Long-Term Average Vertical Motions Observed by VHF Wind Profilers: The Effect of Slight Antenna-Pointing Inaccuracies

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ABSTRACT

This paper shows that a very slight tilt of the vertically directed antenna beam of a VHF wind profiler can produce a measurable change in the observed long-term averaged "vertical" velocity profiles. The results are based primarily on data obtained using the NOAA/CU profiler at Piura, Peru, where phase measurements of individual antenna elements made in 1992 showed that the calculated angle of the 3°-wide vertical beam was skewed only by about 0.06° from true vertical. This small error was corrected in February 1993 by carefully rephasing some of the array feedpoints. Mean vertical velocity profiles obtained prior to the correction were adjusted to account for the slight contamination by the horizontal wind. These corrected vertical profiles compare favorably with vertical profiles obtained after rephasing the antenna, as well as with mean vertical wind profiles from other profiler sites in our tropical Pacific profiler network.

The results show that in order to be confident in long-term averaged vertical wind profiles using VHF profilers in the Tropics, the vertically directed antenna needs to be very carefully phased. The results also suggest that long-term averaging tends to nullify any possible effects of apparent variations of the vertical beam that might arise from short-term echo specularity. In addition, asymmetric biases in the turbulent-scattering process thought to contaminate mean vertical velocity measurements at midlatitudes are not at all apparent in our tropical profiles. This final factor may be due to the much smaller average vertical velocity variances observed at low latitudes.

1. Introduction

Measurements of average vertical profiles of the vertical wind have been reported from a number of wind profiler sites over the past decade or so. The representativeness of these profiles in terms of actual vertical atmospheric motions has been questioned recently in view of possible complicating aspects of the scattering processes. In some cases, these complications are thought to be exacerbated by the reasonably large widths of the antenna beams (a few degrees) normally used in profiling operations.

One possible complicating factor that can affect the accuracy of vertical wind measurements arises from slight tilts of the nominally horizontal stratifications that occur both in the stratosphere and the upper troposphere. These tilted stratifications—which result from gravity wave effects or frontal passages—can cause an apparent deviation of a vertically directed antenna beam at VHF (30–300 MHz) via a "specular" or "Fresnel" scattering process. For relatively wide antenna beams, the strongest echoing regions in such tilted regions can be shifted well away from vertical toward the surface normal of the stratifications. Under these conditions, the resulting "vertical" wind profiles could be contaminated by the introduction of a small horizontal wind component into the measurements. The net effect of tilted stratifications would be to produce an apparent slight tilt of the vertical antenna beam. This process has been shown to be important in short-term measurements of the vertical wind field at midlatitudes (Larsen and Rottger 1991; Palmer et al. 1991).

A second complication suggested recently by Nastrom and VanZandt (1994) is independent of the Fresnel tilting process outlined above and arises from the dynamics of the scattering process itself. In this situation, the mean motions of the small-scale turbulent refractive index fluctuations that provide the scattering elements at VHF may have an apparent motion slightly different from that of the mean atmospheric motion. This effect is postulated to arise from differences in the total scattering cross sections of "upgoing" and "downgoing" gravity waves. According to VanZandt and Nastrom, this asymmetry biases the profiler vertical wind measurements. They have postulated this mechanism to explain anomalous vertical wind profiles observed at various midlatitude profiler sites, where the observed profiles exhibit consistent downward velocities of a few centimeters per second at all heights. It should be pointed out in passing that such large down-

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ward motions are not observed at lower-latitude profiler sites (Balsley et al. 1988; Gage et al. 1991). Observed lower latitudes values are much smaller.

A third potential complicating factor for long-term average vertical wind measurement lies in the pointing accuracy of the vertical beam. Even in the absence of the above two factors, very slight inaccuracies in the vertical beam direction can severely compromise the measurements. For example, assuming a typical mean horizontal wind of 15 m s^{-1}, a mere 0.05° off-vertical skew of the vertical beam will add a 1.3 cm s^{-1} component of the horizontal wind to the observed vertical velocity. Under some conditions, such a skew would heavily compromise the accuracy of mean vertical velocity measurements. For example, the mean atmospheric subsidence under clear sky conditions is of this same order of magnitude (Reed and Recker 1971).

Note that a beam tilt of a few hundredths of a degree does not appreciably affect *instantaneous* vertical velocity values. This is true because the approximate 1–2 m s^{-1} *instantaneous* vertical velocity fluctuations in tropical sites are not too different from the 10–20 m s^{-1} *instantaneous* fluctuations of the horizontal wind, while the *mean* vertical motions (a few centimeters per second) are some 2–3 orders of magnitude less than the *mean* horizontal motions.

With the increasing use of profiler wind data, it is becoming increasingly important to assess the impact of each of these three factors in order to better evaluate the feasibility of making useful mean vertical velocity measurements. One step in this process is to establish the effect of a slight off-vertical beam tilt on long-term vertical wind measurements under clear-air conditions, when the mean vertical velocities are certain to be very small. Provided that we can show that a properly directed vertical beam yields reasonable results under such quiet conditions, then it will be easier to evaluate with confidence the importance of the other two factors in long-term vertical wind measurements.

In this paper we examine the effects of a slight error in the pointing of the vertical beam on long-term average vertical wind profiles. We do this at a near-equatorial site when the midtropospheric subsidence under clear-air conditions should be only about 1–2 cm s^{-1} due to radiation cooling to space (Reed and Recker 1971).[1] We have used selected data from the wind profiler located at Piura, Peru (5.2°S, 80.6°W). This site is located in the desert in northern Peru. Briefly, we made a series of measurements of the vertical beam direction at Piura (deduced from phase measurements of individual feed points and described in a subsequent section) during 1992 and 1993, which indicated that the vertical beam direction was tilted about 0.06° away from true vertical. This error was corrected in February 1993. The resulting database obtained from extended periods both before and after the antenna beam was corrected is used to study the effects of beam tilting on long-term average vertical profiles.

