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Horizontal wind disturbances induced by inertial instability in the equatorial middle atmosphere as seen in rocketsonde observations

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[1] Rocketsonde observations at Kwajalein (8.7°N, 167.7°E) were used for investigation of horizontal wind disturbances induced by inertial instability. Two characteristic cases were found in the 1978–1979 northern winter during which the limb infrared monitor of the stratosphere (LIMS) made observations. In both the cases the eastward component and the northward component of horizontal winds are negatively correlated in the vertical direction near the stratopause level, which is thought to be due to inertial instability. The wind disturbances have a wavelength of about 10 km, and their maximum amplitudes are estimated as over 10 ms^{-1}. Examinations of the LIMS temperatures support a possibility that the wind disturbances are induced by inertial instability. It was revealed that temperature disturbances characteristic of inertial instability, called "pancake structures," appear in the same height and time as the wind disturbances do. The relationship between the rocketsonde wind disturbances and the LIMS pancake structures is 90° out of phase, as expected by the theory of inertial instability. In addition, it was confirmed that the two inertial instability events follow enhancements of the midlatitude planetary wave. This is consistent with a mechanism of the inertially unstable disturbances in the equatorial region inferred in some observational and numerical studies. Analyses of rocketsonde data were extended to the entire observation period at Kwajalein, which suggests that the occurrence of inertially unstable disturbances is biased toward the winter season. However, at some other stations in the tropics, wind disturbances which may be induced by inertial instability do not appear so frequently as they do at Kwajalein. This seasonality and regionality of inertially unstable disturbances would be due to the seasonality and regionality of planetary wave breakings at midlatitude. *INDEX TERMS:* 3334 Meteorology and Atmospheric Dynamics: Middle atmosphere dynamics (0341, 0342); 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology; 3319 Meteorology and Atmospheric Dynamics: General circulation; 3384 Meteorology and Atmospheric Dynamics: Waves and tides; *KEYWORDS:* inertial instability, planetary wave breaking, equatorial stratosphere, rocketsonde, LIMS

1. Introduction

[2] Inertial instability is known as a kind of hydrodynamic instability in a rotating fluid that occurs when the angular momentum gets larger with approaching the rotation axis. In the earth's atmosphere it is realized in the case of the larger angular momentum in the higher latitude. A criterion of inertial instability is expressed, on the assumption of zonal symmetry, as [see, e.g., *Holton*, 1992]

$$f\left(f - \bar{u}_y\right) < 0$$

or, considering zonal asymmetry, as [*O'Sullivan and Hitchman*, 1992]

$$f(f + \zeta) < 0,$$

where f is the Coriolis parameter, $\bar{u}_y$ is the meridional shear of the zonal basic flow and ζ is local relative vorticity. Once the atmosphere turns inertially unstable, meridional circulations are supposed to arise in order to redistribute the angular momentum imbalance.

[3] *Dunkerton* [1981] discussed inertial instability on the equatorial β-plane in the framework of linear, zonally symmetric perturbations on a zonal basic flow with a constant static stability and a constant meridional shear, but without vertical shear. He showed that unstable disturbances in the meridional plane as revealed in Figure 1 are induced by inertial instability: Zonal and meridional flows arise to transport the westerly momentum, namely, the large

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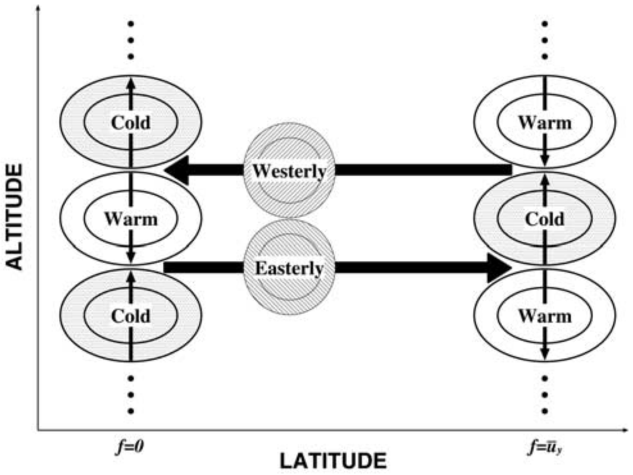


Figure 1. Schematic view of inertially unstable disturbances in the meridional plane. Note that the meridional flows indicated by the thick arrows have maximum amplitudes at the central latitude of the unstable region and exponentially decay going from the center to the boundaries.

angular momentum, toward the equator for stabilization. These meridional flows lead to vertical motions through divergences and convergences at (or inside) the side boundaries of the unstable region, which are accompanied by temperature extrema due to adiabatic expansion and compression. This pioneering paper on inertial instability in the equatorial region has been followed by some theoretical studies; for example, an extension to zonally asymmetric modes by *Boyd and Christidis* [1982] and *Dunkerton* [1983] or to the framework of a nonparallel basic flow by *Dunkerton* [1993] and *Clark and Haynes* [1996].

[4] Observational evidence for inertial instability in the real atmosphere was first introduced by *Hitchman et al.* [1987]. They demonstrated using the limb infrared monitor of the stratosphere (LIMS) data that there sometimes appears vertically stacked temperature extrema of alternating sign, named "pancake structure," in the equatorial lower mesosphere during the observation period (October 1978 – May 1979). Pancake structures persist for about two weeks and are almost stationary with a short vertical wavelength of about 14 km. These characteristic temperature structures were thought to be manifestation of the equatorial boundary of inertially unstable disturbances. Our previous study [*Hayashi et al.*, 1998] found, in the cryogenic limb array etalon spectrometer (CLAES) temperature data, that pancake structures having a vertical scale of about 10 km come out near the equatorial stratopause a few times per winter season of both the Northern and Southern Hemispheres. We indicated that the equatorial pancake structure has its counterpart with the reversed phase in the winter midlatitude, which corresponds to the theoretical temperature disturbances at the boundaries of the unstable region as shown in Figure 1. Such examples of pancake structures in the real atmosphere were also reported by *Knox* [1996] and *Smith and Riese* [1999].

[5] As for wind disturbances induced by inertial instability, there have been few studies trying to reveal observational evidence for them. Using data from the mesosphere-stratosphere-troposphere (MST) radar at Jicamarca (12°S, 77°W), *Fritts et al.* [1992] showed the existence of meridional wind disturbances with vertical scales of 6–10 km in the upper mesosphere in the southern winter. They inferred from the persistency and characteristic vertical wavelength of the disturbances that the features might be due to inertial instability, though their analyses depend on the one-point ground-based observations alone. *Hitchman et al.* [1987] estimated velocity fields from the LIMS temperatures by the use of a balance wind approximation introduced by themselves. While they exhibited localized strong meridional winds in the winter subtropics during pancake structure events, it was not shown whether the wind disturbances have the same vertical scale as the pancake structures. It seems, therefore, that reliable evidence for wind disturbances due to inertial instability has not been reported yet.

