Average Vertical Motions in the Tropical Atmosphere Observed by a Radar Wind Profiler on Pohnpei (7°N Latitude, 157°E Longitude)

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ABSTRACT

Average vertical profiles of the vertical wind obtained under clear sky conditions as well as under conditions of both light-to-moderate and heavy rainfall are presented from data obtained using a radar wind profiler located on the island of Pohnpei (latitude 7°N, longitude 157°E). The average profiles for the precipitation conditions were obtained, insofar as possible, under conditions similar to those present within the stratiform and convective regions of tropical mesoscale convective complexes. Comparison between the vertical wind profiles obtained from the wind profiler and vertical wind profiles obtained earlier by more conventional methods (i.e., deduced from the convergence–divergence of mesoscale horizontal winds) shows that, while the general features of the profiles obtained by both techniques are similar, the profiler results exhibit somewhat more detail. The profiler is able to resolve long-term average vertical motions down to the ~cm s^{-1} subsidence that occurs under clear air conditions. Additional evidence for an apparent difference between vertical wind profiles in the Atlantic and Pacific regions in heavy convection reported earlier, is presented.

1. Introduction

A vertically directed 50 MHz radar wind profiler has operated continuously since May 1984 on the Island of Pohnpei (formerly Ponape) in the East Caroline Islands (7°N, 157°E). The resulting dataset, which consists primarily of vertical profiles of the vertical wind obtained roughly every minute, has been used in the present study to determine the average characteristics of vertical motions under differing atmospheric conditions. Since the 50 MHz wind profiler is essentially an all-weather device, we have been able to obtain average vertical wind profiles under conditions ranging from clear-air subsidence, through light-to-moderate rainfall, to heavy rainfall. These profiles can be compared directly with vertical wind profiles deduced earlier by a number of investigators using more conventional techniques, particularly during GATE (GARP Atlantic Tropical Experiment) and MONEX (International MONsoon EXperiment).

One of the major dynamic features of the tropical atmosphere is the tropical Mesoscale Convective Complex (tropical MCC) or cloud cluster. These systems have been studied extensively during both GATE and MONEX (see, for example, the reviews by Houze and Hobbs, 1982; Johnson and Houze, 1987). Briefly, tropical MCCs comprise large areas ($\geq 10^4$ km^2) of cloud systems that: 1) are organized on both the synoptic scale and the mesoscale, 2) contain distinct regions of both stratiform and convective precipitation, and 3) strongly influence the large-scale atmospheric circulation, both by the release of latent heat as well as by altering the local radiation budget. Precipitation from tropical MCCs, moreover, provides a major portion of the rainfall in the tropics. Specifically, the stratiform rain regions are associated with the extensive outflow regions corresponding to the mesoscale "anvil" that generally occurs downwind of the convective regions of mature MCCs. In general, stratiform rainfall is lighter, more uniform, and more spatially extensive than the intense but sporadic rainfall associated with the smaller-scale convective regions.

Vertical circulation within the stratiform portion of these complexes consists primarily of deep but gentle updrafts (~10–50 cm s^{-1}) in the cloud layer above the freezing level (Gamache and Houze, 1982; Houze, 1982; Houze and Hobbs, 1982). These updrafts are superposed over an unsaturated mesoscale downdraft (Zipser, 1969; 1977). A somewhat different picture describes the convective portion of the complexes, where both moderate convection and the narrow regions of intense updrafts and downdrafts (the "hot towers" first described by Riehl and Malkus, 1958) are supported by low-level convergence.

In order to examine the Pohnpei data in terms of the vertical motions within tropical MCCs as well as in the ambient environment in which they are embedded, we have selected our averaging process in terms

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of the hourly rainfall rate as recorded by the local NWS station on Pohnpei. Proper averaging of our vertical wind profiles relative to local rainfall rate enables us to compare our data with vertical wind profiles deduced by other techniques for similar precipitation (and non-precipitation) conditions.

Note that the results discussed here pertain to the tropical atmosphere directly over Pohnpei, a relatively large island with pronounced orography (diameter ~ 20 km; maximum elevation ~ 780 m). While it is premature at this point to interpret our observations in terms of the general features of atmospheric motions over the equatorial Pacific, we will show that in many respects they closely resemble the results deduced for general vertical circulation characteristics obtained from other studies (i.e., GATE and MONEX) over the open ocean. Indeed, Reed and Recker (1971) point out that the influence of Pohnpei on divergence measurements is likely to be small above about 1 km, and suggest that the effects of the island on rainfall and moisture convergence is, at most, a secondary perturbation.

2. Radar system description

The Pohnpei wind profiler is an improved version of the profiler originally installed by NOAA's Aeronomy Laboratory at Platteville, Colorado, in 1978 (Ecklund et al., 1979). Except for minor details, the overall system description included in this reference applies equally well to the Pohnpei profiler, and will not be repeated here. Specific operating parameters at Pohnpei include the antenna area (=100 m × 100 m), the two-way half-power beamwidth (~2.1°), the operating frequency (49.920 MHz), the transmitted peak pulse power (~40 kW), the average transmitted power (~200 W), and the vertical range resolution (~2.4 km). Note that the data presented herein have been plotted at 1.2 km intervals; this is because the radar returns have been sampled at twice the resolution to "smooth" the vertical profiles for visual continuity.