Our paper is organized as follows. In section 2 we present a brief description of the Piura radar. In section 3 we outline the experimental procedure used to deduce the antenna beam direction via phase measurements of the 32 separate feed points of the antenna array. Analyses of the antenna beam direction are shown for the initial measurements as well as for the period after the antenna was rephased to point more nearly vertical. The theoretical beam pattern is then compared with the beam pattern found after the beam direction was corrected. In section 4 we show trimestrally averaged vertical wind profiles obtained prior to rephasing the antenna beam 1) without taking into account the contaminating effects of the horizontal winds on the slightly off-vertical beam and 2) after subtracting out the horizontal wind contamination. We then compare these profiles with profiles obtained after rephasing the vertical antenna to look more vertically. Finally, in section 5 we discuss the implications of our results in terms of long-term average vertical wind profiles and also in terms of the midlatitude results of Nastrom and VanZandt (1994).

2. Description of the VHF wind profiler at Piura, Peru

The Piura, Peru, VHF wind profiler is located on the campus of the University of Piura in the city of Piura, Peru, at an altitude of 35 m MSL. The profiler is operated jointly by the National Oceanic and Atmospheric Administration (NOAA), the Cooperative Institute for Research in Atmospheric Sciences (CIRES) of the University of Colorado, and the University of Piura, Peru.

The Piura profiler was installed in 1989 and was operated initially in a vertical-only mode to observe vertical motions. It was modified in February 1991 to monitor both horizontal and vertical velocities. The subsequent monitoring technique sequentially switched between three antenna beam positions (i.e., vertical and 15° off vertical toward the east and south) roughly every 7 min. Currently, since 1994, the system has been operating in a five-beam configuration.

The antenna itself is an orthogonal set of 32 × 32 COCO (coaxial–collinear) dipole elements constructed using standard coaxial cable. The one-way beamwidth of each beam is about 3°. The total antenna area is 10^4 m^2. The transmitter operates at 49.92 MHz using a 6.7-μs pulse width (i.e., a radial range resolution of about 1 km), a peak transmitted power of approximately 30 kW and an average power of a few hundred watts.

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[1] Mass balance for this clear-air downward motion typically would be maintained by local convective regions; in the case that the entire region is normally clear, then mass balance would require that the requisite upward motions occur outside the boundaries of the clear region.

3. Antenna-pointing determination using phase measurements

a. Technique

It is possible to determine the antenna beam direction of a VHF profiler by at least three different methods. The first method involves observing a precisely known celestial radio source (a radio ''star'') as that star passes directly through the antenna beam. The second method involves observing enhanced solar ''noise'' as the sun passes through the antenna fixed beam during a few-day window twice per year (Riddle 1985). The third method involves computing the beam direction from careful measurements of the relative phase of the individual antenna feed points.

For the present purposes, the first method requires knowing the exact position of a radio source at precisely the latitude of the Piura profiler with an accuracy better than that of the desired measurement. This approach is unreasonable owing to the paucity of known VHF radio sources at this low latitude.

The second method is applicable in principle since the sun passes through the Piura vertical beam twice per year. The measurements, however, must be made during relatively quiet solar activity to preclude errors in the measured beam pattern arising from transient solar ''noise'' bursts, since bursts will contaminate the received signal intensities as the sun traverses the beam. Results obtained from other equatorial sites indicate that the inherent accuracy of the technique is insufficient for the present measurements.

In the third method—the one we have used here—accurate amplitude and phase measurements are made at the feed points of each of the 32 elements of the vertically directed antenna relative to a reference signal. The 50-MHz reference signal is fed into the main transmission line at the transmitter terminal and the phase of this signal is measured at each of the 32 antenna feed points. This phase is measured relative to a signal from the same source carried to the antenna field along a second coaxial cable. The relative phase difference between these two signals should be constant over the entire array for a vertically directed beam. Provided that the amplitudes of all 32 measurements are comparable, a linear regression analysis of the phase values, taking into account the spatial separation of the feed points, results in a line whose slope is equivalent to the progressive phase shift across the array and thereby to the mean pointing direction of the antenna beam relative to the antenna surface. The plane of the antenna surface at Piura has been accurately surveyed and has been found to be level to within about 1 cm in 100 m. This difference is equivalent to an error in off-vertical beam direction on the order of 0.006° (more than an order of magnitude less than the error that we are concerned with here) and can be ignored.

In view of the measurement repeatability that will be demonstrated below, the accuracy of each feedpoint phase measurement under the conditions experienced here is of the order of a few degrees of phase difference. Taking into account the 100-m total array length and the 32 measurements, the resulting accuracy of the mean pointing direction for a single array phase measurement is of the order of 0.01°. Repeated determinations of the same feed point phase values improve the accuracy of the pointing directions roughly by the inverse square root of the number of determinations.

It is important to point out that the above procedure establishes only the mean pointing direction. The beamwidth and the beam shape will also be degraded somewhat by slight variations in the amplitudes of the individual feedpoint measurements. We have not considered these effects in the present measurements because they are almost undetectable, as we will show in section 3c.

b. Initial phase measurements (1992–93)

A series of pointing-direction determinations was made during 1992–93, prior to any antenna phase modification. The antenna feedpoint phases and amplitudes were measured as described above. Figure 1a shows two separate measurements made on 3 June 1992. An additional three separate measurements made on 4 February 1993 appear in Fig. 1b. Note the repeatability of both the 1992 and 1993 measurements that demonstrates the few-degree accuracy of the measurements. Slight differences between the separate year measurements almost certainly arise from slight changes in the length of the phasing cables with time.

In Fig. 1a, a linear regression fit to the 1992 measurements after averaging together both measurements shows a −0.06325° off-vertical skew of the vertical beam (the negative sign indicates that the tilt is toward the west). A similar fit to the 1993 measurements (Fig. 1b) shows a comparable slope of −0.0666°. Given the relative consistency of the measurements over both years, we have also calculated the mean slope using all five measurements. The result appears in Fig. 1c and shows a mean slope of −0.06526°.