[6] In this study we intend to show a clear observational evidence for horizontal wind disturbances caused by inertial instability in the equatorial middle atmosphere. Data from the rocketsonde are used, which can observe the horizontal wind components in the upper stratosphere and the lower mesosphere with a high enough vertical resolution for this study. We make detailed analyses of the rocketsonde observations at Kwajalein (8.7°N, 167.7°E), since the location is thought to be suitable for this study. *Dunkerton*'s [1981] theory (Figure 1) inferred that the meridional flows are maximized at the central latitude of the unstable region while the zonal flows have their maxima in the lower latitude off the center. Our previous study [*Hayashi et al.*, 1998] estimated the characteristic meridional extent of the inertially unstable region as 30°–40°; this means that the center is located around 15°–20°. In the equatorward flank of 15°–20° (and not on the equator), both zonal and meridional wind disturbances induced by inertial instability are expected to be observed. In addition, Kwajalein is so close to the equator that temperature profiles should be affected by equatorial pancake structures in the case of inertial instability. It will be interesting to investigate the rocketsonde profiles of the zonal wind, the meridional wind, and the temperature over the station. The LIMS data are also used to examine the background temperature field, that is, to check the existence of pancake structures.

[7] Another purpose of this paper is to examine the climatology of inertial instability. Previous studies of inertial instability in the real atmosphere used data whose periods are less than 16 months [*Hitchman et al.*, 1987; *Hayashi et al.*, 1998; *Smith and Riese*, 1999; *Fritts et al.*, 1992]. The rocketsonde observations, on the other hand, had been made for more than 20 years at Kwajalein, though the observation interval is not regular and sparse after the 1980s. The data during the entire observation period are investigated to find the seasonality of inertial instability at Kwajalein. Adding rocketsonde data at several stations other than Kwajalein, we try to examine the regionality of inertial instability.

[8] In section 2 we briefly describe the rocketsonde data and the LIMS temperature data. Section 3 displays some profiles of the rocketsonde horizontal winds and temperatures for two possible cases of inertial instability, associated with the LIMS temperature fields during the instability events. The relationship between them and planetary wave breakings are also mentioned. We extend the analyses to the

entire observation period at Kwajalein and to data at other stations for investigation of the climatology of inertial instability in section 4. Finally, section 5 summarizes the present study.

2. Data

2.1. Rocketsonde Data

[9] Rocketsonde data supplied by the U.S. National Climate Data Center (NCDC) were used in this study. The data have been archived from many observation stations in the world since 1957, though mainly located in the Northern Hemisphere. Among them our analyses were concentrated on data of the horizontal wind and the temperature at Kwajalein, Marshall Islands (8.7°N, 167.7°E), where the data were stored from April 11, 1969, to August 25, 1993. The rocketsondes were launched at irregular intervals (a few hours to several months), and measured atmospheric parameters (wind speed, temperature, pressure, density,...) through the stratosphere and the mesosphere. Since the vertical intervals are usually less than 1 km (not constant), we interpolated the data on a grid at 1 km intervals.

[10] As the previous studies using satellite data suggested that disturbances induced by inertial instability appear in the upper stratosphere and the lower mesosphere with a vertical scale of about 14 km [*Hitchman et al.*, 1987] or 10 km [*Hayashi et al.*, 1998; *Smith and Riese*, 1999], we limited analyses of the rocketsonde data to a height range of 30–70 km and applied a band-pass filter to them designed to extract disturbances with wavelength of about 8–15 km. (Small changes of the filter shape do not influence significantly the results described below.) This filtering procedure should remove the background structure having a deeper scale so that filtered profiles are thought to be composed of eddy components. Before filtering, we got rid of a component increasing or decreasing linearly in the vertical and assumed a periodicity that the top of the height range connects with the bottom to save data around the height boundaries. Since some features near the edges of profiles might, therefore, be artificial, correlation coefficients and covariances between profiles were calculated for a height range of 35–65 km.

[11] Note that rocketsonde profiles in this study are exhibited along a logarithmic pressure axis so that we can compare them with global temperature fields observed by LIMS whose data are put on a pressure grid (see section 2.2). Pressure observations by the rocketsonde were used to convert the vertical coordinate from geometric height to pressure.

2.2. LIMS Data

[12] In order to investigate background temperature fields when the rocketsonde observations at Kwajalein capture wind disturbances possibly induced by inertial instability, we made use of the version 4 (V4) LIMS data. LIMS was an infrared spectrometer on board the Nimbus 7 satellite and observed the earth's atmosphere at the limb in the stratosphere and the mesosphere from October 25, 1978, to May 30, 1979. The mapped data are available in the form of 13 harmonic coefficients (the zonal mean and the cosine and sine coefficients of the first six zonal wave numbers) at 18 pressure levels from 100 hPa to 0.05 hPa and at 4° intervals in latitude from 64°S to 84°N. The original intervals of the pressure levels are not constant (1.6–4.8 km), and we interpolated the data onto the pressure grid with a constant interval of about 2.7 km defined as $p = 100 \times 10^{-(i-1)/6}$ hPa ($i = 1, 2, \ldots, 20$) in case of filtering in the vertical direction as mentioned below.

[13] In the investigation of the LIMS temperatures in the meridional plane, a simple high-pass filter was applied to the data in order to remove vertically deep structures associated with extratropical planetary waves. The filter is the same as employed in our previous study [*Hayashi et al.*, 1998] using the temperature data of CLAES on board the UARS satellite; this is designed as subtracting about 10 km running mean from the original raw value at each vertical grid point. Using the high-pass filter it was found that an equatorial pancake structure has its counterpart, which is hidden by planetary waves with a deep vertical scale in the winter midlatitude.

[14] We used the V4 LIMS temperatures for this study since the V4 mapped data are more suitable for the analysis of phenomena with a small vertical scale than the version 5 (V5) data, as mentioned by *Hitchman and Leovy* [1986]. However, results shown in the following sections are essentially unchanged even if the V5 mapped temperatures are used. (For more detailed information on the LIMS data, see *Gille and Russell* [1984] and *Gille et al.* [1984].)

3. Case Studies

3.1. Wind Disturbances Measured by Rocketsonde

[15] From Figure 1, the poleward-westward and equatorward-eastward flow correlations (which mean the equatorward flux of angular momentum) are expected to occur in the inertially unstable region. In the Northern Hemisphere the eastward and northward components of horizontal wind disturbances should be anticorrelated in the vertical direction. The wind fluctuations have a quadrature relationship with the temperature fluctuations (pancake structures) at the side boundaries of inertial instability. These phase relationships are used to find profiles of inertial instability in the rocketsonde observations.

[16] To begin with, we investigated the correlation between the eastward component and the northward component of horizontal winds in the height range of 35–65 km observed by the rocketsonde at Kwajalein. It was found that there are two anomalous cases during the LIMS period in which the correlation coefficients are lower than −0.7: one on December 13, 1978 (case 1), and the other on February 24, 1979 (case 2). These are thought to be disturbances induced by inertial instability because the highly negative correlation between the horizontal wind components is one of consequence of inertial instability. We introduce detailed analyses of the two characteristic cases in the following.

