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Winds Measured by a UHF Doppler Radar and Rawinsondes: Comparisons Made on Twenty-Six Days (August–September 1977) at Arecibo, Puerto Rico

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ABSTRACT

Vertical profiles of horizontal winds in the lower stratosphere and upper troposphere were measured by the UHF Doppler radar at Arecibo, Puerto Rico (18.35°N, 66.75°W) on 26 days in August and September 1977. On comparing these with horizontal winds measured by routine rawinsonde balloons launched some 80 km east of Arecibo, fairly good agreement between every wind profile can be seen. Most of the difference between the two sets of measurements in the lower stratosphere is shown to be caused by the experimental error of the rawinsonde, while the spatial and/or temporal variations in the wind field seem to dominate the difference in the upper troposphere.

1. Introduction

Recently, enormous progress has been made in observing the dynamics of the middle atmosphere (the region between the tropopause and 100 km) with ultra-sensitive Doppler radars. This technique, which is generally referred to as the MST (Mesosphere–Stratosphere–Troposphere) radar technique, is capable of observing the wind field with good temporal and spatial resolution. Many of the recent developments have been reviewed by Green *et al.* (1979), Balsley and Gage (1980) and Harper and Gordon (1980).

In order to test the accuracy of the MST radar measurements, vertical profiles of the radar-deduced horizontal wind in the troposphere and the lower stratosphere have been compared with concurrent wind profiles from balloon sounding techniques.

Since Green *et al.* (1975) first compared the horizontal wind in the height range from 4 to 12 km measured by the Sunset VHF radar (Colorado) with the rawinsonde-derived winds, similar comparisons have been reported for various MST radars in the VHF band, e.g., the SOUSY radar (Germany; Röttger *et al.*, 1978), the Poker Flat radar (Alaska; Balsley *et al.*, 1979), the Platteville radar (Colorado; Ecklund *et al.*, 1978) and the Jicamarca radar (Peru; Fukao *et al.*, 1981). As might be expected, the quality of the agreement is best for almost-simultaneous, nearby observations. The agreement seems to deteriorate, to some extent, over rough terrain where temporal and spatial variabilities of the wind field are large.

A good general agreement between the two sets of measurements has also been obtained for the UHF Doppler radars, e.g., the Arecibo radar (Puerto Rico; Farley *et al.*, 1979), the Chatanika radar (Alaska; Balsley *et al.*, 1977) and the Altair radar (Kwajalein; Crane, 1980).

These comparisons are, however, limited to a few profiles for the respective radars, and a detailed examination using many wind measurements has not been made. Warnock *et al.* (1978) launched more than 30 rawinsonde balloons for the Sunset radar, but the comparison was limited to a height of up to 12 km.

In this paper, we present a fairly extensive series of such comparisons executed with the UHF Doppler radar at Arecibo, Puerto Rico (18.35°N, 66.75°W). The wind data obtained by the National Weather Service's routine rawinsondes are used for comparison with the radar data. The height range to be examined here extends from 10 to ~30 km. Some consideration is also given to the difference between the two measurements.

2. Measurement

The MST radar technique utilizes very weak scattering from refractive index irregularities caused by clear air turbulence. The energy spectrum of turbulence falls off rapidly with decreasing scale size in the

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TABLE 1. Date and time of the horizontal wind measurements in the upper troposphere and the lower stratosphere by the Arecibo radar.

Index number	Date (1977)	Time (AST) Meridional	Time (AST) Zonal
1	9 August	1012–1042	1048–1121
2	10 August	1101–1129	1135–1158
3	12 August	1027–1056	1103–1157
4	13 August	1001–1035	1042–1154
5	19 August	1103–1129	1134–1159
6	20 August	1009–1107	1115–1154
7	24 August	1024–1059	1106–1147
*	1 September	1128–1155	—
8	2 September	1028–1058	1105–1155
9	3 September	1019–1048	1055–1130
10	5 September	1014–1044	1051–1125
11	7 September	1003–1034	1041–1112
12	9 September	1015–1046	1051–1122
13	10 September	1012–1042	1049–1117
14	11 September	1015–1045	1052–1119
15	13 September	1026–1055	1101–1134
16	14 September	1002–1031	1038–1108
17	18 September	952–1022	1029–1057
18	19 September	951–1022	1027–1057
19	21 September	1045–1114	1121–1130
20	22 September	950–1022	1030–1158
*	23 September	1014–1042	—
21	24 September	945–951	1100–1105
22	25 September	959–1028	1035–1041
23	26 September	945–956	1048–1053
24	28 September	1032–1056	1101–1126

* Two of the 26 days when only the meridional wind was measured are not numbered.

inertial subrange, and radio waves are scattered only from irregularities with a scale size which satisfies the Bragg condition (e.g., Balsley and Gage, 1980). Therefore, a higher sensitivity to turbulent scattering can be achieved at the UHF and VHF bands rather than at microwave frequencies generally used for meteorological radars.