An approximate 0.065 westward tilt of the vertical beam at Piura is quite significant for long-term average measurements as pointed out above. Since long-term average horizontal wind profiles measured at Piura exhibit magnitudes of the order of 6–8 m s^{-1} at some heights, the resulting contribution of the horizontal wind to the vertical velocity measurements for this magnitude of skew could amount to about 1 cm s^{-1}. This is a significant portion of the measured mean vertical values and cannot be ignored in long-term mean vertical wind measurements. This error must be reduced as much as possible in order to have confidence in long-term average vertical wind profiles, regardless of the possible long-term effects of specularity or of asymmetrical turbulent scattering properties mentioned in the introduction.

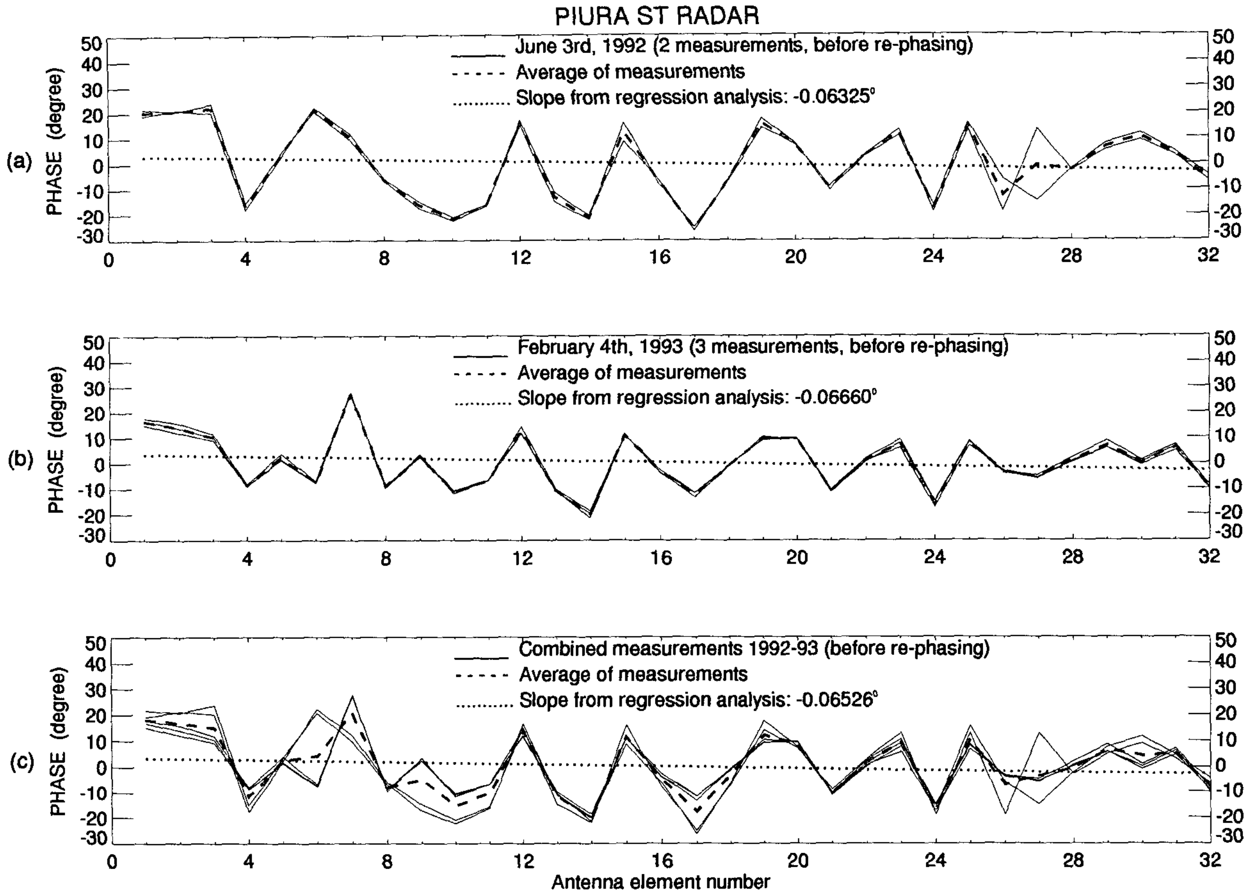

FIG. 1. Antenna phase measurements made prior to rephasing the Piura vertically directed antenna. Relative phase of each feed point is plotted with respect to each antenna element. Elements are spaced 3 m ($\lambda/2$) apart and are numbered from east to west. The dotted line represents a least-mean-square regression fit to the averaged phase values. The indicated negative slope delineates the corresponding off-vertical tilt of the vertical antenna beam toward the west. (a) Two separate measurements (solid lines) and their average value (dashed line) made on 3 June 1992. (b) Similar, showing three measurements and their average value made on 4 February 1993. The lowest panel (c) shows comparable results using all five measurements.

c. Modification of the vertical beam-pointing direction

Following the phase measurements described above, the relative phases of the feed points were modified in February 1993 to correct the vertical beam-pointing direction. This correction was accomplished by carefully adjusting the physical length of some of the coaxial cables leading to the antenna feed points.

Subsequent to this modification, the phases of the antenna feedpoints were again measured, and the results are shown in Fig. 2a for the phase measurement made just after the modifications were made. The mean beam tilt after correction is seen to be −0.00055°. Note that while we do not ascribe to this level of accuracy in the measurement, we are confident that the error in the vertical beam direction has been considerably reduced.

In the following figure (Fig. 2b) we show the mean tilt determined from a set of four phase measurements made in late September 1994. Note that the mean tilt determined from these measurements is again quite small and reaffirms the constancy of the phase over almost an 8-month interval. Figure 2c is similar to Fig. 1c and contains all four phase measurements made after rephasing. Note that the mean pointing direction for the entire period after rephasing remained relatively constant, with the antenna directed at about 0.002° off-vertical toward the west. The two-sigma error of this measurement determined statistically using 3×10^5 possible combinations of the last set of four measurements is ±0.004°.