[17] Figure 2 shows profiles of the eastward wind (U), the northward wind (V) and the temperature (T) for case 1, and Table 1 gives correlation coefficients and covariances between them, using the rocketsonde data on December 13, 1978. Note that the data are filtered by the band-pass filter mentioned in section 2.1, so that the profiles are supposed to consist of eddy components with vertical scales of about 8–15 km. Influence of the diurnal thermal tide,

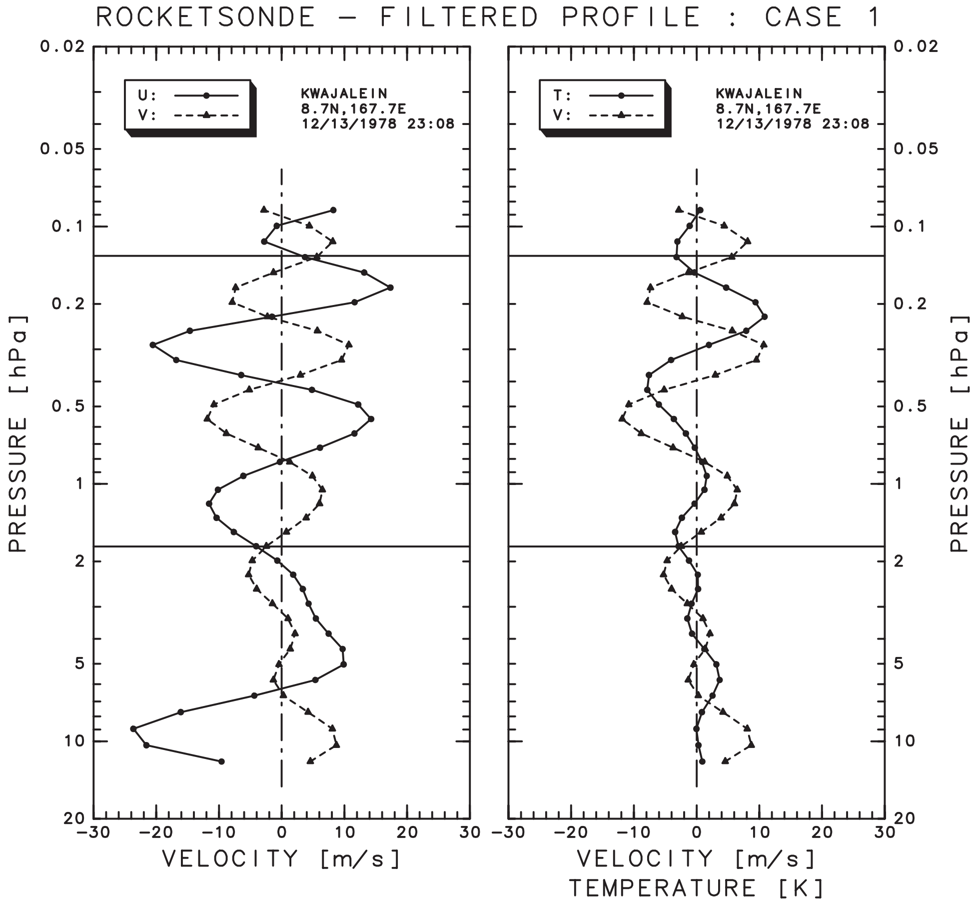


Figure 2. Vertical profiles of the rocketsonde observation on December 13, 1978. The time of observation is expressed in UTC. The eastward wind (U) and the northward wind (V) are shown on the left while the temperature (T) and the northward wind (V) are shown on the right. These data are filtered by the band-pass filter (see text), and are plotted on the pressure grid using pressure data measured simultaneously by the rocketsonde. The pressure range between the two transversal lines at 1.75 hPa and 0.13 hPa corresponds to the box height in Figure 5.

whose vertical wavelength is expected to be much longer [e.g., *Lindzen*, 1967], would be also masked out with this filtering procedure. The profiles of U and V are nearly anticorrelated particularly in the pressure range from 1.75 hPa to 0.13 hPa (indicated by two transversal lines), roughly corresponding to the geometric height range between 44 km and 62 km. The relationship between T and V is 1/4 cycle out of phase with the extrema of T over those of V in the same height range. The wavelength of the disturbances is estimated about 10 km (longer at lower levels) and the maximum amplitude is about 20 ms^{-1} for U, 12 ms^{-1} for V and 10 K for T, respectively. The phase relationships mentioned above are similar to those in *Dunkerton*'s [1981] theory (Figure 1) and the wavelength of about 10 km is consistent with estimations in the previous studies using the limb-viewing satellite data [*Hitchman et al.*, 1987; *Hayashi et al.*, 1998; *Smith and Riese*, 1999]. These results estimated from the figure are supported by the statistical values in Table 1; the correlation coefficient between U and V is close to -1, which indicates a reversed-phase relationship between them and a good linearity. The covariance shows a large negative value as inferred from the amplitudes of U and V. Those values for the relationship between T and U(V) are almost zero, and well represent the quadrature relationship seen in Figure 2.

[18] The same analyses were made for case 2, and the results are shown in Figure 3 (filtered rocketsonde profiles at Kwajalein using the data on February 24, 1979) and in Table 2 (correlation coefficients and covariances between the profiles). It is recognized in Figure 3 that the profiles of U and V are 180° out of phase while those of T and V are 90° out of phase mainly in the height range indicated by two transversal lines at 4.25 hPa ($\sim$ 38 km) and 0.33 hPa ($\sim$ 56 km), though these phase relationships are not so clear near the boundaries. In case 2, the vertical wavelength of the

Table 1. Correlation Coefficients and Covariances Between the Eastward Wind (U), the Northward Wind (V), and the Temperature (T) of the Rocketsonde Profile at Kwajalein on December 13, 1978[a]

	U–V	T–U	T–V
Correlation coefficient	−0.78	0.03	0.00
Covariance	−44.08	1.21	0.01

[a] These values are calculated in the height range between 35 and 65 km.