3. Accuracy of the average vertical velocity measurements

In the following discussions we will ascribe uncertainties as small as a few mm s^{-1} to the long-term average vertical velocity profiles obtained by the Pohnpei profiler under some conditions. In view of the relatively small error bars that are assigned under such conditions, it is important to outline the process of error-bar determination in our analyses, and to discuss briefly a series of additional factors that could affect our results. Because these discussions are relatively lengthy and do not contribute directly to the main research effort reported here, they are included as an Appendix. In this Appendix we outline our general technique for obtaining statistically significant long-term averages of the vertical wind. We also discuss a variety of potential sources of error inherent in these kinds of observations (systematic biases in our data-taking routines, antenna pointing accuracy, and the aspect sensitivity of the echoing region that can effectively "tilt" a vertically directed antenna beam).

Based on the discussions given in the Appendix, a critical examination of the possible errors that could arise in accurately measuring the long-term average vertical wind velocity using the VHF wind profiler technique points to a number of potential problems. While some of these problems can be shown to be insignificant, the possibility exists that other problems could preclude an accurate determination of long-term vertical velocities. It is impossible at this point to establish an absolute measurement accuracy under these conditions.

Fortunately, however, it is possible to establish a reasonable estimate for the accuracy of our measurements independent of these limitations. We do this by comparing our measured average vertical profiles obtained under very quiet (clear-sky) conditions with profiles deduced for the same conditions by conventional techniques. The vertical velocities so deduced fall in the range of fractions of a cm s^{-1}. Our measured values will be shown to agree quite well with those deduced values. It is therefore reasonable to conclude that, since we have agreement on the scale of a fraction of a cm s^{-1} under quiet conditions, then our remaining results, which exhibit vertical velocities one to two orders of magnitude larger than these values, also exhibit the same inherent precision. This result strongly suggests that the potential computational biases, antenna-pointing directions and aspect sensitivity problems discussed above, at least for long-term averaged measurements, do not seriously modify our results.

4. The average vertical profile of the vertical wind under "clear-air" conditions

The average vertical profile of the vertical wind over Pohnpei under relatively clear conditions during the period 8 December 1984 to 13 June 1985 is shown in Fig. 1. To produce this profile we have averaged 240 hours of vertical wind profiles from the Pohnpei profiler corresponding to all of the individual hourly periods when the sky cover determined by the Pohnpei NWS station was reported to be ≤30%. The horizontal error bars shown on the profiler data represent the standard error of the mean discussed in the Appendix (the larger error bars between 14 and 16 km arise both from the fact that fewer data values were available in this region of weaker signals just below the tropopause and because the vertical wind variance near the tropopause is larger). The relatively small magnitude of these error bars (typically ±0.25 cm s^{-1}) can be attributed to the large number (~10^4) of individual profiles incorporated in this average as well as to the relatively small magnitude of the instantaneous vertical wind fluctuations during nondisturbed (i.e., clear) conditions (Ecklund et al., 1986).

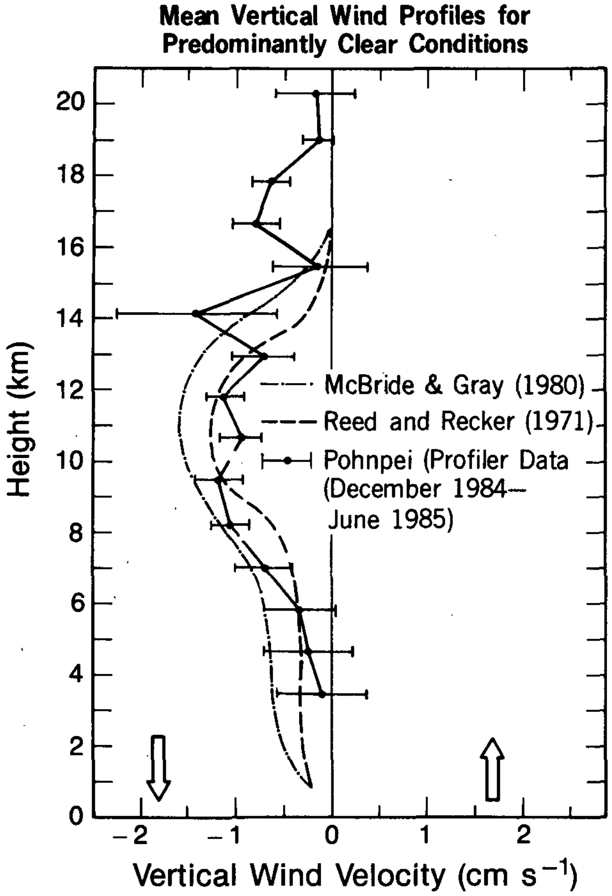

FIG. 1. Average vertical wind profile determined by the Pohnpei wind profiler for 250 hourly periods between December 1984 and June 1985, when the sky cover was ≤30% as determined by the Pohnpei NWS station. The two additional profiles were deduced earlier for similar conditions by more conventional techniques.