Given this corrected value for the tilt of the vertical beam and assuming a worst case mean horizontal wind of 15 m s^{-1}, the vertical velocity observations would be contaminated by less than 0.02 cm s^{-1}. This value corresponds to only a few percent error for typical observed (and predicted) mean vertical velocities. For smaller, more typical horizontal velocities, the resulting error will be commensurately smaller.

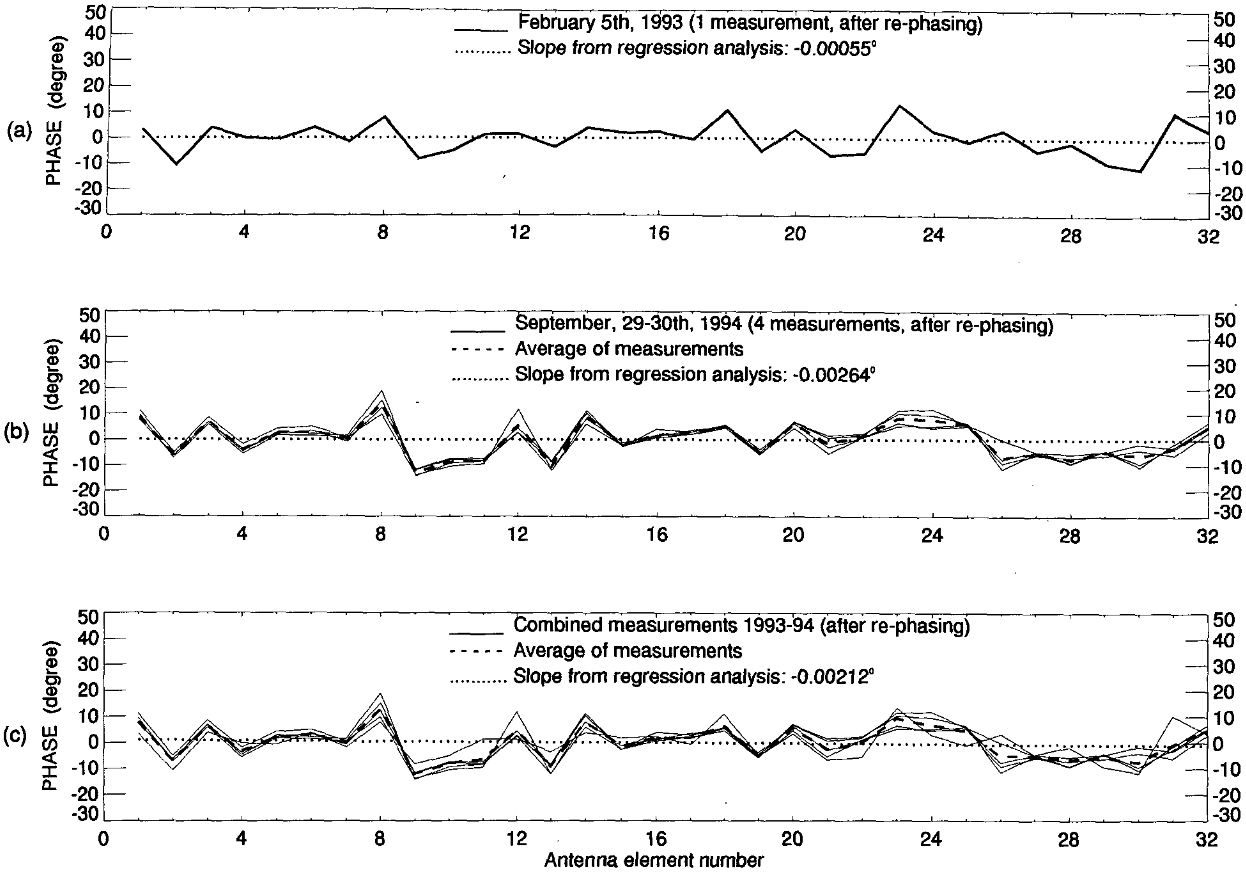

FIG. 2. Same as Fig. 1 except for measurements made after the antenna was rephased: the upper panel shows a single measurement made on 5 February 1993; the middle panel shows four measurements made on 29–30 September 1994; the lowest panel shows the mean value and antenna tilts for all five measurements made over this 8-month period. Note here the very slight tilt (0.002° toward the west) of the antenna after rephasing and also the repeatability of the phase measurements.

In Fig. 3 we show the theoretical vertical beam pattern and the pattern calculated using both the phase and amplitude values of the averaged measurements (after correction). There is essentially no difference in the shapes of these two curves, except that the measured pattern is slightly wider.

4. Corrected vertical wind profiles

a. Correction of the mean vertical wind profiles observed prior to the antenna modification

The observed mean vertical wind profiles prior to February 1993 were corrected by subtracting out the expected contamination arising from the horizontal wind component due to the measured antenna tilt. This was done using the observed mean zonal wind profiles for the pertinent periods.

Trimestral-averaged profiles of the vertical wind over Piura obtained using the 0.06° tilted beam appear in the upper two panels and in the first profile of the bottom panel in Fig. 4. The dotted curves depict noncorrected profiles, while the darker continuous curves represent profiles corrected for the assumed contamination by the mean zonal wind. Note that the final three trimestral plots for 1993 that also appear in this figure were obtained after the antenna was modified and therefore have not been corrected for an antenna tilt. The January–March 1993 solid profiles, on the other hand, have been corrected only for the period prior to the antenna modification, that is, until mid-February.