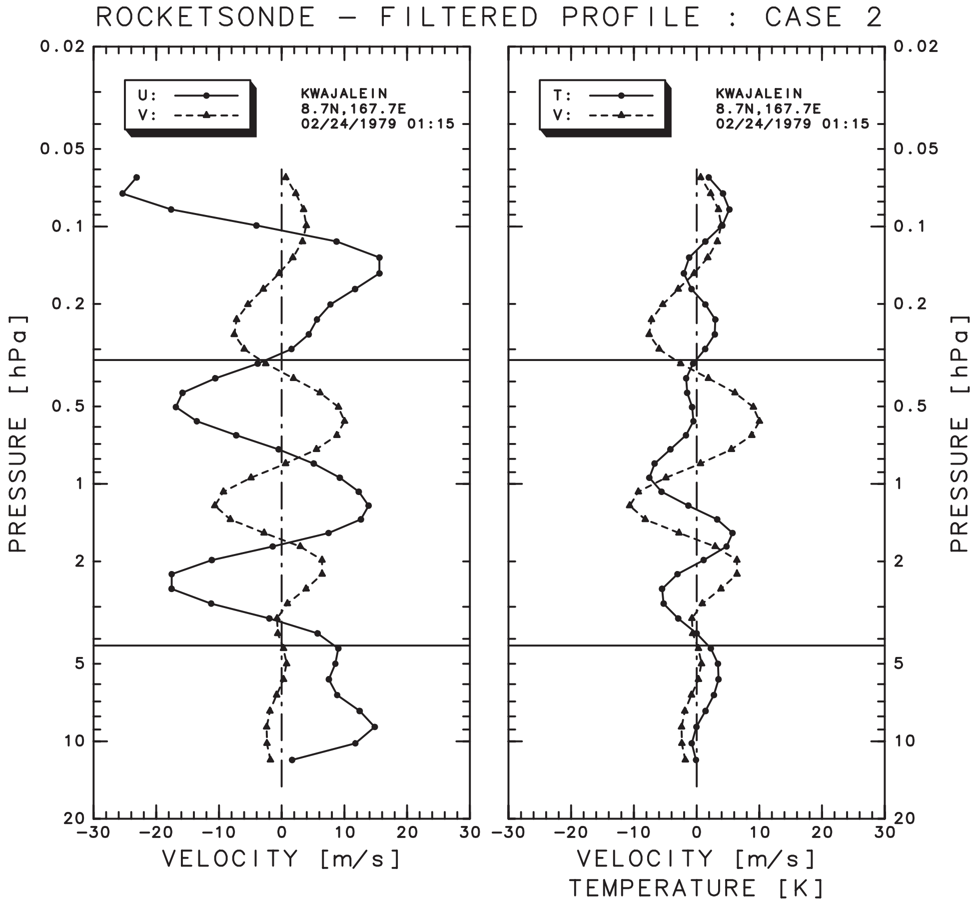


Figure 3. As in Figure 2, except the data on February 24, 1979. The pressure range between the two transversal lines at 4.25 hPa and 0.33 hPa corresponds to the box height in Figure 6.

disturbances is estimated about 10 km (longer at higher levels) and the maximum amplitude is about 18 ms^{-1} for U, 10 ms^{-1} for V and 8 K for T, respectively. The statistics given in Table 2 are consistent with the phase relationships and the amplitudes shown in Figure 3.

3.2. Pancake Structures in the LIMS Temperatures

[19] If the wind disturbances detailed above are really caused by inertial instability, pancake structures should be found in the temperature field over the equator and in the midlatitude [*Hayashi et al.*, 1998]. We checked first the activity of equatorial pancake structures around the two cases using the LIMS temperatures. Figure 4 exhibits a time-longitude section of the equatorial pancake structure index which indicates when and where pancake structures appear. The index is consist of temperature variance over 4.6–0.15 hPa (roughly corresponding to the height range where correlation coefficients and covariances of the rocketsonde profiles are estimated) calculated from the LIMS anomaly data. Before the calculation of index, the LIMS data were smoothed in time by 7-day running mean to remove high frequency phenomena such as fast Kelvin waves and filtered in vertical by the high-pass filter to weaken influences due to vertically deep structures such as planetary waves. This procedure is the same as employed in our previous study [*Hayashi et al.*, 1998], where the index was proved to represent the activity of pancake structures. On the diagram, observations of the rocketsonde at Kwajalein are indicated by small dots, and the two cases discussed are emphasized by stars. Figure 4 clearly shows the existence of pancake structures corresponding to the two cases; it is seen that case 1 is located in the western boundary of a huge inertial instability event while case 2 is located around the center of a tiny one. We next investigated spatial features of the pancake events and compared them with those of the wind disturbances described in the previous subsection.

[20] Since Figure 4 suggests that a pancake structure in case 1 stays for about 10 days, the LIMS temperature anomalies averaged during that period were examined. In Figure 5a, displaying a longitude-height section of the temperature anomalies over the equator, a set of vertically stacked temperature extrema, namely, a pancake structure, is obvious in the area indicated by a box. Note that the top and bottom of the box are corresponding to the two transversal lines in Figure 2. The equatorial pancake structure staying near 200°E in the lower mesosphere was already reported

Table 2. As in Table 1, Except for the Data on February 24, 1979

	U–V	T–U	T–V
Correlation coefficient	−0.70	0.23	−0.13
Covariance	−40.51	8.28	−2.46

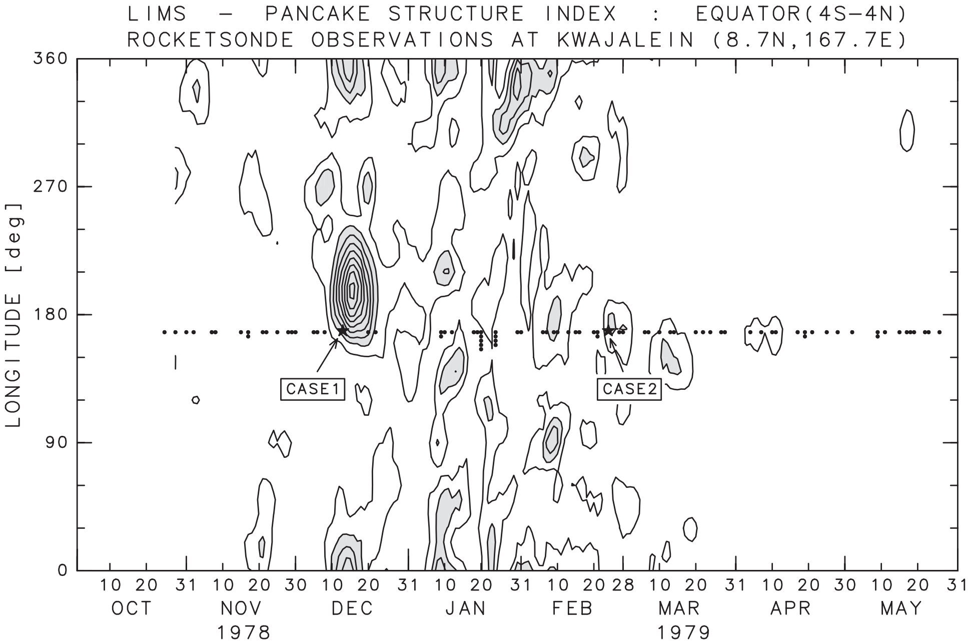


Figure 4. Time-longitude section of the LIMS temperature variances in the height range of 4.6–0.15 hPa (approximately corresponding to 37–61 km). All wave numbers (k = 1–6) are included. The values are averaged over 4°S-4°N. The contour interval is 1.5 K^2 and the regions exceeding 3 K^2 are shaded. Dots and stars indicate a launch (or launches) of the rocketsonde at Kwajalein on the corresponding days. These are plotted at the longitude of Kwajalein (167.7°E).

by *Hitchman et al.* [1987]. Figure 5b shows a latitude-height section at the longitude of Kwajalein (167.7°E), in which the data are filtered vertically by the simple high-pass filter mentioned in section 2.2 in order to avoid contamination due to extratropical planetary waves. We can see not only the equatorial pancake structure as indicated by a box but also another one with the reversed phase in the midlatitude (centered near 32°N). The couple of antiphased pancake structures is evidence for inertially unstable disturbances, though the midlatitude one is shifted slightly downward compared with the equator one. Comparing Figure 2 with Figure 5, we see, in the height range indicated by the lines and boxes, that the temperature profile of the rocketsonde at Kwajalein coincides with the equatorial pancake structure of the LIMS temperatures and that the relationship between the rocketsonde wind disturbances and the LIMS pancake structures is quite similar to the schematic view of inertially unstable disturbances in Figure 1. On the basis of these results, it may be safely said that the horizontal wind disturbances in case 1 are induced by inertial instability.