By this technique, large UHF and VHF radars are capable of observing a clear atmosphere up to the stratosphere and the mesosphere, respectively. Even higher ionospheric regions can be observed by means of incoherent scattering from free electrons using the same radar system (e.g., Evans, 1969).

The wind velocity is determined from the mean Doppler shifts of the scattered echoes caused by the line-of-sight component of the ambient air motion. The wind measurement is usually made by tilting the antenna beam direction by more than 10° from the zenith. The horizontal velocity component is calculated from the line-of-sight velocity thus obtained, by a simple transformation which assumes that the vertical component is much smaller than the horizontal component. This assumption is valid for those periods sufficiently longer than the Brunt–Väisälä period, which is on the order of 5 min in the lower stratosphere and 10 min in the upper troposphere. The details of the technique employed for the present measurement were previously described by Fukao *et al.* (1980).

The current wind measurements of the lower stratosphere and the upper troposphere were made for ~1 h before noon on 26 days in August and September 1977. The dates and times of the measurements are shown in Table 1. All of them were made between the hours of 1000 and 1200 AST (Atlantic Standard Time) on the respective days. Normally, the first half of this period was dedicated to the meridional wind measurement and the latter half to the zonal wind measurement. The mean measuring period was ~30 min for each wind component, although some measurements were as short as 5–10 min.

The meridional and zonal wind profiles were obtained every minute at 30 heights spaced at intervals of 600 m. They were averaged over the measuring period for comparison with wind profiles inferred from rawinsonde balloons.

Rawinsonde balloons were launched at 0700 AST from San Juan, Puerto Rico, approximately 80 km east of Arecibo. The balloons took ~35–40 min to rise to a height of 10 km, and ~80–95 min to reach 25 km. Thus, the balloon ascents to the height of 10–25 km preceded the radar measurement of the same height range by 2–3 hours.

Balloon trajectories are shown in Fig. 1, for 24 days when both meridional and zonal winds were measured by the Arecibo radar. The portions between 10 km and the maximum balloon heights (30 km if balloons rose to more than 30 km), where the radar and rawinsonde wind measurements are compared, are shown by solid lines, while those below 10 km are shown by broken lines. The number included on each trajectory corresponds to those in Table 1. Every balloon drifted toward the west-northwest in the lower stratosphere due to the prevailing ESE wind. In the troposphere, on the other hand, the balloon trajectories seem to be more variable than in the lower stratosphere, although a fairly systematic clockwise daily change can be seen, for example, from 21–28 September. Sharp turns seen in several trajectories occurred near the tropopause. Fig. 1 also shows that the distance between the radar and the balloons varies from ~50 to 100 km below the tropopause, while the separation significantly decreases above that height.

3. Results

Fig. 2 shows vertical profiles of the mean meridional and zonal wind velocities measured by the Arecibo radar. The velocities are positive northward (southerly) and eastward (westerly), respectively. The horizontal bars, which are generally very short except in a few profiles, are standard deviations which indicate the magnitude of wind fluctuations around the mean values.