For reference, examples of trimestral mean zonal wind profiles used in this correction are shown in Fig. 5 for 1992. Corresponding meridional wind profiles are also shown in this figure. Note that the lower-level winds are reasonably consistent from trimester to trimester, while the winds at the higher levels are more variable.

b. Comparison of profiles obtained prior to the antenna modification with those obtained afterward modification

Although we expect that the differences between the solid and dotted curves in Fig. 4 arise from horizontal

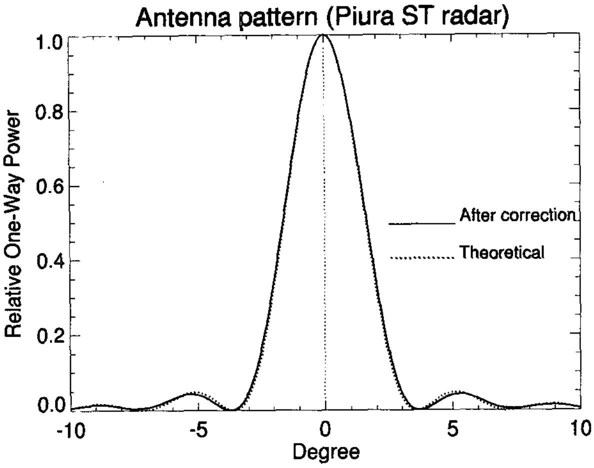

FIG. 3. Theoretical and calculated (after correction) one-way beam patterns of the vertically pointed antenna.

wind contamination via a skewed antenna, it is possible that all we have done is to subtract out a *speculated* contribution. The same set of curves would have resulted even if the antenna tilt had no effect at all. We need to establish that these differences in fact arise from differing vertical beam directions. We can do this by comparing both the corrected and uncorrected profiles obtained before the antenna modification with profiles obtained after the beam direction was changed. If the corrected profiles before modification agree well with profiles obtained after modification, then we can be reasonably sure that the calculated differences (i.e., the difference between the solid and dotted curves) arose from a misaligned beam. In making this comparison we only make the reasonable assumption that the mean vertical wind conditions remain the same throughout the entire observing period, that is, that they are unaffected by interannual processes such as El Niño.

Note, however, that even though we do find that the observed differences are indeed related to the antenna beam position, we cannot establish a priori that the corrected beam is directed vertically. We will discuss this point in the next section.

In Fig. 6 we show the result of subtracting the mean profile obtained after antenna modification from 1) the "unadjusted" profiles (dotted curves) and 2) the "adjusted" profiles (solid curves) obtained prior to the antenna modification. For this comparison we have averaged the entire datasets both before and after rephasing. Values close to zero in this figure indicate that the before–after comparisons are close.

Examination of Fig. 6 shows that—at least in the height range 3–10 km—the adjusted mean vertical profile before modification compares much more favorably with the profile obtained after the antenna was modified than does the *unadjusted* curve. The small (<1.0 mm) differences shown by the solid curve indicate that the adjusted premodified profiles are essentially identical to profiles obtained after the antenna was modified. The unadjusted mean profile, on the other hand, shows much stronger differences.

We conclude, based on the 3—10-km results in Fig. 6, that the observed differences in vertical profiles before and after the antenna modification arise from the antenna-pointing direction.

The discrepancies in Fig. 6 below 3 km are not too surprising and almost certainly arise from a combination of ground clutter and receiver overload.

The lack of a satisfactory comparison above 10 km in this figure is puzzling. It is not unreasonable that the mean vertical winds above about 10 km are much more variable from year to year than they are at the lower heights. Indeed, this is borne out in some of our prelim-

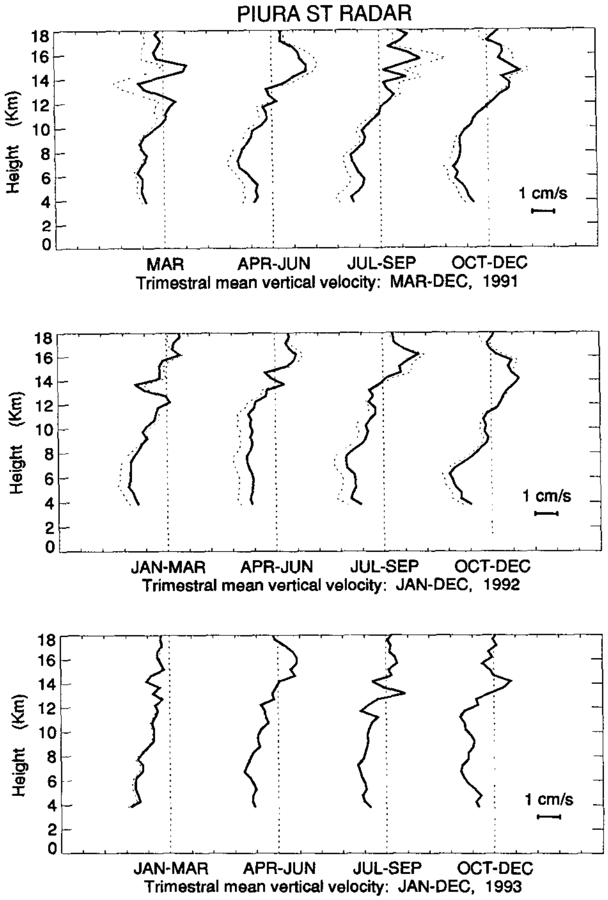

FIG. 4. Plots showing trimestrally averaged mean vertical velocity profiles before (dotted curve) and after (continuous curve) correction for possible contamination by horizontal winds. The dashed vertical lines centered approximately on each set of profiles indicates zero velocity. Values to the right (left) of zero denote upward (downward) velocities. Note that the final three profiles in the lowest panel have not been modified since the antenna was rephased in early February 1993. (January–March 1993 corrections include results both before and after rephasing.)