[21] Another inertial instability event around case 2 lasts for only a few days, and the LIMS temperatures averaged for 4 days were analyzed with the same procedure as in case 1. The spatial structures of the pancake event are shown in Figure 6. An equatorial pancake structure exists near 180°E in the upper stratosphere as indicated by boxes. It has a subtropical counterpart in 20°N–28°N, where some temperature extrema at higher levels appear closer to the equator. The spatial scale of inertially unstable disturbances in case 2 seems to be a bit smaller than in case 1. A comparison between the pancake structures and the horizontal wind disturbances in Figure 3 shows a quadrature phase relationship as expected by *Dunkerton*'s [1981] theory. The wind disturbances in case 2, therefore, can be regarded as evidence of inertial instability.

[22] Note that the rocketsonde wind profiles exhibit no signal of inertial instability except the two cases discussed. The situation is true even for the following observations of the two cases (December 20, 1978, and February 27, 1979), when the pancake structure index is still large (see Figure 4). This might imply that the temperature structures on the equator remain for a few days after the meridional circulations due to inertial instability themselves have disappeared. It seems reasonable that it takes a few days for large temperature disturbances, such as pancake structures, to be fully damped. We can see another large index near Kwajalein in early February 1979 (Figure 4). The pancake structure indicated by the large index, however, might be artificially produced by the data processing procedure. The doubtful large index is not recognized in the V5 LIMS temperature, which seems rather smoother than the V4, while the pancake structures in the two cases detailed above are robust in both the versions. Some other pancake structures (e.g., centered 0°E in mid–December 1978 and near 150°E in early March 1979) are also thought to be artifacts for the same reason. Whether an equatorial pancake structure is really caused by inertial instability would be decided by examining activity of midlatitude planetary waves, as will be described below.

3.3. Planetary Wave Breaking

[23] *Hitchman et al.* [1987] indicated that equatorial pancake structures are synchronized with strong planetary waves in the midlatitude. *Hayashi et al.* [1998] revealed in potential vorticity maps that inertially unstable regions are

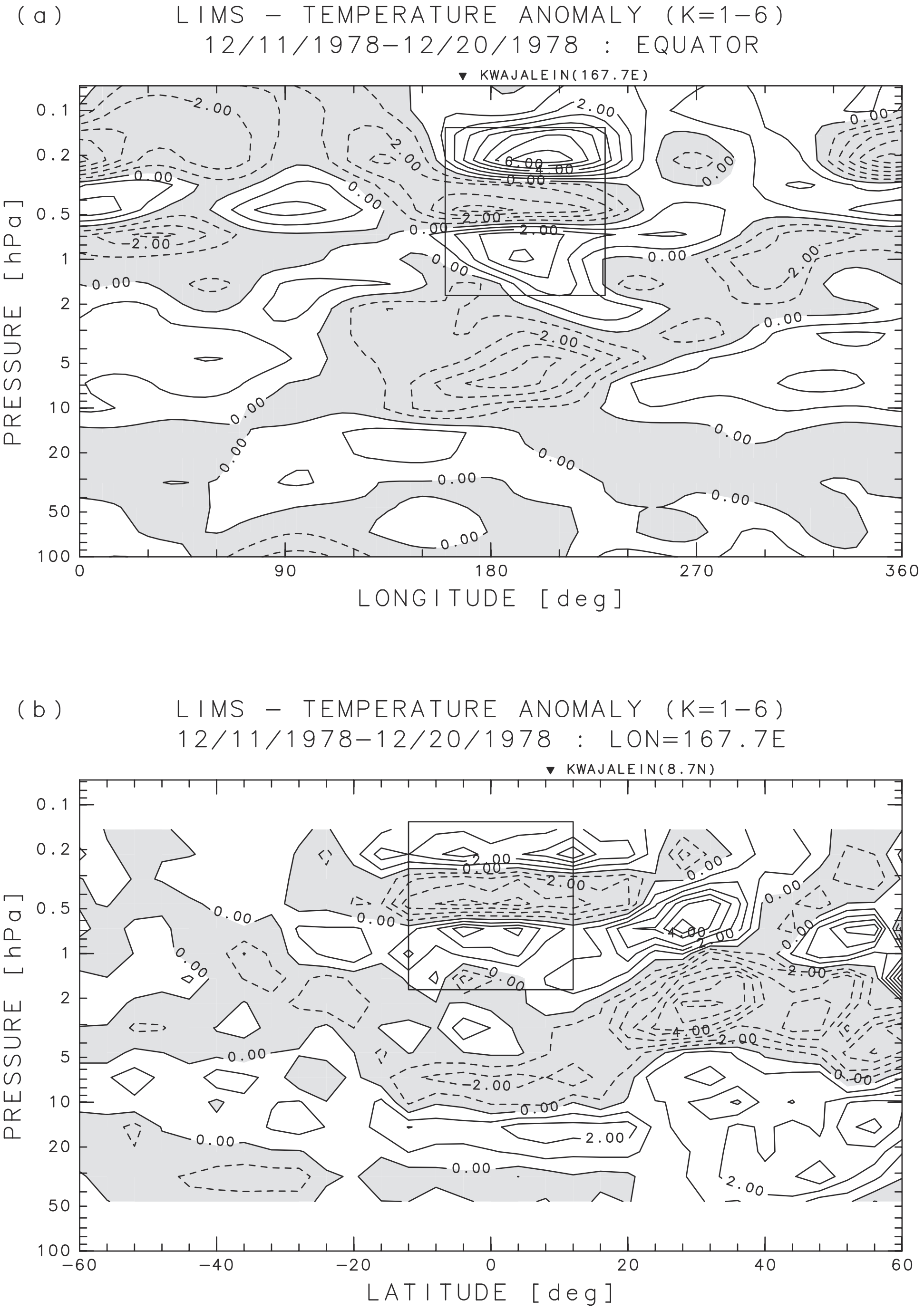
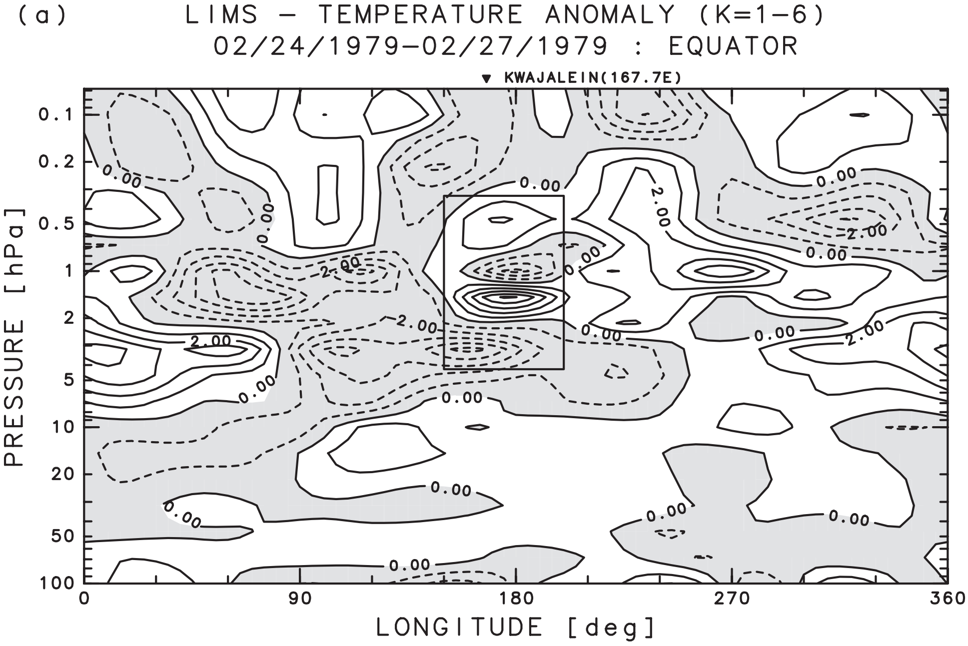