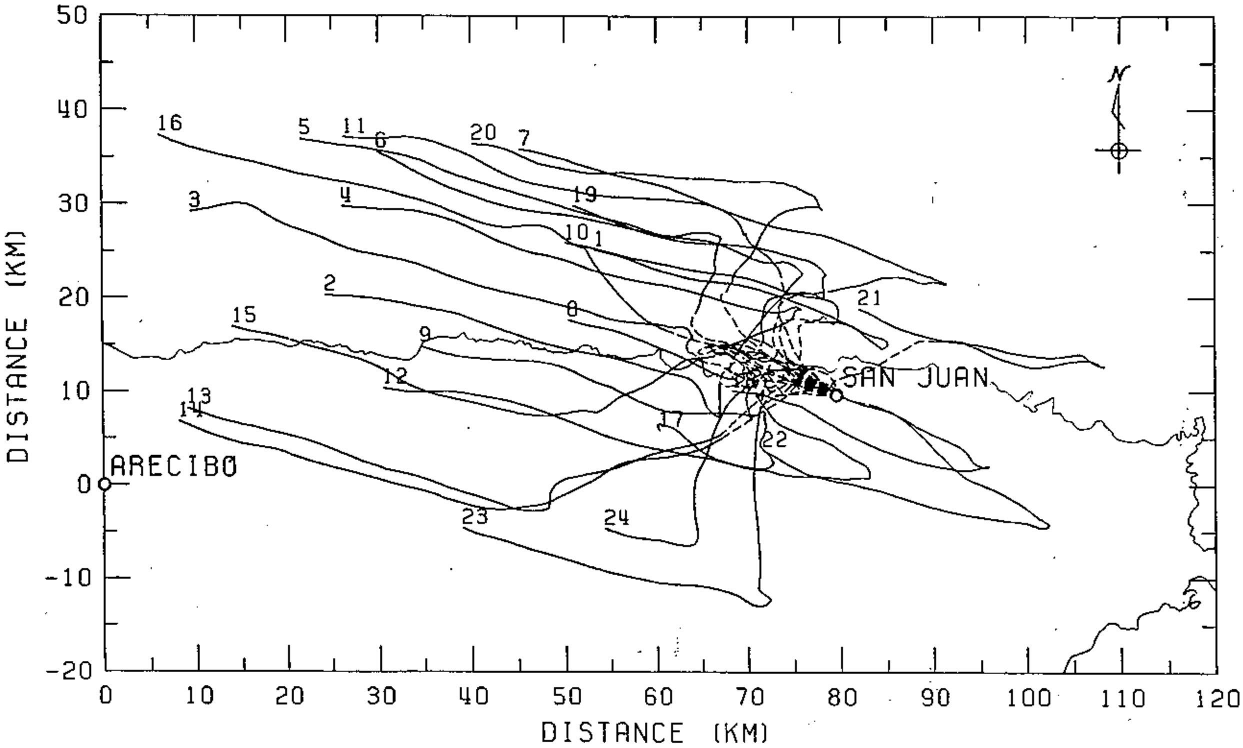


FIG. 1. A map showing locations of Arecibo and San Juan, and trajectories of rawinsonde balloon ascents on 24 days in August and September 1977 when both meridional and zonal winds were measured by the Arecibo radar. The trajectories above and below 10 km are shown by solid and broken lines, respectively. Trajectory numbers correspond to those in Table 1.

Also shown in Fig. 2, are the wind profiles obtained by the routine rawinsondes launched daily at 0700 AST. The comparison between the two measurements shows that general agreement is excellent on each day. The coincidence is fairly good even in the profiles with such a marked wavy structure as seen in the meridional wind on 24 September.

Any significant short-period gravity waves, occasionally found by Doppler radars in this height range (e.g., Balsley and Gage, 1980), were not observed in the present measurements. Thus, the magnitude of the wind fluctuations measured by the radar was generally smaller than ± 1 m s^{-1}.

In Fig. 3, all of the radar-deduced winds are plotted against the rawinsonde-derived winds. Since the tropopause was around 16 km in height during this period, the comparison is made separately for the upper troposphere (10–16 km) and the lower stratosphere (16–28 km). The standard deviation between the two measurements is 4.9 m s^{-1} in the upper troposphere and 3.3 m s^{-1} in the lower stratosphere. No appreciable difference is found between the mean values.