For comparison purposes, we include the dashed curve obtained from an earlier study by Reed and Recker (1971). This profile was deduced from horizontal divergence profiles obtained from a triangular configuration of weather stations consisting of Pohnpei, Kwajalein, and Eniwetok. We plot here their average results for the "ambient" (i.e., cloud-free and gently subsiding) phase of 18 separate synoptic wave disturbances between July and September 1967). Such average conditions correspond reasonably well to our ≤30% sky cover criterion.

For an additional comparison, the dot-dashed curve included in the same figure was deduced from an average of the 1000 and 2200 local time vertical velocity profiles shown in Fig. 6 of McBride and Gray (1980b). These results were obtained from a composite analysis of the mean divergence and deduced vertical motions within large clear areas in the western Pacific during 1967–68.

Comparison between these three profiles shows reasonably good agreement below about 16 km. At heights above 16 km, however, the two deduced profiles go to zero. This results from the assumed boundary conditions in these analyses (Reed and Recker, 1971, required mass balance between the surface and 80 mb; the McBride and Gray, 1980b, results assumed that the vertical velocity was identically zero at the tropopause).

The good agreement between the observed and deduced profiles below ~16 km attests to the accuracy of the profiler measurements. Moreover, this magnitude of subsidence is required in the clear air to adiabatically balance atmospheric radiation to space (Johnson, 1982). On the other hand, the downward motions above the tropopause revealed by the profiler measurements suggest that the zero vertical velocity boundary condition used in the other analyses should, if possible, perhaps be assigned at a somewhat higher level in future studies.

It is important to note that the Pohnpei sky-cover records are not kept continuously, but are recorded only between 0700 and 2400 local time. It is therefore possible that diurnal effects have not been entirely averaged out. On the other hand, the maximum expected diurnal variations under clear conditions would be roughly one-half of the mean value at any given height (McBride and Gray, 1980b). This value is very roughly of the same order as the magnitude of the error bars in the Pohnpei data. Moreover, since we are averaging vertical velocity profiles over the 18-h period of the day when sky coverage data are available, the effect of any diurnal variability should be considerably reduced. It is reasonable to expect, therefore, that our results are indeed representative of the mean subsidence during clear periods.

5. The average vertical wind profile for extended periods with moderate rainfall

Two average vertical wind profiles obtained during periods of moderate but temporally extended rainfall at Pohnpei between October 1984 and September 1986 are shown in Fig. 2, where the area between the two curves has been shaded for clarity. In this case we have chosen a set of criteria for our averaging period which, insofar as possible, brackets the typical rainfall conditions observed in stratiform regions of tropical MCCs. Toward this end we have averaged only those vertical wind profiles when the Pohnpei NWS station (located about 3 km from the profiler site) recorded rainfall rates of at least 0.02 in h^{-1} (~0.5 mm h^{-1}) for at least three consecutive 1-h periods. Two separate upper limits of the individual hourly averaged rainfall rates of 0.5 in h^{-1} (12.7 mm h^{-1}) and 0.7 in h^{-1} (17.8 mm h^{-1}) were chosen to produce the two profiles shown in Fig. 2. A total of 414 hours of data are included in the 0.5 in h^{-1} (12.7 mm h^{-1}) average, and a total of 482 h of data are contained in the 0.7 in h^{-1} (17.8 mm h^{-1}) average.