Figure 5. Temperature anomaly fields ($k = 1-6$) in the LIMS data; (a) longitude-height section over the equator (averaged in the latitude band 4°S-4°N) and (b) latitude-height section at the longitude of Kwajalein (167.7°E). The data are averaged for 10 days (December 11–20, 1978). The contour interval is 1 K and the negative anomalies are shaded. The box height corresponds to the specified pressure range in Figure 2.

locally enhanced to the east of planetary wave breaking regions, around where pancake structures are recognized. The linkage between planetary wave breakings in the midlatitude and inertially unstable disturbances in the equatorial region has been reported as well in other observational studies [*Knox*, 1996; *Orsolini et al.*, 1997; *Smith and Riese*, 1999] and numerical studies [*O'Sullivan and Hitchman*, 1992; *Dunkerton*, 1993; *Sassi et al.*, 1993; *Clark and Haynes*, 1996; *Rosier and Lawrence*, 1999]. We examined the occurrence of planetary wave breakings around the two cases, employing the method introduced by *Hayashi et al.* [1998].

[24] Figure 7 shows a time-longitude section of the LIMS temperature anomalies averaged in the midlatitude band (24°N–36°N) and over the same height range as in Figure 4. A localized region of large negative values in Figure 7



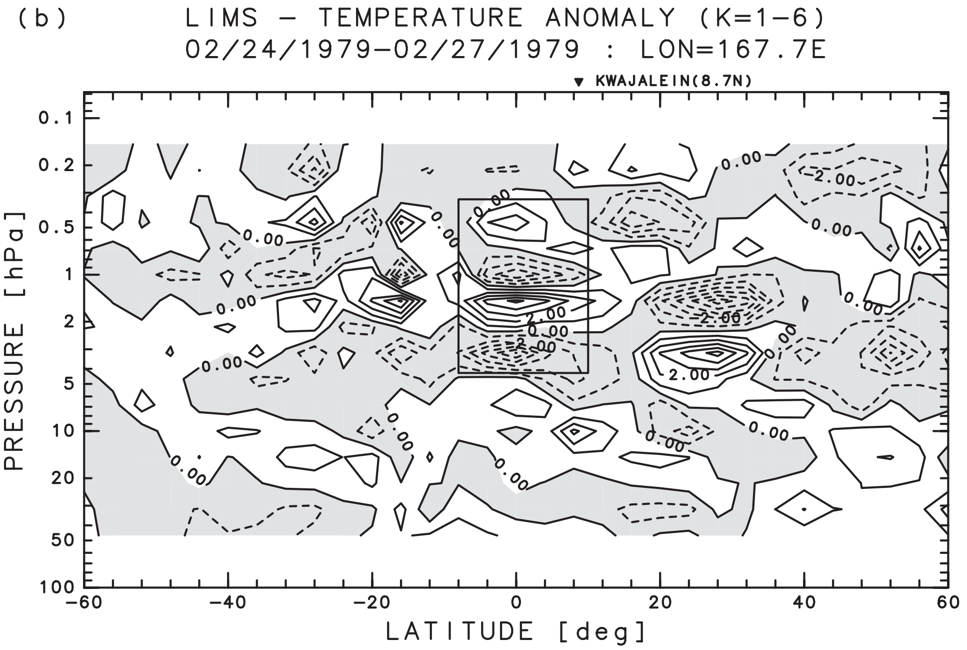


Figure 6. As in Figure 5, except the data averaged for 4 days (February 24–27, 1979). The box height corresponds to the specified pressure range in Figure 3.

would be a good index of a planetary wave breaking event because it is associated with asymmetric outflows of cold air in the polar vortex toward lower latitudes. Our previous study [*Hayashi et al.*, 1998] revealed that this wave breaking index has large negative value to the west of the longitude band where an equatorial pancake structure appears. We see, in Figure 7, large negative indices to the west of Kwajalein in the same time of (or slightly before) the two inertial instability events indicated by star marks. The two cases are consistent with the scenario that inertially unstable disturbances are associated with planetary wave breakings. It is clearly seen that the two wave breaking events are different in scale and strength; this would be related to the difference of inertially unstable disturbances between case 1 and case 2.

3.4. A Comparison Between the Two Cases

[25] Figures 5 and 6 (and Figure 4) show that the pancake extrema in case 1 have wider horizontal extent than in case 2. Daily snapshots of the LIMS temperature anomalies (not shown) indicate much larger amplitude of pancake structures in case 1 (exceeding 10 K) than in case 2 (about 6 K at

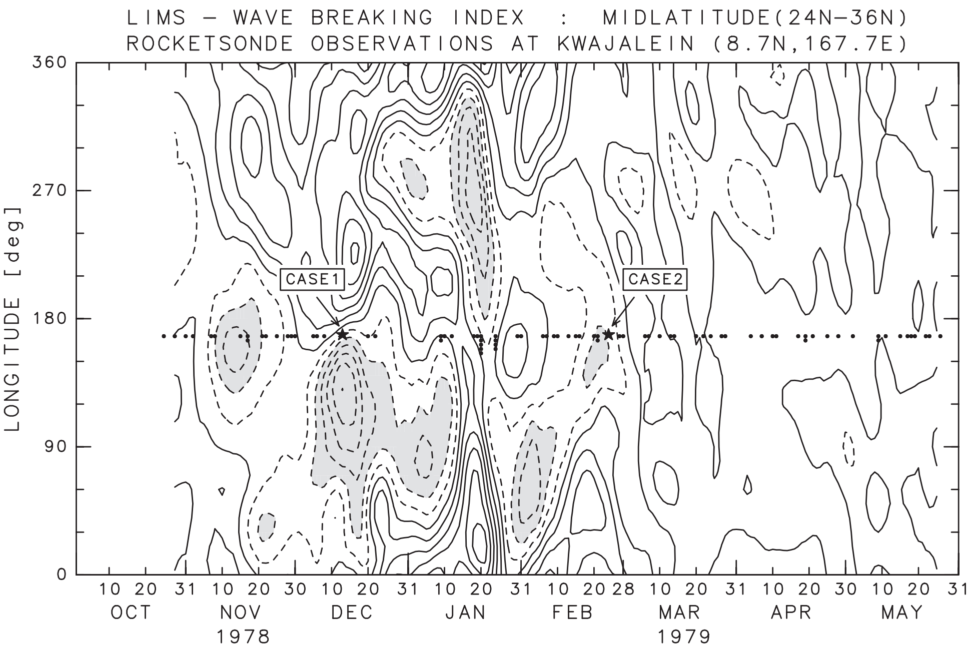


Figure 7. Time-longitude section of the LIMS temperature anomalies averaged over the height range of 4.6–0.15 hPa (approximately corresponding to 37–61 km), the same as in Figure 4. All wave numbers (k = 1–6) are included. The values are averaged in the midlatitude (24°N-36°N). The contour interval is 1.75 K and the regions below −3.5 K are shaded. Dots and stars indicate a launch (or launches) of the rocketsonde at Kwajalein on the corresponding days. These are plotted at the longitude of Kwajalein (167.7°E).