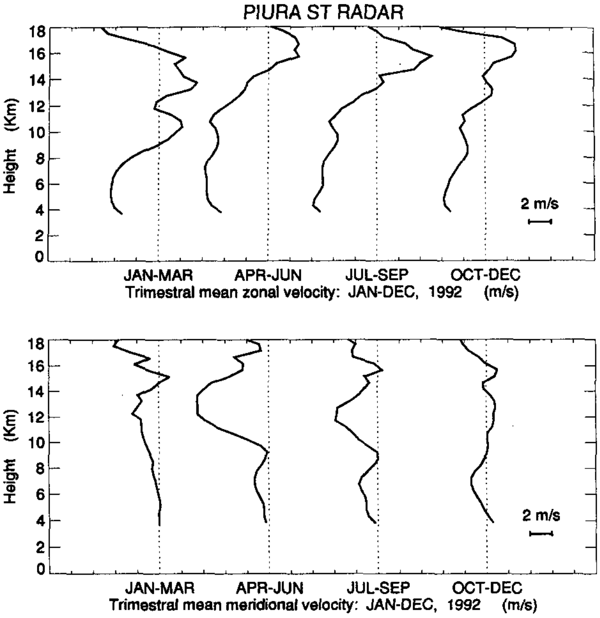

FIG. 5. Trimestral mean zonal and meridional wind profiles for 1992. These profiles are reasonably consistent from trimester to trimester at low altitudes, with less consistency at the reach higher altitudes.

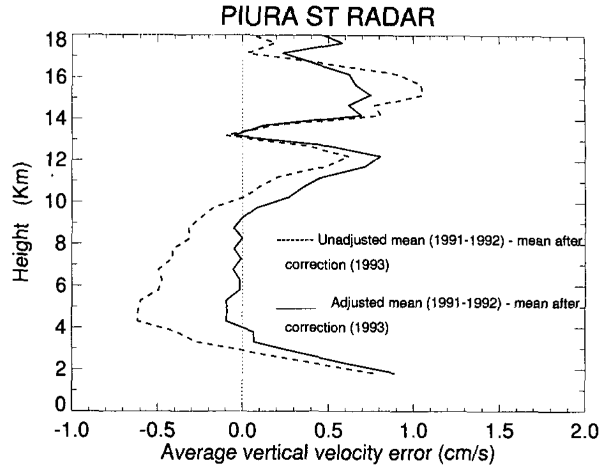

FIG. 6. Showing the difference between profiles obtained before and after antenna rephasing. Dotted results show differences between pre- and post-rephasing profiles without subtracting out the horizontal wind contamination in the pre-rephased data. The solid curve is similar, except that the horizontal wind contamination has been subtracted from the pre-rephased data. The solid curve shows that, at least below 10 km, the pre-rephasing profiles agree very well with profiles obtained after rephasing, when the contaminating effects of horizontal wind contamination are taken into account. The lack of a good comparison above 10 km probably arises from strong interannual differences in the vertical winds at these levels, which would preclude this type of comparison.

inary studies of horizontal wind variability. For example, we show in Fig. 7 a superposition of trimestral zonal profiles. Examination of these profiles shows that while the profiles are similar below about 10 km, they exhibit pronounced differences above this height. One would therefore expect that our accuracy testing procedure would be invalid for these upper heights since the assumption of mean wind constancy over the entire period of comparison has been violated.

It is also possible that the poor comparison at higher heights in Fig. 6 is somehow exacerbated by the weaker echo returns above 10 km. To demonstrate the possibility, we present in Fig. 8 profiles of the returned signal power on all three beam positions. All profiles show weaker signals with increasing until about 16 km. In Fig. 9 we show a corresponding set of three curves that depicts the percent of useful data points used in the vertical profiles at each height (i.e., the total number of used data points relative to the total possible points) for 1991–93. The Fig. 9 results shows that below about 10 km the averaged profiles incorporate all possible points, while above 10 km the number of usable points is decreased substantially, except for the region just above the tropopause (17–18 km) where enhanced echoes typically are observed, mostly on the vertical antenna. Another possible reason for the differences at stratospheric heights in Fig. 6 is that the stratospheric results are affected by long-term stratospheric "tilts." We can discard this possibility since the observed aspect sensitivity in the lower troposphere (5–8 km) is of the same order as it is between 15 and 20 km, while the errors in Fig. 6 occur only in the stratosphere.

Finally, note that the near zero difference in Fig. 6 near 14 km probably arises because the zonal wind is also going through zero at that height. Since correction requires multiplying by the mean wind, then a zero difference is reasonably observed.

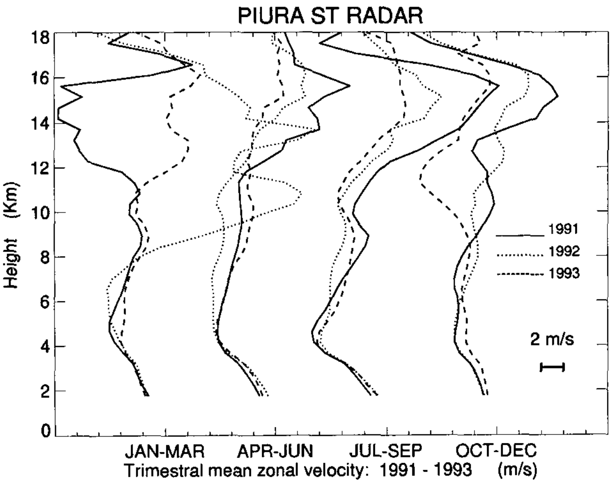

FIG. 7. Trimestral mean zonal wind profiles for 1991–93. These profiles show a rough constancy of the zonal winds below about 10 km, with increasing variability above 10 km.