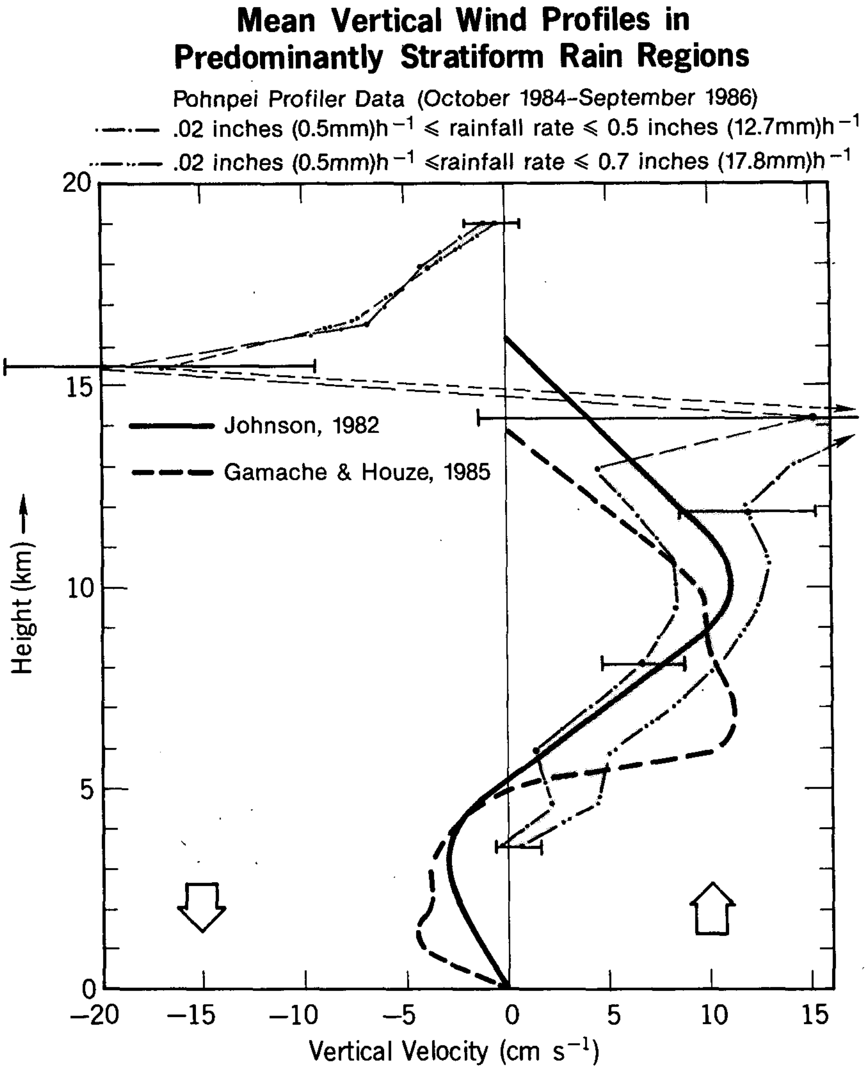

FIG. 2. Average vertical wind profiles from the Pohnpei profiler between October 1984 and September 1986 for rainfall rates corresponding as closely as possible to stratiform conditions. The shaded area delineates the region between profiles obtained for 0.02 inches (0.5 mm) h^{-1} $\leq$ rainfall rate ≤ 0.5 in (12.7 mm) h^{-1} and 0.02 inches (0.5 mm) $h^{-1} \leq$ rainfall rate ≤ 0.7 in (17.8 mm) h^{-1}. The Johnson (1982) profile was obtained by conventional techniques in the south China Sea, while the Gamache and Houze (1985) profile was obtained during GATE in the eastern Atlantic.

The selection of these limits was based on previously observed characteristics of stratiform rain regions of tropical MCCs. For example, Johnson (1982) describes the stratiform region of tropical MCCs over the South China Sea during MONEX as consisting of ". . . generally light precipitation, less than 10 mm h^{-1} . . .". Houze (1982) describes the stratiform region of an idealized cloud cluster as having an area of 2×10^4 km^2 and a total hourly rainfall of 2.5×10^{11} kg, so that the corresponding average hourly rainfall rate is 12.5 mm h^{-1}. In a series of papers that used C-Band radar echo strengths to study tropical squall-line complexes (Gamache and Houze, 1982, 1983; Houze and Rappaport, 1984) the boundary between stratiform and convective rainfall rates was set variously between 8 mm h^{-1} (32 dBZ) and 16 mm h^{-1} (38 dBZ).

Support for the difficulty of establishing a reasonable dividing line between stratiform and convective rainfall rates is provided, for example, by Houze and Rappaport (1984), who demonstrate that both regions exhibit considerable variability, both temporally as well as from region to region. Their measured variability in rainfall rate in both stratiform and convection region was well over an order of magnitude.

In view of these limitations, both the minimum and the two maximum limits given above for our analyses appear reasonable, particularly in view of the fact that a further increase in an upper maximum for our study would tend to include more of the convective (i.e., nonstratiform) regions of the tropical MCCs, which have considerably different vertical profiles (see the following section).

For comparative purposes, Fig. 2 includes vertical profiles deduced for stratiform regions of tropical complexes in both the eastern Atlantic and western Pacific regions. The solid-curve profile was obtained by Johnson (1982) in the South China Sea during MONEX by using rawinsonde data gathered over a triangular area ~ 400 km on a side. These results, which include data obtained over an 11-day period, were obtained in the early afternoon, when the diurnal evolution of the convection (at least in that region of the western Pacific) assured that the complexes were primarily stratiform in character.

A second profile, shown by the dashed curve in Fig. 2, was obtained from an objective analysis of the composite wind and thermodynamic fields of the stratiform region of a single GATE squall line cluster in the tropical eastern Atlantic (Gamache and Houze, 1985). Although tropical squall clusters are somewhat different from the nonsquall clusters that comprise the predominant type of tropical MCCs, they exhibit strong similarities in their structure (Houze and Hobbs, 1982).

Examination of the four curves in Fig. 2 reveals a reasonable correspondence in their overall shapes and magnitudes below 12–13 km: both the Johnson (1982) profile and the Gamache and Houze (1985) profile show ~10 cm s^{-1} upward motions above about 5 km and somewhat smaller downward motions below this level; the average vertical profile of the shaded region between the two profiler curves exhibits similar variations, although the downward motion in the lower regions is not as pronounced in these particular averages (more pronounced downward motions in the lower heights are apparent if somewhat lower values for the minimum rainfall rate are included in the averaging).