4. Discussion

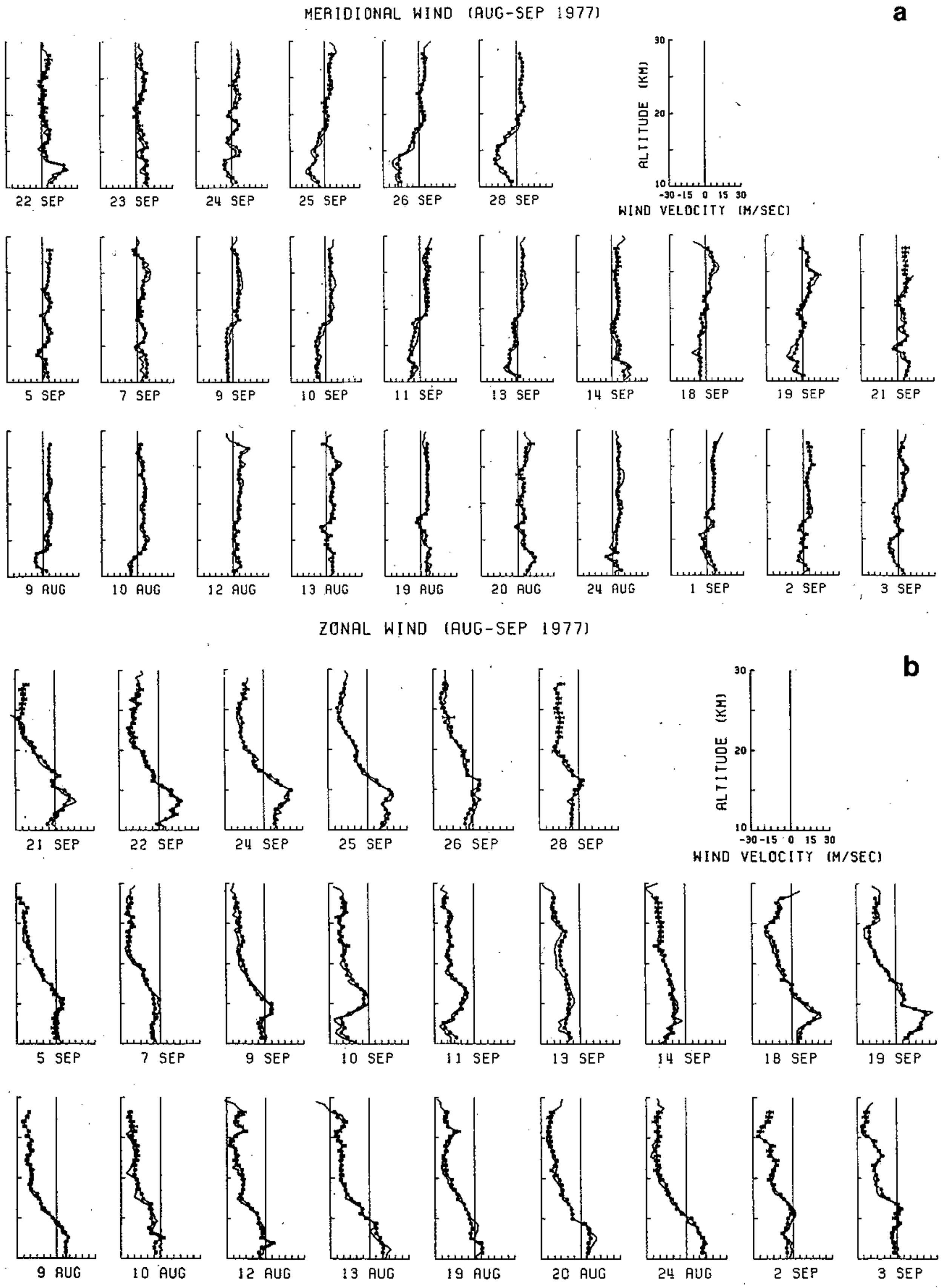
Fig. 3 shows that a considerable scatter exists between the individual wind data obtained by the radar and that obtained by the rawinsondes, despite the fairly good agreement between the overall wind profiles shown in Fig. 2. Here we consider the source of this scatter.

There are two major sources which make a difference between the two wind measuring techniques. One is the inherent experimental errors in each technique and the other is the spatial and temporal variations between the two measurements.

The largest source of error in the MST radar technique is the statistical fluctuation in received echo power spectra. Since the scattering is a random stochastic process, the power spectrum contains fluctuations with a variance equal to its power spectral density. In practice, $N (>1)$ consecutive power spectra are averaged together, and the variance of the fluctuation component $F(\omega)$ in the resulting power spectra is reduced to

$$\langle F(\omega)^2 \rangle = \left(\frac{P_s + P_n}{B}\right)^2 \Big/ N, \qquad (1)$$

where P_s and P_n are the signal and noise power within the effective receiver bandwidth B. The mean Doppler shift of the scattered echoes is determined by the first-order moment of the spectra, from which the noise component is subtracted beforehand. The error in the estimated mean Doppler shift is given as