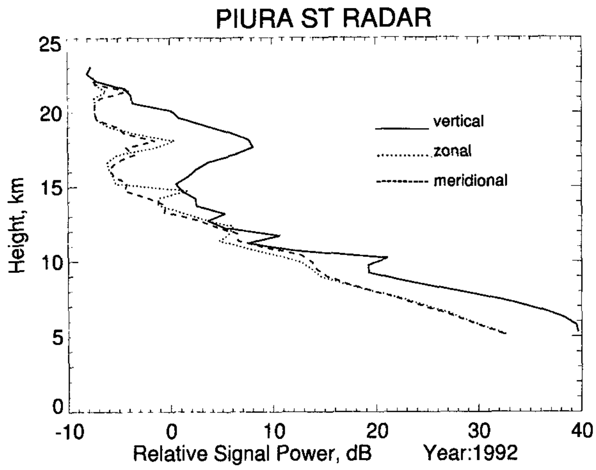

FIG. 8. Returned signal power profiles (dB) for 1992 for three antenna beam positions.

c. *Comparison of the corrected mean vertical wind profile from Piura with comparable profiles from other tropical profiler sites*

We have established that the Piura mean vertical wind profiles were contaminated by the effect of a slightly tilted antenna beam and have shown that rephasing of the antenna has eliminated this problem. We pointed out in a previous section, however, that we have not established that the rephased beam looks precisely vertically.

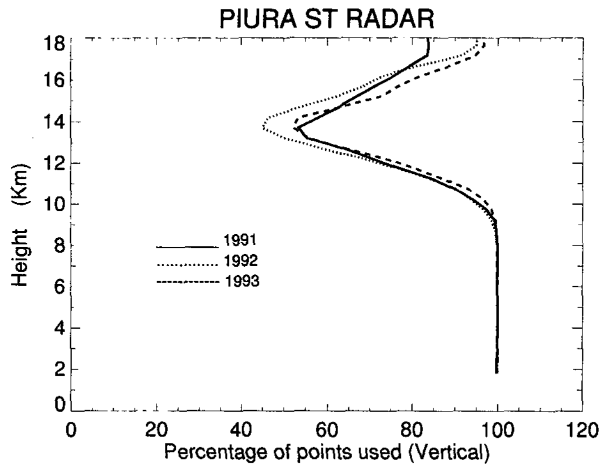

FIG. 9. Plot of the percentage of velocity values used to calculate the average vertical velocity in 1991, 1992, and 1993 relative to the total possible number. The use of less than 100% of the total available values indicates that some of the signals were too weak to include. Below about 10 km the percentage of points used is close to 100%. However, except for heights near 18 km where echo strengths at vertical incidence typically increase, a significant reduction in usable values can be seen above 10 km.

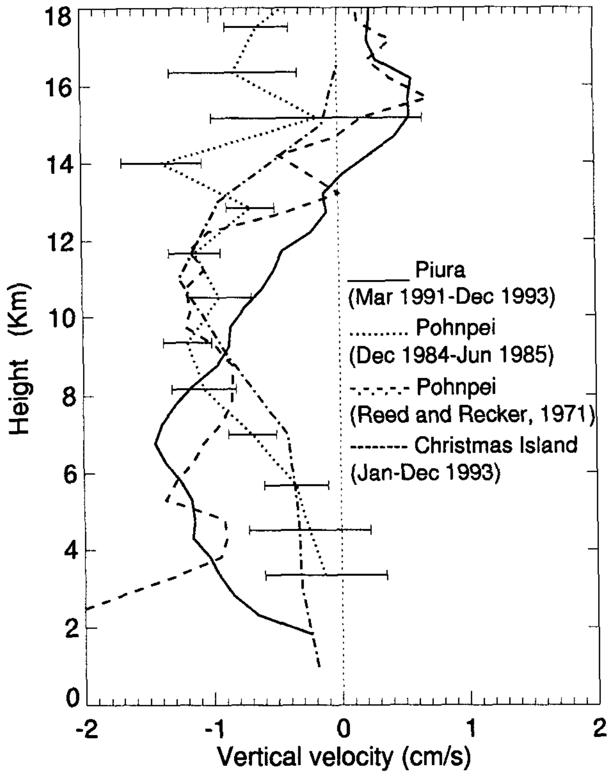

FIG. 10. Mean profiles of the vertical wind from three separate equatorial sites obtained under reasonably clear sky conditions. The Piura profile for the almost 3-yr period discussed in this paper appears as a solid curve. Corresponding profiles for Christmas Island (dashed curve) and Pohnpei (dotted curve) are also plotted. The Christmas Island profile was reproduced from Balsley et al. (1988). Error bars on the Piura and Christmas Island curves are typically smaller than those shown for Pohnpei. The dash–dot curve (Reed and Recker 1971) was obtained for clear sky conditions in the western tropical Pacific using conventional Rawinsonde data and standard convergence techniques. Note that all four curves show comparable 1 cm s^{-1} subsidence in the troposphere, suggesting that profilers are capable of this accuracy.

It would be difficult, if not impossible, to establish the precise verticality of the Piura beam by any reasonable measurement. On the other hand, we can intercompare our results with results from two other tropical Pacific profiler sites. Further, we can compare our results with vertical wind profiles deduced for tropical clear-air conditions using a convergence technique in conjunction with conventional rawinsonde data. If all of these comparisons show similar results, then it is reasonable to assume that our antennas are directed vertically and that the vertical profiles measured by the profilers are representative of the true wind profiles.

In Fig. 10 we show as a solid curve the corrected average vertical wind profile for Piura for the entire period March 1991–December 1993. This single profile includes both the corrected profiles prior to the antenna modification and the data following the modification. An additional vertical wind profile obtained for Pohnpei, FSM (Balsley et al. 1988), appears in the same figure as a dotted curve. The Pohnpei profile (which comprises a much smaller temporal average) was obtained only under reasonably clear atmospheric conditions, a situation that prevails virtually all of the time over the Piura profiler. A comparable profile obtained from our profiler site on Christmas Island in the central Pacific is shown as a dashed curve. Finally, a profile shown by dashes/dots illustrates a profile deduced using rawinsonde data from three Pacific sites under clear conditions (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.