The vertical wind profiles obtained from Pohnpei show two additional features of the mean vertical motion, which appear in both curves. The first feature concerns the small positive enhancement in the Pohnpei profiles at about 5 km. This feature is only marginally significant on a statistical basis but is more apparent in different averaging schemes. A similar velocity enhancement has been noted at midlatitudes (Srivastava et al., 1986) within a trailing anvil associated with a squall line. In that instance the enhancement was deduced from a multiple-Doppler analysis using three meteorological (nonclear-air) radars operating at much higher frequencies. This enhancement appears to be associated with the so-called "bright line" feature observed on conventional C-Band radars, and appears to be useful as an indicator of stratiform rain conditions (Cheng and Houze, 1979; Gamache and Houze, 1983).

The other unusual feature in the Pohnpei profiles is a secondary maximum in the upward velocity near 14–15 km coupled with a corresponding downward motion with a maximum near 15.5 km, roughly 1 km below the nominal tropopause. This downward motion extends well into the lower stratosphere. This feature is not apparent in either of the deduced profiles, shown in Fig. 2, possibly because of the upper boundary conditions used in their analyses. However, earlier evidence for a downward flow at near-tropopause heights over tropical cloud clusters has been presented by Williams and Gray (1973) from the analysis of a two-year set of upper-air soundings in the Western Pacific. The average height of vertical wind reversal from their results occurred at about 14 km, with the downward velocities near the tropopause extending to at least 10 cm s^{-1}, a value comparable with our results. Additional support for the existence of these near-tropopause peaks (both positive and negative) is provided by Gray and Jacobson (1977), who present a vertical profile of inferred temperature changes induced by net radiation changes ". . . in a tropical disturbance with an opaque high-cloud cover". The $\pm 1\,^{\circ}C\ d^{-1}$ changes at these altitudes shown in their Fig. 12, while insufficient to produce the magnitude of our observed velocities, are clearly in the sense consistent with our observations (i.e., a negative temperature perturbation situated above a positive perturbation).

6. The average vertical wind profile for heavy rainfall periods

In Fig. 3 we present two curves of the average vertical wind profile obtained by the Pohnpei profiler under the heavy rainfall conditions that should correspond primarily to the convective regions of tropical complexes. Again the area between the curves has been shaded for convenience. Note that these results were not obtained under the same restriction (i.e., continuous rainfall for at least 3 h) used for the stratiform rain studies. Indeed, some of the heavy rainfall could have occurred only in a fraction of the hour-long samples. Under these conditions the hourly averaged vertical velocity values could be somewhat "contaminated" with periods of reduced vertical motions corresponding to lighter rainfall periods.

The dashed curve in Fig. 3 shows the average vertical profile for all hourly periods between November 1984 and July 1986 having rainfall rates ≥ 0.5 in (12.7 mm) h^{-1}; the solid curve was obtained by including only rainfall rates ≥ 1.0 in (25.4 mm) h^{-1} for the same period. The 12.7 mm h^{-1} curve represents 99 hours of averaging, while the 25.4 mm h^{-1} contains only 21 hours of data.

Both profiler curves in Fig. 3 exhibit vertical velocity maxima in the mid-to-upper troposphere with reversed

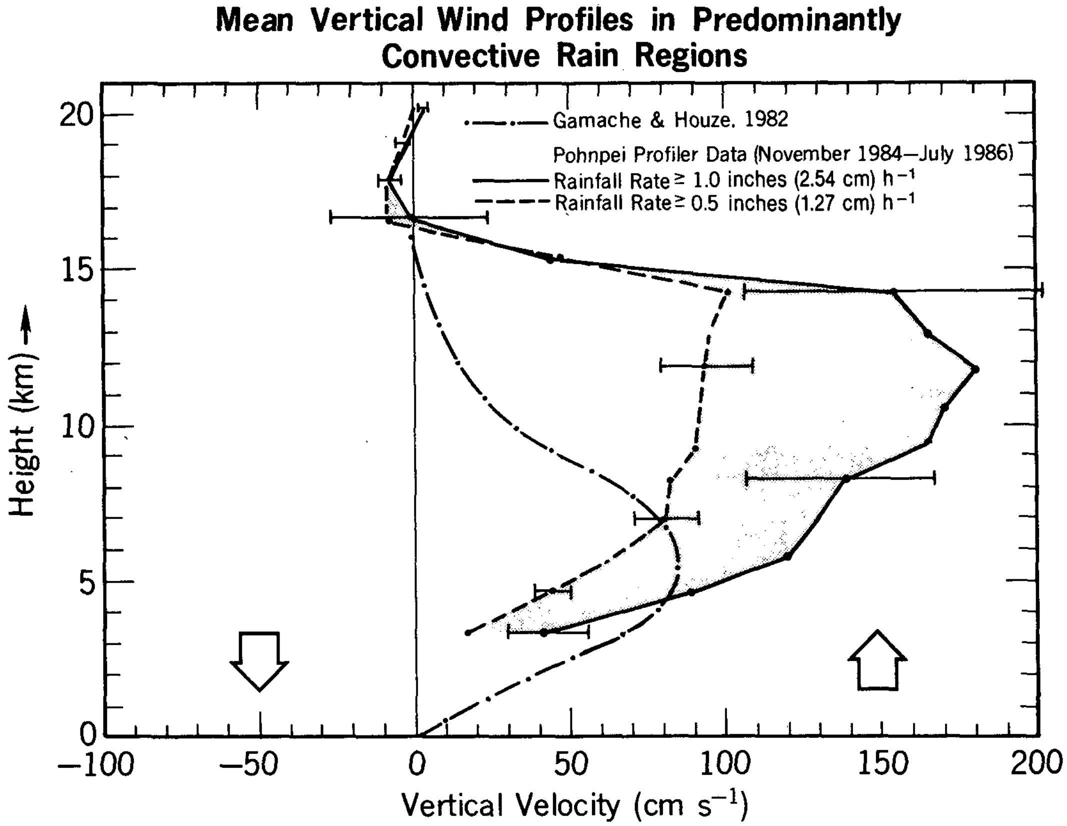
Mean Vertical Wind Profiles in Predominantly Convective Rain Regions