MERIDIONAL WIND (AUG-SEP 1977)
a
ALTITUDE (KM)
WIND VELOCITY (M/SEC)
-30 -15 0 15 30
22 SEP
23 SEP
24 SEP
25 SEP
26 SEP
28 SEP
5 SEP
7 SEP
9 SEP
10 SEP
11 SEP
13 SEP
14 SEP
18 SEP
19 SEP
21 SEP
9 AUG
10 AUG
12 AUG
13 AUG
19 AUG
20 AUG
24 AUG
1 SEP
2 SEP
3 SEP
ZONAL WIND (AUG-SEP 1977)
b
ALTITUDE (KM)
WIND VELOCITY (M/SEC)
-30 -15 0 15 30
21 SEP
22 SEP
24 SEP
25 SEP
26 SEP
28 SEP
5 SEP
7 SEP
9 SEP
10 SEP
11 SEP
13 SEP
14 SEP
18 SEP
19 SEP
9 AUG
10 AUG
12 AUG
13 AUG
19 AUG
20 AUG
24 AUG
2 SEP
3 SEP

$$E_\omega = \int_{-B/2}^{B/2} \omega F(\omega) d\omega / P_s . \quad (2)$$

Since $F(\omega)$ is a random function, the variance of E_ω is expressed as

$$\langle E_\omega^2 \rangle = \int_{-B/2}^{B/2} \omega^2 \langle F(\omega)^2 \rangle \Delta\omega d\omega / P_s^2$$
$$= \left(\frac{P_s + P_n}{P_s}\right)^2 \frac{B\Delta\omega}{12N}, \quad (3)$$

where $\Delta\omega$ is the correlation width of $F(\omega)$, which is determined by the data length used to calculate a single power spectrum.

Using the time resolution $T = 2\pi N/\Delta\omega$, the standard deviation of the error is written as

$$\sigma_f \equiv \frac{1}{2\pi} \langle E_\omega^2 \rangle^{1/2} = \frac{P_s + P_n}{P_s} \left(\frac{B_f}{12T}\right)^{1/2}, \quad (4)$$

where $B_f = B/2\pi$ is the effective bandwidth in Hz. Thus the error in the horizontal wind is given as

$$\sigma_{vh} = \frac{c}{2f_0 \sin\theta} \sigma_f , \quad (5)$$

where c is the speed of light, f_0 is the radar frequency (=430 MHz), and θ is the zenith angle. For the present data, B_f = 50 Hz and T = 60 s (Fukao *et al.*, 1980). Therefore, σ_{vh} = 0.36 m s^{-1} for case $P_s \gg P_n$, and σ_{vh} = 0.71 m s^{-1} when $P_s = P_n$. The former case applies to most tropospheric data, and the latter case is for the data around 30 km.

In most of the MST radar measurements, errors due to the sphericity of the radar wave front should be accounted for. However, this is not the case for the tropospheric and stratospheric measurements made by the Arecibo UHF radar, because these heights fall within the antenna near-field, where the wave front has no curvature. An additional error caused by height smearing due to the instrumental resolutions (Sato and Fukao, 1982) is thought to be comparably small for the wind data obtained at Arecibo when the height resolution was as high as 150 m.

The random error estimated to be 0.4–0.7 m s^{-1} in the 10–30 km height range is consistent with the result that temporal fluctuations of the radar-inferred wind are less than 1 m s^{-1}.

Next, we examine the random error in the rawinsonde wind measurement. With this technique, horizontal wind velocity is deduced from the temporal displacement of a rawinsonde balloon. The balloon position is determined by three parameters; the atmospheric pressure at the balloon height, the azimuth and the elevation angles of the balloon seen by the ground-based tracking antenna. In the following, we consider only the error in the zonal wind velocity. The same amount of error is also expected in the meridional component.