Comparison of these profiles shows that all are reasonably similar. All profiles exhibit a small but measurable subsidence throughout the troposphere under clear-air conditions. The magnitude of this subsidence is of the order of 1 cm s^{-1}, a value well in line with the mean vertical wind profile deduced independently by a convergence technique for the tropical Pacific region under clear-air conditions (Reed and Recker 1971).

On the basis of the above discussions, we conclude that the Piura mean vertical wind profile is comparable to profiles obtained from both Pohnpei and Christmas, as well as with a profile obtained by an independent technique, and that all of these profiles are reasonably consistent with a theoretically determined subsidence due to atmospheric radiation to space. It is therefore reasonable to conclude that the mean vertical profile from Piura provides a good measure of the vertical wind at that location.

5. Discussion

The main purposes of this paper have been to show 1) that the accuracy of mean vertical velocity profiles obtained using VHF wind profilers is markedly affected by very small tilts of the vertical antenna beam pointing direction and 2) that vertical velocity profiles obtained with carefully oriented vertical antenna beams—at least in the Tropics—are reasonable measures of the vertical wind.

We have demonstrated that even a slight off-vertical tilt (a few hundredths of a degree) of the approximate 3°-wide profiler beam can produce measurable differences in the apparent vertical velocity. Thus, if the beam is not directed precisely vertically, the observations will be contaminated by contributions from the more intense horizontal wind components. We stress again that these slight beam tilts are unimportant for short-term observations, since the observed velocity fluctuations on both vertical and oblique beams are more or less comparable. It is only when the (long-term mean) vertical motions are orders of magnitude smaller than their horizontal counterparts that a slightly tilted beam can cause a problem. This is particularly true when the vertical velocities are very small, that is, under clear-air conditions in the Tropics.

With regard to the representativeness of our observed profiles in terms of the actual vertical wind, we have shown a good correspondence between mean vertical wind profiles observed at three separate tropical profiler locations under clear-air conditions. We have shown further that these profiles compare favorably with an independent estimate of the vertical velocity in the tropical Pacific under comparable conditions.

In the process of these studies, we have demonstrated that our checks for beam correction work well below about 10 km but not so well above this height. We tentatively associate this discrepancy with the strong interannual variability of the vertical winds at the higher heights, which would invalidate such a comparison. We also allow for the possibility that the loss of signal strengths above 10 km could affect our measurements, since only the strongest signals contribute to the average vertical velocity. In view of the enhanced interannual variability at the upper levels shown in Fig. 7, however, we view the first possibility as the more important.

We also need to compare our results in light of the studies described by Nastrom and VanZandt (1994) for midlatitudes profiler wind measurements. Basically, Nastrom and VanZandt show that vertical velocities observed at the Flatland Radar depend strongly on the variance of the vertical wind: the stronger the hourly averaged mean variance, the more negative the observed mean vertical winds. Their observations cover a range of variances between 0.01 and 0.50 $m^2 s^{-2}$, with all values below 0.01 being grouped together. They show

$$\langle w \rangle = \frac{5677\sigma_w^2(\Delta\alpha)}{\lambda_z^0},$$

where $\langle w \rangle$ is the mean observed vertical wind, σ_w^2 is the mean variance of the vertical wind, $\Delta\alpha$ is essentially the ratio of upgoing versus downgoing wave energies, and λ_z^0 is a typical gravity wave vertical wavelength.

Typical hourly mean variance values for the midlatitude sites discussed by Nastrom and VanZandt are about 0.1 $m^2 s^{-2}$. From (1), this magnitude of variance, if one assumes a reasonable value (as in Nastrom and VanZandt) for $\Delta\alpha$ of -0.2, leads to an apparent downward "wind" of about 5 cm s^{-1} (e.g., Nastrom and VanZandt 1994). This motion, if present in the Tropics, would completely obscure the velocities observed at the tropical sites.

However, as we show in Fig. 11, comparable values of the hourly mean variance in the Tropics are about 0.005 $m^2 s^{-2}$ (at least below 11 km, where the signals are strong). This is about a factor of 20 less than in the midlatitudes. Even if one assumes the same dynamic character of the atmosphere in the Tropics and midlatitudes, the resulting apparent vertical velocity computed from the equation above using our observed vari-

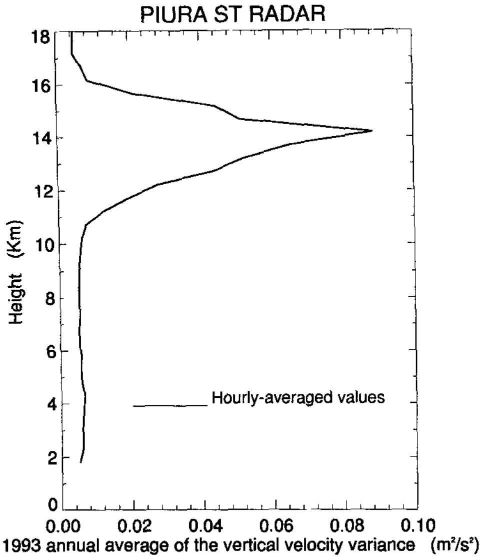

FIG. 11. Annual average profiles of the hourly averaged vertical velocity variance at Piura for 1993.

ance is only a fraction of a centimeter per second, that is, much too small to contaminate our profiles.

Moreover, since the observed vertical wind oscillations at Piura are typically in phase throughout the troposphere (Liziola 1995, personal communication), much of the wave energy seen in the vertical variance arises from quasi-trapped, not upward propagating, waves. Trapped waves have very large vertical wavelength. A typical vertical wavelength over Piura is therefore much larger than the value used by Nastrom and VanZandt (1994), and the value for $\Delta\alpha$ is ambiguous at best. Under these conditions, the mean apparent wind computed from Nastrom and VanZandt should be exceedingly small.

On the basis of these arguments, we conclude that, while midlatitude observations of the true vertical wind might be clouded by the Nastrom and VanZandt effect, the tropical profiles are not so affected. Thus, we are confident that our (tropical) results reflect actual atmospheric motions.

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