FIG. 3. As in Fig. 2, except for rainfall rates corresponding as closely as possible to convective conditions. The Gamache and Houze (1982) profile was obtained by conventional methods and corresponds to the region of maximum convection associated with a GATE squall line.

(downward) flows near the tropopause that extend well into the lower stratosphere. The magnitude of the upward motions are greater for the heavier rainfall curves.

The dash-dot profile in Fig. 3, which has been included for comparison, was deduced from Gamache and Houze (1982), from a front-to-back cross section of vertical velocity through the most intense portion of the 12 September 1974 GATE squall line. Their results were extracted with a resolution of 50 km × 50 km from composited radar and wind observations.

Comparison between the GATE profile and the Pohnpei profiles shows that the magnitudes of the vertical motions are roughly comparable. The heights of the respective velocity maxima, however, are appreciably different: the two Pohnpei profiler maxima lie above ~11 km, while the GATE profile maximum occurs ~4–5 km. This particular GATE profile resembles profiles obtained during the developing phase of a number of GATE squall-line clusters studied by various investigators, albeit with much coarser resolution (see Houze, 1982, for a summary of these results). According to their studies a second velocity maximum at ~9 km occurs during the later development of the clusters. However, even this height is significantly below the observed maximum at Pohnpei. Moreover, the hourly selection criterion for averaging the Pohnpei profiles for heavy rainfall rates was chosen specifically to include both the developing and mature phases of the complexes. It appears, therefore, that the differences between the height maxima of the vertical velocity profiles at Pohnpei and the profiles obtained during GATE are real.

It is interesting to note that a similar disparity in vertical wind profiles in the western Pacific and eastern Atlantic regions has been reported earlier in a study of the structure of westward-traveling wave disturbances by Thompson et al. (1979). Their study included results from GATE as well as from the study by Reed and Recker (1971), which used the western Pacific triangle of islands (Pohnpei, Kwajalein, and Eniwetok) that yielded the clear air vertical velocity profiles discussed earlier. Among other things, the Thompson et al. study compared vertical wind profiles deduced from horizontal wind data obtained over an area of ~10^5 km^2 in both the western Pacific and the GATE (eastern Atlantic) regions. The Thompson et al. vertical wind profiles (cf. their Fig. 6) showed appreciable differences between the two regions, although the deduced magnitudes were considerably smaller than those presented here, owing in part to the larger area of the examined regions. Their result for the western Pacific showed a vertical velocity profile with a single broad maximum at 8–9 km, in contrast to the double peaked eastern Atlantic profile which maximized between 3–4 km. Thompson et al. (1979) showed that, while the energy source for the eastern Atlantic wave disturbances was provided primarily by conversion from zonal kinetic energy, the western Pacific wave energy source came from condensation heating.

In addition to the Thompson et al. (1979) results, additional studies (e.g., McBride and Gray, 1980a,b) have shown that convergence in the western Pacific is spread over a much deeper layer than the Atlantic convergence in the GATE area.

7. Discussion and conclusions

The purpose of this paper has been to assess the capability of a radar wind profiler located in the tropical Pacific to accurately determine long-period average vertical wind profiles in the troposphere and lower stratosphere in both the clear atmosphere as well as in the convective and stratiform regions of tropical MCCs. In order to accomplish this study we have averaged our continuously measured vertical wind profiles in subsets determined by the hourly rainfall rate measured at the nearby NWS weather station on Pohnpei. The criteria for each subset was established to correspond as closely as possible to these three distinct categories.

In most instances our results compare very favorably with results inferred by more conventional techniques, even down to the ~cm s^{-1} subsidence levels that correspond to clear air conditions. The agreement between the wind profiler results and results from the more conventional horizontal convergence studies (which used appropriately situated rawinsonde sites) establishes a good degree of confidence in the profiler vertical wind measurements, particularly for the regions where the average vertical winds are large, i.e., within tropical MCCs.