maximum). We could infer stronger disturbances induced by inertial instability in case 1 than in case 2. Nevertheless, the amplitudes of the meridional wind disturbances observed by the rocketsonde in the two cases are estimated to be nearly the same. Two reasons for this inconsistency are supposed: One is that the unstable disturbances occur to the east of Kwajalein in case 1 while just in the longitude of Kwajalein in case 2, as seen in Figures 5a and 6a (and Figure 4). The other reason is that Kwajalein is located slightly nearer the central latitude of the inertially unstable region in case 2 than in case 1. *Dunkerton* [1981] theoretically showed that the meridional flows due to inertial instability have their maxima at the center of the unstable region. It is known from Figures 5b and 6b that the inertially unstable disturbances are centered on 14°N–16°N in case 1 while on 10°N–14°N in case 2. If the strength of circulations induced by inertial instability were identical in both cases, the meridional wind disturbances observed by the rocketsonde at Kwajalein would display larger amplitude in case 2. The zonal wind fluctuations in the two cases also exhibit almost the same amplitude. This would be because Kwajalein is located closer to the axis of the induced zonal flows or to the central longitude of the unstable region in case 2 than in case 1.

[26] The height ranges of each inertially unstable disturbances are different; the wind fluctuations appear in the lower mesosphere in case 1 while in the upper stratosphere in case 2. This might be influenced by the time evolution of equatorial easterlies related to the stratopause semiannual oscillation (SAO), as stated by *Hitchman et al.* [1987]. It is believed that easterlies of the equatorial SAO and westerlies of the polar night jet provide inertially unstable conditions in the winter subtropics. *Hitchman and Leovy* [1986] revealed that the position of maximum easterlies goes down from the lower mesosphere to the upper stratosphere as the SAO westerlies descend during the period of December 1978 – February 1979 (see Figure 3 in their paper).

[27] From a comparison of the rocketsonde temperature profiles, it is seen that the vertical wavelength of the temperature disturbances is a bit shorter in case 2 than in case 1, though the difference is not recognized in the wind disturbances for unknown reason. The pancake structures in the LIMS temperatures clearly reveal a smaller spatial scale in case 2 not only in the vertical but also in the meridional dimension. This observational result might lead to a hypothesis that the vertical wavelength of disturbances due to inertial instability depends on their meridional scale. *Hitchman et al.* [1987] demonstrated an equation relating the vertical scale of unstable perturbations to the meridional scale of them assuming the synchronization of an equatorial unstable mode to the stationary planetary wave in the midlatitude. They and *Hayashi et al.* [1998] estimated, in this way, a theoretical vertical scale of inertially unstable disturbances from the meridional scale of pancake structures; the results were consistent with the observations. On the other hand, *Dunkerton* [1981] assumed eddy diffusivity to get a finite vertical scale of the inertially unstable disturbances, and *Hitchman et al.* [1987] and *Fritts et al.* [1992] tried to estimate a vertical scale with the value of diffusivity predicted by the gravity wave breaking. *Smith and Riese* [1999] discussed a possibility that the equatorial Kelvin wave might control the vertical scale of the unstable disturbances. To answer this problem, what determines the

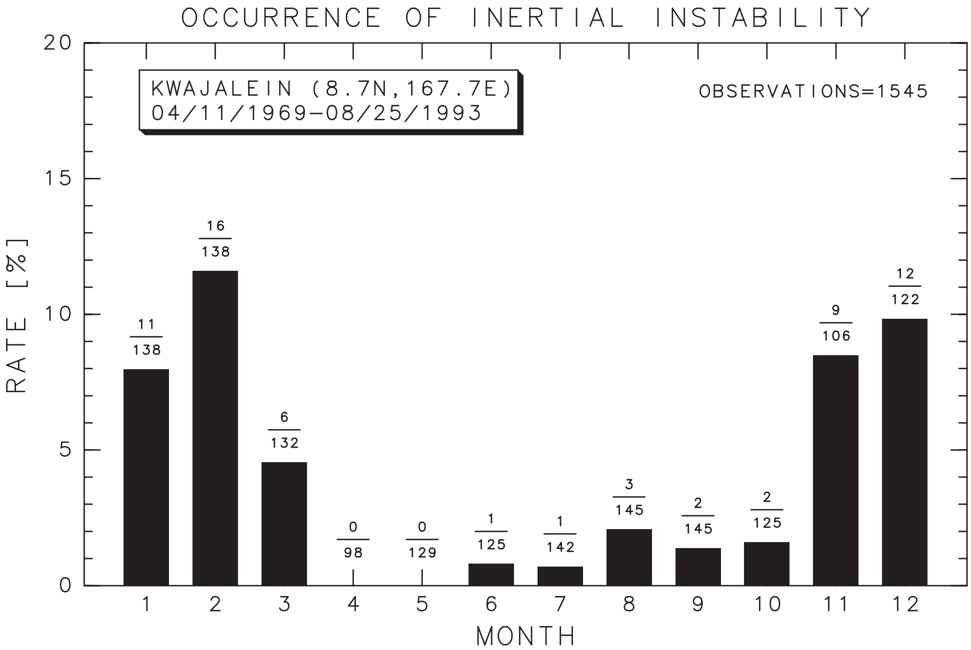


Figure 8. Occurrence frequency of inertially unstable disturbances at Kwajalein in each month. Numerics over each bar express the number of wind profiles possibly influenced by inertial instability (numerator) and that of total available observations (denominator) in each month through the entire period.

vertical scale of inertially unstable disturbances, much more observational studies will be needed.

4. Seasonality and Regionality of Inertial Instability

[28] We tried to extend analyses to all rocketsonde wind profiles during the entire observation period at Kwajalein. It has been known from the case studies in section 3 that the horizontal wind profiles representative of inertially unstable disturbances have a large amplitude and a highly negative correlation between the eastward component and the northward component, as revealed by the correlation coefficients and covariances given in Tables 1 and 2. Except for the two cases discussed, the wind profiles during the LIMS period show no signal of inertial instability, and the correlation coefficients and covariances are never below -0.65 and -25.0, respectively. On the basis of these values, we adopt the following criterion for the occurrence of inertially unstable disturbance: A correlation coefficient between the eastward component and the northward component of horizontal winds is below -0.65 and a covariance below -25.0 in the height range of 35–65 km. Note that this criterion implicitly includes a limitation of vertical scales of about 8–15 km since the band-pass is applied to the original profiles as mentioned above. A phase correlation between the zonal (meridional) wind profile and the temperature profile is not added to the criterion because temperature observations do not always accompany wind observations.

[29] This criterion was applied to all observations at Kwajalein; the results are represented by a histogram of Figure 8 which shows the occurrence frequency of inertially unstable disturbances for each month. We can see a clear seasonality that most unstable disturbances occur in the northern winter season. The seasonality was already speculated as well from the analyses of the CLAES temperatures in our previous study [*Hayashi et al.*, 1998], though its observation period was over only about 16 months. This result is consistent with the scenario relating inertially unstable disturbances to planetary wave breakings which usually occur in winter. The figure shows that the occurrence rate is not zero even in summer when the realization of inertial instability is doubtful. This might be because some internal gravity waves or dissipative equatorial waves cannot be excluded by the criterion. Although it is not a perfect criterion for inertial instability, the plausible seasonality sufficiently demonstrates its usefulness.