The zonal wind velocity u is given by

$$u = \left(\frac{z_2 \sin A_2}{\tan E_2} - \frac{z_1 \sin A_1}{\tan E_1}\right) \Big/ \Delta t, \quad (6)$$

where z is the balloon height, and A and E are the azimuth and elevation angles of the balloon, respectively. Subscripts 1 and 2 denote two measuring times separated by an interval Δt. Assuming that errors in z, A and E (δz, δA and δE, respectively) are mutually independent, the variance of u is expressed as

$$\langle \delta u^2 \rangle = 2\left(\frac{\partial u}{\partial A}\right)^2 \langle \delta A^2 \rangle + 2\left(\frac{\partial u}{\partial E}\right)^2 \langle \delta E^2 \rangle + 2\left(\frac{\partial u}{\partial z}\right)^2 \langle \delta z^2 \rangle$$
$$= \frac{2}{\Delta t^2}\left[\left(\frac{z \cos A}{\tan E}\right)^2 \langle \delta A^2 \rangle + \left(\frac{z \sin A}{\sin^2 E}\right)^2 \langle \delta E^2 \rangle + \left(\frac{\sin A}{\tan E}\right)^2 \langle \delta z^2 \rangle\right]. \quad (7)$$

It is fair to assume that $\langle \delta A^2 \rangle \approx \langle \delta E^2 \rangle$ for general tracking antennas. We also use the relationship $\langle \sin^2 A \rangle = \langle \cos^2 A \rangle = 0.5$, which is valid for the average of many measurements. Thus, the standard deviation in the zonal wind error is written as

$$\sigma_u = \frac{\{[(D^2 + z^2)^2 + z^2 D^2]\langle \delta E^2 \rangle + D^2 \langle \delta z^2 \rangle\}^{1/2}}{z\Delta t}, \quad (8)$$

where $D = z/\tan E$ is the horizontal distance between the balloon and the tracking antenna.

The practical accuracy in azimuth and elevation angles determined from a comparison with an optical tracking technique is of the order of 0.2° (M. Shimizu, 1982, personal communication). The error in the balloon height determination is harder to estimate. We adopt here the standard of accuracy required by the WMO (1971), i.e., 5%, above the 100 mb pressure level. Although this value is specified for the absolute balloon height, we apply it to the height difference of the balloon during the measuring interval Δt or 2 min for the rawinsonde. In general, this does not overestimate the error in balloon height. Since the mean rate of balloon ascent is 6–7 m s^{-1}, it corresponds to an error of ~40 m. Numerical examples show that δz is less important than δE in Eq. (8), if this value is used.

As can be expected, σ_u is largely affected by D. The

FIG. 2. Comparison between vertical profiles of (a) meridional wind (26 days) and (b) zonal wind (24 days) measured by the Arecibo radar and by rawinsondes launched at 0700 AST from San Juan, some 80 km east of Arecibo. The radar and rawinsonde data are shown by dots with horizontal bars and light solid lines, respectively.