While these comparisons are in general quite reasonable, the profiler results show additional features of the average vertical wind profiles that are not apparent in profiles obtained by other techniques. For example, profiler results show that the weak subsidence observed during clear periods is not limited to heights below the tropopause, but rather appears to extend well into the lower stratosphere, at least up to our maximum observable height.

An additional interesting feature of the profiler results is the secondary feature in the vertical circulation observed during stratiform rain conditions between roughly 14 and 19 km, with maximum upward flow occurring at ~14–15 km and a corresponding downward motion maximizing at ~15–16 km. The presence of this relatively fine structure in the average vertical wind profile during stratiform rain conditions suggests that radiative effects in the upper levels of the mesoscale anvil could be responsible for locally modified circulation patterns (as discussed, for example, by Gray and Jacobson, 1977; and Houze, 1982).

In contrast to the good-to-excellent correspondence between profiler-obtained average vertical wind profiles and those obtained by more conventional techniques during both clear air and stratiform rainfall conditions, the profiler results obtained during heavy rainfall (i.e., convective) conditions are not in as good an agreement with existing GATE profiles. We tentatively attribute this difference to the fact that the vertical velocity profile for strong-to-moderate convection appears to maximize at a much higher height in the Pacific than in the Atlantic as pointed out by Thompson et al. (1979).

It is important to stress that the convergence patterns and vertical wind profiles obtained by both Thompson et al. (1979) and McBride and Gray (1980a,b), which show considerable differences between the Pacific and GATE regions, relate to fairly extensive areas of tropical disturbances. On the other hand, the results of Gamache and Houze (1982) and those obtained by the Pohnpei profiler (Fig. 3) relate to more localized regions of strong convection. While it would be premature at this point to interpret our results solely in terms of differences in local convergence processes between the Pacific and GATE regions, the fact that 1) the Pohnpei vertical wind profile during heavy convection maximizes at a relatively high height comparable to the vertical wind profile of larger-scale Pacific disturbances, and that 2) both the large-scale and local-scale vertical wind profiles in the GATE region maximize at much lower levels points to a need to improve our understanding of the differences between these two regions.

Finally, it is worthwhile to outline some of the overall advantages and disadvantages of incorporating the profiler technology into long-term observing programs in the tropics. A partial list of the advantages include the following points:

1) Profiler sites are relatively low cost (~$300K initial investment, ~$60K annual operating costs) and operate virtually unattended, except for minimal maintenance.

2) Operations are essentially continuous, with individual wind values available on approximately a minute-by-minute basis.

3) The full wind vector is directly measurable (zonal, meridional, and vertical components).

4) The 50 MHz profiler is virtually insensitive to precipitation echoes, so that the full wind vector can be obtained even under heavy precipitation conditions.

5) The high time resolution of the data enables studies of gravity waves and gravity wave momentum fluxes; the capability of relatively inexpensive extended

observing periods on the other hand, enables complete climatologies of winds and wave activity at each site.

6) Profilers could be operated in a network configuration to directly examine larger-scale atmospheric features concurrent with the individual point measurements available from each individual component.

A comparable list of disadvantages includes

1) The profiler data are essentially single-point (i.e., nonspatially averaged) measurements of the wind field so that the measured wind values relate to only a small atmospheric volume directly over the profiler site.

2) Typical observations are made directly over island sites, so that the complicating effects of terrain and island heating need to be considered.

3) The current profiler measurement capability restricts the useful observed heights from between 3–4 km in the lower limit, to the lower stratosphere in the highest limit. Extension of this capability to both lower and higher height would be very desirable.

4) Profiler sites do not provide concurrent temperature and humidity profiles, unless the profiler site is located nearby a conventional weather service facility, or unless thermodynamic profilers are employed.

Careful consideration of all of the above points suggests that the profiler technology could be usefully incorporated into future long-term programs to study the tropical atmosphere. Indeed, some of the data available from profilers are unique (e.g., point profiles of the vertical wind and gravity wave fluctuations), while other profiler data would provide supplementary measurements (e.g., horizontal wind profiles) at locations where such data are currently unavailable. Furthermore, a number of the disadvantages listed above (e.g., points 2–4) are actively being studied, and it appears feasible to considerably reduce these limitations in the relatively near future.

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APPENDIX

Discussion of the Long-Term Average Measurement Accuracy of Vertical Winds Using a VHF Radar Wind Profiler

1. Statistical uncertainties

Initially, a discrete time series of the measured vertical velocities, $w_j(z)$ is formed from the first moment of the 64-point Doppler spectrum at each height interval (see Carter et al., 1980, for details of the sampling and spectral analysis processes). Because of the random nature of the scatterers that produce the radar returns, these velocity estimates, which are available every 70 to 80 sec, typically have a statistical uncertainty of a few cm s^{-1}. This uncertainty is small relative to the inherent variability ($\geqslant$10s of cm s^{-1}) of the time series, and so can be considered to be contained within the random fluctuations of the time series itself.