[30] Furthermore, we extended this examination to data at rocketsonde stations other than Kwajalein. Figure 9 shows results at 4 stations located in the tropics. Note that the conditions of inertial instability are reversed in the Southern Hemisphere: A correlation coefficient and a covariance must be above 0.65 and 25.0, respectively. Comparing with the analyses at Kwajalein, it is seen that the rates of occurrence of inertially unstable disturbances are extremely low at the 4 tropical stations. We can recognize hardly any striking seasonality there apart from an unusual large rate in December at Fort Sherman (9.3°N, 80.0°W), which is probably an artifact due to small amount of total observations in the month. The high frequency at Kwajalein is confirmed anomalous in terms of a simple statistics as well. We estimated the mean and standard deviation (σ) for occurrence rate of inertially unstable disturbances at 11 stations (Kwajalein, the 4 tropical stations mentioned above and other 6 stations in the extratropics), where a large number of observations were made for many years. It turned out that the occurrence frequency at Kwajalein differs from the mean by about 2.6σ (if this statistical test

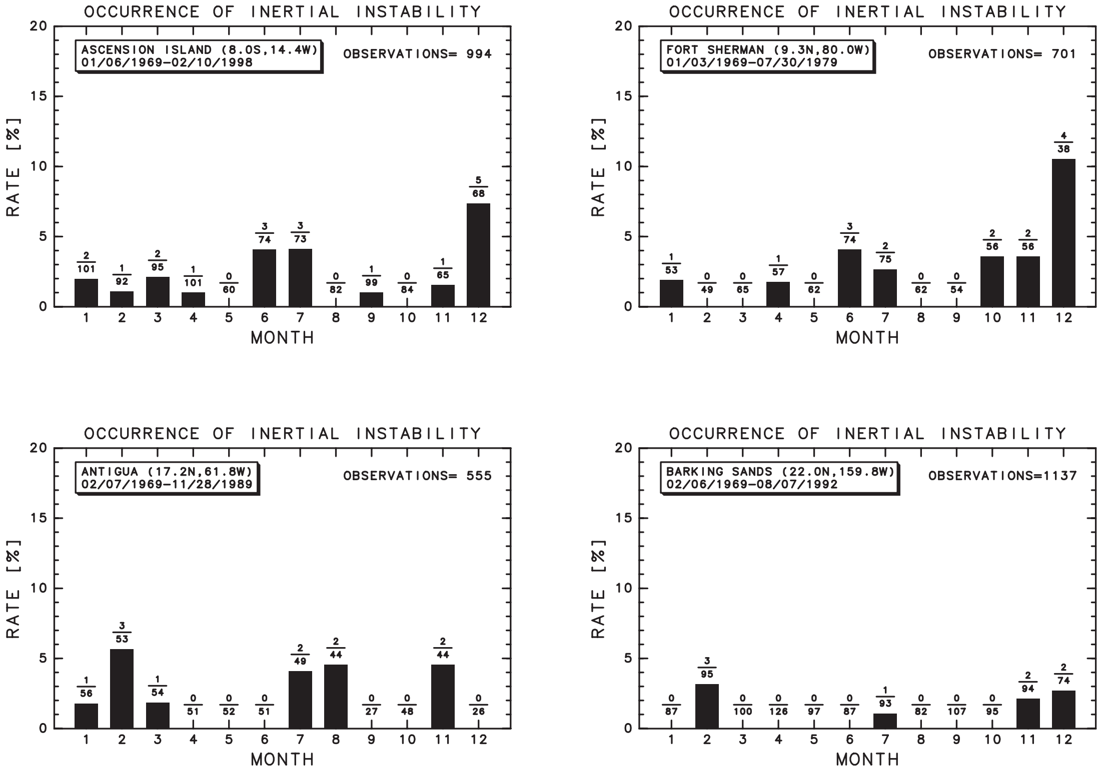


Figure 9. As in Figure 8, except at 4 tropical stations other than Kwajalein.

is limited to the winter season, the difference reaches to about 3.0σ). The large difference from the mean indicates that Kwajalein is distinct from other stations in activity of inertial instability. Particularly, the difference between Kwajalein and Fort Sherman, which are in almost the same latitude, implies regionality that inertially unstable disturbances prefer to occur over the Pacific rather than over the Atlantic. This is a reasonable result as long as the close connection between inertially unstable disturbances and planetary wave breakings is true. It has been reported that wave breakings frequently occur in geophysically preferred regions, near the Aleutian high [*Baldwin and Holton*, 1988]. The Aleutian high is commonly found in the winter stratosphere over the Pacific [*Harvey and Hitchman*, 1996], and irreversible deformation of potential vorticity contours is seen to the south of it [see, e.g., *McIntyre and Palmer*, 1983, 1984]. Few occurrences of unstable disturbances at Ascension Island (8.0°S, 14.4°W) might suggest existence of a preferred longitude band of wave breakings in the Southern Hemisphere, or reflect lower activity of midlatitude planetary waves there. The result at Barking Sands (22.0°N, 159.8°W) and those at several extratropical stations (not shown) indicate much lower occurrence frequency compared with the other tropical stations. Regions of inertial instability seem to be limited to the lower latitude, which is also consistent with the linking between inertially unstable disturbances and planetary wave breakings.

5. Summary

[31] With the use of rocketsonde observations at Kwajalein, we have succeeded in finding clear evidence for horizontal wind disturbances induced by inertial instability, and have investigated them in detail.

[32] Two characteristic wind profiles during the LIMS observation period were expected to be caused by inertial instability since they show highly negative correlation between the eastward component and the northward component: a necessary result of inertial instability (Figures 2 and 3). The characteristics of wind disturbances induced by inertial instability were estimated, though from the two cases alone, as follows: wavelength, about 10 km; amplitude, exceeding 18 ms^{-1} (zonal) and 10 ms^{-1} (meridional), respectively; active height, in the lower mesosphere (early winter) and the upper stratosphere (late winter).

[33] These results were strongly supported by the analyses of the LIMS temperature data. It was revealed that pancake structures, a strong piece of evidence for inertially unstable disturbances, appear simultaneously in the longitude of Kwajalein over the equator and the midlatitude (Figures 5 and 6). Comparisons between the wind disturbances and the pancake structures showed that they have the same vertical wavelength and a 1/4 cycle phase difference as expected by *Dunkerton*'s [1981] theory (Figure 1). It was confirmed that planetary wave breakings in the winter midlatitude precede these inertial instability events (Figures 4 and 7), as had been indicated in the previous studies.

[34] The analyses of rocketsonde observations were extended to other periods at Kwajalein and to other observation stations. We found that the occurrence of inertially unstable disturbances at Kwajalein is strongly biased toward the winter season (Figure 8). At other stations, the occurrence frequency of unstable disturbances is extremely small and the seasonal difference is vague even in the equatorial region (Figure 9). These results imply that inertially unsta-

ble disturbances usually occur in a certain longitude band in the tropics. The seasonality and regionality of inertial instability would be due to those of planetary wave breakings in the midlatitude which have a similar climatology.

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