Are Radiosonde Time Scales Appropriate to Characterize Boundary Layer Wind Profiles?

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ABSTRACT

One approach under investigation for obtaining regional-scale surface fluxes of water vapor, heat, and momentum from complex terrain involves the applicability of flux-profile relationships in the atmospheric boundary layer (ABL). Mean humidity, temperature, and wind speed profiles in the ABL can be measured by means of radiosondes. A disadvantage, however, of this method is the relatively quick passage of the sonde through the ABL compared to the characteristic time scales or memory of the turbulence. Remote sensing with sodar (Sound Detection and Ranging) allows the measurement of mean wind profiles over time scales which are perhaps more appropriate for the turbulence. Wind profiles measured by both radiosondes and sodar over the Landes Forest in southwestern France, as part of the HAPEX-MOBILHY experiment, are compared under conditions of neutral stability. The sodar wind profiles were measured by a team from the CRPE (Centre de Recherches en Physique de l'Environnement, Saint-Maur-des-Fossés/Issy-les-Moulineaux, France); the sodar measurements were taken over 15-min periods. The lower limit of the inner region of the ABL was found to be the same for both sets of profiles. Approximately the same regional scale surface roughness was obtained with both types of sounders, namely $z_0 = 1.2$ m; the corresponding shear stresses derived from both sets of profiles were well correlated.

1. Introduction

Many concepts and ideas concerning the structure and flux processes in the atmospheric boundary layer have developed through careful experimental observation with radiosondes. Although related efforts were going on in several places, radiosounding of the atmosphere appears to have been carried out first by R. Bureau and P. Idrac on 3 May 1927; they introduced the name radiosonde in 1931 (Marcorini 1988, p. 530). The measurement of temperature, humidity, and winds with radiosondes quickly became standard atmospheric technology. The radiosonde is extensively used within a vast global network of synoptic releases. In addition to these observations, usually taken twice daily, numerous major field experiments to study the atmospheric boundary layer have used radiosondes. For instance, among the better known observations of the boundary layer, which have received extensive use in validation studies, are those made by Clarke et al. (1973) on 16 July 1967 (Day 33) in Hay, New South Wales, Australia.

Despite the wide use of radiosondes, there are serious drawbacks regarding their application for boundary layer studies. Such factors as instrumental noise, self-induced balloon oscillations (Armendariz and Rachele 1967) or wind shear layers (Fichtl 1972), may affect the wind profile derived from balloon ascent observations. One of the most restrictive aspects, which is of concern in the present study, is a consequence of the time required, generally less than 5 minutes, to traverse the entire boundary layer depth. (Ascent rates of the sondes are typically around 5 m s^{-1}.) Characteristic time scales of the turbulent flow in the atmospheric boundary layer range roughly from 15 minutes up to a few hours. Hence, it would appear that the radiosonde is not quite capable of capturing the integral time and space properties associated with boundary layer phenomena as the measurements are made over significantly smaller time and volume scales. The consensus is that the radiosonde is difficult to interpret as it does not provide a good time or space average (Stull 1988, p. 416).

Nevertheless, in recent years successful efforts have been made to obtain regional-scale turbulent surface fluxes by means of radiosonde data within the context of (Monin–Obukhov) boundary layer similarity theory (Brutsaert and Kustas 1985; Kustas and Brutsaert 1986, 1987; Brutsaert et al. 1989; Parlange and Brutsaert 1989; Sugita and Brutsaert 1989). Despite these positive and encouraging results the question remains: Are the radiosonde measurements capturing enough crucial and reliable information such that they can be used to apply similarity concepts?

This paper addresses this issue by presenting a comparison of results obtained from analysis of mean wind speed profiles under neutral stability measured by both a radiosonde system and two Doppler acoustic

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sounders (sodar, i.e., sound detection and ranging). These wind profiles were acquired during the HAPEX–MOBILHY field experiment during the summer of 1986 in the Landes Forest in southwestern France. The sodars were operated by C. Mazaudier and A. Weill of the Centre de Recherches en Physique de l'Environnement (CNET/CNRS). Mazaudier and Weill (1989) have presented some observations on the basis of these sodar measurements.

In an earlier analysis of the neutral radiosonde wind speed profiles, the regional scale roughness, z_0, the surface-layer height range, and friction velocities, u_*, were obtained (see Parlange and Brutsaert 1989). The analysis is also carried out here with the sodar mean winds, which represent 15-minute time averages, appropriate for surface layer profiles; the results are compared with the radiosonde findings.

2. Experiment and data analysis

a. Measurements of mean wind velocity profiles

General details regarding the HAPEX–MOBILHY experiment have been described by André et al. (1988). Mean wind and humidity profiles measured with the radiosonde system have been analyzed under neutral stability conditions (Parlange and Brutsaert 1989; Brutsaert et al. 1989). Specific aspects of the radiosounding program and local site conditions are presented in these papers. Besides this intensive radiosonde flight program, two sodar stations were operated by the team from CRPE. One sodar was located in a large clearing (about 2 km across) next to the release point of the radiosondes near Lubbon, and the other was located in the forest some 5 km away near Estampon. Figure 1 shows examples of wind speed profiles measured at the Lubbon site by the sodar and by the radiosonde; the sodar profile represents a mean over 15 min, whereas the radiosonde profile was taken over approximately 1 minute.