Now, consider a time series (not necessarily sequential) of N values of the hourly averaged wind values $\langle w(z)\rangle_k$ derived from the $w_j(z)$ series. Assume that this series has an associated variance $\sigma^2(z)$. Since under most conditions the dominant vertical wind fluctuations occur near the Brunt–Väisälä period (~10 min), then each value of $\langle w(z)\rangle_k$ may be considered as an independent sample of the vertical wind field. Under these conditions, it is possible to determine the variance $\sigma_M{}^2(z)$ of the "sample mean", where the sample mean value is given (Davenport and Root, 1958) by

$$w_M(z) = \frac{1}{N}\sum_{k=1}^{N}\langle w(z)\rangle_k$$

and where the sample mean standard deviation (the square root of the variance) is given by

$$\sigma_M(z) = \sigma(z)/\sqrt{N}$$

For example, the time series of vertical velocities obtained by the profiler under "clear sky" conditions discussed in section 4 and shown in Fig. 1 consists of about 240 separate values of $\langle w(z)_k\rangle$. The variance of this series at, say, 8.2 km is determined to be approximately 4.5 cm s^{-1}. For these values, the standard deviation for the mean of the 240 hour series is then

$$\sigma_M(z) = (4.5)/(\sqrt{240})\ \text{cm s}^{-1}$$

$$\approx \pm 3\ \text{mm s}^{-1}$$

as indicated by the error bars in Fig. 1. Error bars shown for the rainfall profiles in Fig. 2 and 3, on the other hand, are considerably larger. This is primarily because the rms fluctuations of the vertical winds are much larger under precipitation conditions.

2. Systematic biases

Additional errors in estimating the small average vertical velocities discussed above can arise from systematic biases, either in the data-taking process or in the analysis procedure. Such biases could conceivably produce erroneous results in long-term averages of weak signals. It is possible to evaluate the magnitude of these biases by examining the long-term averages of simulated Doppler returns that have been added to existing records at heights where no echoes are present (e.g., above about 25 km). Such tests show that system biases in the long-term average profiles, if they exist at all, are well below 0.1 cm s^{-1}.

3. Antenna pointing accuracy

Another equally important factor in assessing the validity of the average vertical wind measurements is the pointing accuracy of the vertically directed beam. If the beam is not directed precisely vertically, then the actual "vertical" velocities will be contaminated by contributions from horizontal winds (Balsley and Riddle, 1984). While only reasonably small pointing accuracies are required for studies involving the relatively large ($\sim$m s^{-1}) values of instantaneous vertical velocities, the true pointing direction becomes a critical factor in correctly measuring small ($\sim$cm s^{-1}) long-term averaged vertical velocities. For example, if the actual mean antenna beam center were directed away from the vertical by 0.1°, then a 7 m s^{-1} average horizontal wind speed would produce an error in the average vertical wind measurements of $\sim$1 cm s^{-1}. This value represents a significant error in the long-term average vertical velocity. Moreover, since the calculated full two-way half-power beamwidth is $\approx$2.1°, the required pointing accuracy is only a small fraction of the beamwidth.

Fortunately it is possible to measure the actual beam direction quite accurately by observations of solar "noise" as the sun passes through the antenna beam during a few-day window twice a year. Since the sun's position is very well established, relatively high time-resolution observations of the received "quiet" solar noise as the sun passes through the beam can be used to establish the actual beam-pointing direction with an error less than ±0.1° (Riddle, 1985). Such measurements were performed at Pohnpei in April and August 1985, and the resulting antenna pointing direction was established to be within less than ±0.1° of true vertical. Indeed, as we show in section 3, the close correspondence between clear-sky profiles obtained by both the Profiler technique and more standard techniques suggest a vertical pointing error much less than this worst-case limit.

4. Errors due to aspect sensitive echoes

A number of studies have been done over the past few years relative to the aspect sensitivity of VHF wind profiler echoes at near-vertical incidence (Gage and Green, 1978; Röttger and Liu, 1978; Gage et al., 1985). Briefly stated, for a nearly vertically directed beam, the strongest echoes are returned from those regions within the area illuminated by the antenna beam whose surfaces of constant refractive index are perpendicular to the radar $\bar{\mathbf{k}}$ vector (i.e., the vector defining the propagation direction of the radar pulse). Typically, these surfaces correspond to isentropic surfaces (i.e., surface of constant potential temperature) which are horizontally stratified. Under conditions when the isentropic surfaces over a specific profiler site are consistently tilted, e.g., when the profiler is looking vertically at a stationary lee-wave structure, then the *effective* angle of a vertically directed antenna beam can be "tilted" off vertical by at least a few tenths of a degree (provided, of course, that the actual beamwidth is somewhat greater than this value). Such a situation could seriously affect the accuracy of the observed vertical wind profiles. Indeed, in the short term, such conditions undoubtedly exist over the Pohnpei radar.

However, as we show in the main text, the preponderence of the results presented here consists of hundreds of hours of data averaged under specific rainfall/nonrainfall "events". Because of the large number of events in these averages, it is reasonable to expect that the off-vertical "tilt" of the antenna beam (if indeed this phenomenon occurs at midtroposphere heights and above) will be evenly distributed over all azimuths and over all phases of the postulated lee waves, so that the resulting contamination will be essentially averaged out.

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