geographical coverage available. Given the slow zonal phase speed for this wave, it is likely strongly affected by the geographic variations in the prevailing wind near the tropopause. In fact it is quite conceivable that this wave

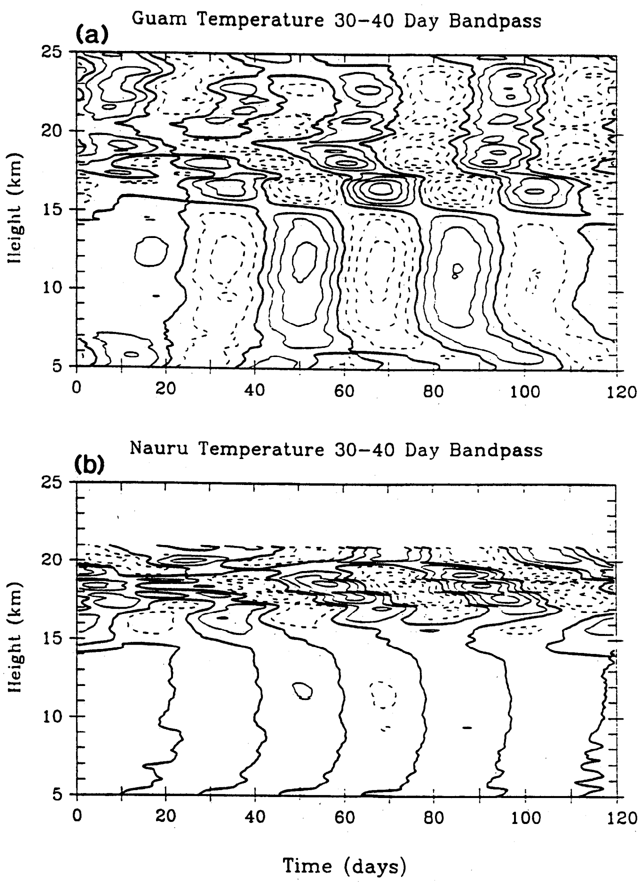

Figure 10. As in Figure 7 but for (a) Guam and (b) Nauru. The contour interval is 0.4°C in Figure 10a and 0.8°C in Figure 10b.

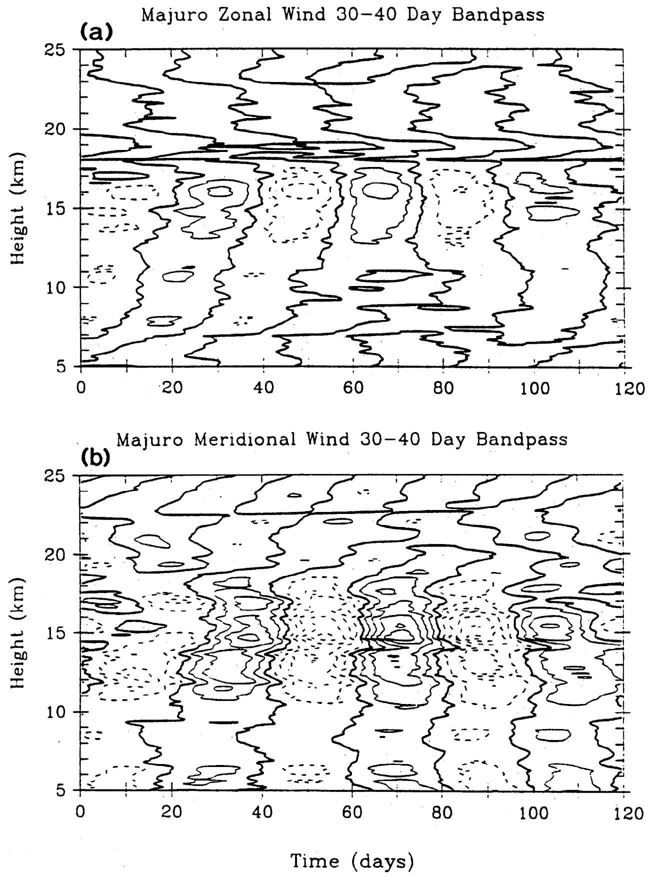

Figure 11. Height-time section of the 30- to 40-day band-passed (a) zonal wind and (b) meridional wind at Majuro. The contour interval is 0.8 $\mathrm{m\ s}^{-1}$, and dashed contours denote easterly or southerly winds.