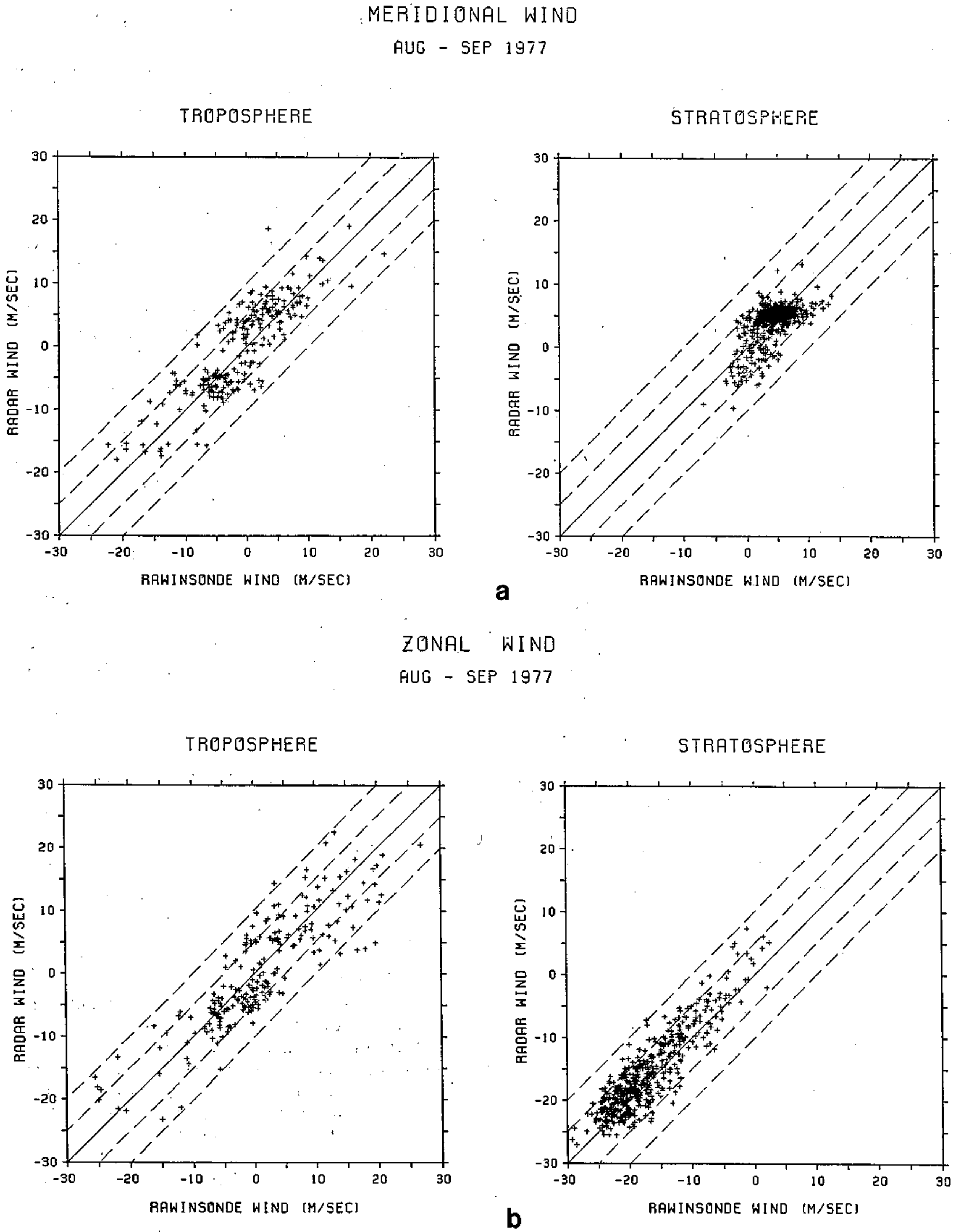


FIG. 3. Comparison of Arecibo radar winds with San Juan rawinsonde winds measured on 24 days in August and September 1977 when both wind components were measured by the Arecibo radar. (a) Meridional wind and (b) zonal wind.

best accuracy is obtained when $D = 0$ and z is small. For example, σ_u is 0.3 m s^{-1} for $D = 0$ and $z = 10$ km. The error increases rapidly with increasing D. The worst accuracy in the present rawinsonde data corresponds to the case $D = 80$ km and $z = 30$ km, for which σ_u becomes 7.1 m s^{-1}. As shown in Fig. 1, the typical value of D at $z = 20$ km is ~30 km, which results in $\sigma_u = 1.9$ m s^{-1}.

Therefore, the major portion of the difference between the winds deduced by the Arecibo UHF radar and the San Juan rawinsondes in the lower stratosphere can be explained by the inherent experimental error in each technique, mostly by that of the rawinsondes.

On the other hand, the difference of about 5 m s^{-1} in the upper troposphere cannot be explained by these errors, because D is usually <20 km in the troposphere, and correspondingly such a large error is not expected from the rawinsonde measurements. The fact that rawinsonde balloons were always drifting more than 50 km from the Arecibo radar in the troposphere suggests that the spatial variation, or local wind field disturbances near the ground, dominates the difference. It should also be noted that the radar-derived winds are the real average of the wind velocity in the measuring period, while the wind deduced from a rawinsonde is a sample at one particular time. Thus, any short-period wind fluctuation affects the rawinsonde data, but not the radar data. It is reasonable that these localities decrease with increasing height, giving better agreement in the stratosphere, as is demonstrated by the current comparison.

5. Concluding remarks

The upper tropospheric and the lower stratospheric winds measured by the UHF Doppler radar at Arecibo, Puerto Rico, on 26 days in August and September 1977 are compared with those deduced by the routine rawinsondes at San Juan, some 80 km east of Arecibo.

A fairly good agreement is obtained between the two overall wind profiles. The standard deviation between the two measurements is 4.9 m s^{-1} in the upper troposphere and 3.3 m s^{-1} in the lower stratosphere. It is shown that most of the difference in the lower stratosphere can be explained by experimental errors, especially those of the rawinsonde. The spatial and/or temporal variations in the wind field seem to dominate the difference in the upper troposphere. These comparisons augment the growing evidence that UHF and VHF Doppler radar measurements of winds provide greater frequency and accuracy than the use of conventional rawinsondes.

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