exists only in the region of strong prevailing tropopause easterlies in the western Pacific: at other longitudes the Doppler-shifted phase speed (and hence vertical wavelength and attenuation scale) would be significantly reduced. It seems reasonable to ascribe the 30- to 40-day oscillation to the forcing associated with the low-frequency modulation of tropical convection. While the 30- to 40-day period is similar to that of the familiar MJO, the most prominent components of the MJO appear to be characterized by zonal wavenumbers 1 and 2. It is possible that the zonal scale of the 30- to 40-day wave documented here could be determined to some extent by geographical modulation of the MJO convection itself.

The radiosonde wind observations have been examined in a similar manner as the temperature observations. Figure 11 shows the 30- to 40-day band-passed zonal and meridional winds at Majuro. Unfortunately, the oscillation near the tropopause that appears in the temperature is not seen clearly in the wind data. Taking the simple interpretation of the temperature data as a single equatorial Kelvin wave with amplitude at Majuro of ~1°C, one would anticipate a corresponding signal in the zonal wind of amplitude ~1 $\mathrm{m\ s}^{-1}$. The lack of such a signal may be a consequence of the effective smoothing in the wind observations (when filtered for higher frequencies, the wind observations do display downward phase propagation in the stratosphere with vertical wavelengths comparable to those seen for the temperature variations in Figure 5).

4. Conclusion

The present analysis has taken advantage of the availability of high-resolution radiosonde temperature observations to document a prominent 30- to 40-day oscillation near the tropical tropopause with vertical wavelength $\sim$3 km. While earlier studies using high-resolution soundings have found considerable short vertical scale wave activity at individual stations [e.g., *Allen and Vincent*, 1995], the present analysis shows that the high-resolution data contain information on disturbances with zonal coherence and regular phase propagation over large regions. It seems reasonable to suppose that the 30- to 40-day tropopause wave is forced by a large-scale low-frequency modulation of tropospheric convection. The fact that the wave is clearly present in the data for only about one vertical wavelength suggests a very strong attenuation above the region of excitation. This is consistent with the very small vertical group velocity expected for large-scale, slow horizontal phase speed waves. Unfortunately, no clear signal of this oscillation is seen in the corresponding radiosonde wind observations. This may simply be a consequence of the effective broad vertical smoothing in the wind data.

The limited data discussed here are consistent with the presence of an equatorial Kelvin wave with eastward phase speed relative to the ground of $\sim$3 m s^{-1} and zonal wavelength $\sim$8000 km. However, there is not enough data to definitely claim that the 30- to 40-day variance is explained by such a Kelvin wave, nor that such a wave is a global phenomenon. Given the strong zonal asymmetries in the mean flow near the tropical tropopause, such a slow Kelvin wave would be greatly altered in structure as it propagates zonally. The amplitude of the 30- to 40-day near-tropopause oscillation at the 8°N stations appears to be $\sim$1°C, with a suggestion that right at the equator it could be somewhat stronger. This is quite modest, but it is conceivable that this oscillation could play some role in cross-tropopause transport of water vapor at low latitudes [e.g., *Holton et al.*, 1995]. Such a possibility is enhanced by the rapid attenuation of the wave with height right near the tropopause, since strongly dissipated waves will be more likely to produce irreversible tracer transport.

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K. Hamilton, Geophysical Fluid Dynamics Laboratory/NOAA, Princeton University, P.O. Box 308, Princeton, NJ 08542. (e-mail: kph@gfdl.gov)

(Received October 16, 1996; revised January 27, 1997; accepted January 31, 1997.)