The acoustic sounder is the simplest and least expensive of the "dar" systems for remotely probing turbulent and mean quantities in the lower atmosphere (Schwiesow 1988); its operation has been discussed by Spizzichino (1974). Extensive comparisons between sodars and other atmospheric sensors have been made. For example, radiosondes have been tested against sodars for measurements of temperature structure (Wyckoff et al. 1973; Goroch 1976). Sodar turbulence measurements have been shown to be satisfactory in comparison with aircraft data (Thomson et al. 1978; Weill et al. 1978). Comparison studies have demonstrated the reliability of sodar to measure characteristic mean surface layer wind profiles (Kaimal and Haugen 1977; Peters et al. 1978; Kaimal et al. 1984). A good measure of the reliability of a particular profile is the magnitude of the acoustic-scattering cross section ("reflectivity") (Weill 1981).

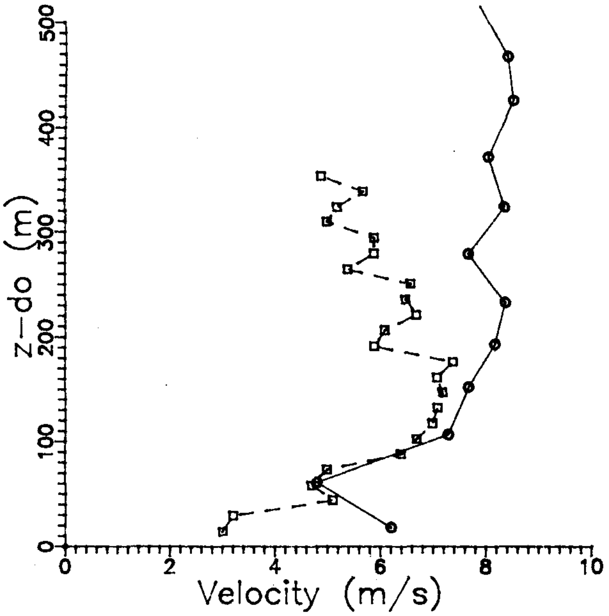

FIG. 1. Comparison between the wind profiles measured at Lubbon on 16 June 1986 by means of the radiosonde (circles) launched at 2321 UTC and by means of the sodar (squares) sounding over the time period 2336–2351 UTC. The displacement height is taken as $d_0 = 5z_0$.

b. Analysis of neutral radiosonde wind profiles

Fourteen radiosounding flights, which took place under conditions of neutral stability, were identified in an earlier study (Parlange and Brutsaert 1989). Initial screening of possibly neutral stability was based on local weather conditions, namely moderate to strong winds and extended cloud cover. After the initial screening, specific criteria applied were the vertical gradient of the virtual potential temperature, Pasquill's (1961) class rating, and the absolute value of Obukhov's length, L, larger than 200; the latter was taken as the decisive criterion. The dates and the times of these neutral flights are listed in Table 1.

The profile analysis was carried out by means of the logarithmic wind profile equation

$$V = \frac{u_*}{k} \ln\left(\frac{z - d_0}{z_0}\right) \qquad (1)$$

where V is the mean wind speed, z_0 the roughness height, d_0 the (zero-plane) displacement height, z the height above the base level of the roughness obstacles and $k = 0.4$ von Kármán's constant. Because d_0 is difficult to determine from noisy data, and the performance of (1) is not very sensitive to its exact value, it was expressed in terms of z_0, on the basis of evidence obtained in other experiments. For flat topography covered with vegetation (as found in the Landes forest), it appears reasonable (Brutsaert 1982; Parlange and

TABLE 1

		Lubbon sodar			Estampon sodar		
Flight	Date (Time of radiosonde release, UTC)	Time interval (UTC)	Range of z (m)	z_0 (m)	Time interval (UTC)	Range of z (m)	z_0 (m)
156	86/6/5	0519–0534	78–107	1.527	0515–0530	49–93	0.996
	(0531)	0605–0620	78–107	0.757			
157	86/6/5				1046–1101	49–93	1.145
	(1118)				1101–1116	107–152	1.349
203	86/6/11	1653–1708	107–137	1.091	1653–1708	78–137	0.630
	(1740)						
221	86/6/14						
	(1724)						
232	86/6/16				0817–0831	63–107	0.953
	(0757)				0831–0846	122–181	1.053
238	86/6/16	2336–2351	93–181	0.922			
	(2321)	2351–0006	63–122	1.042			
239	86/6/17	0451–0506	78–107	1.353			
	(0519)						
241	86/6/17	1704–1719	63–181	1.004	1702–1717	107–168	1.638
	(1733)	1719–1734	63–122	1.503	1802–1817	49–122	1.163
269	86/6/22	1637–1652	63–107	1.280	1655–1710	107–168	1.382
	(1719)	1708–1723	49–211	1.129	1710–1725	137–181	1.690
272	86/6/23	0710–0725	49–78	0.905	0713–0728	122–196	0.966
	(0740)	0740–0755	107–181	1.234	0743–0758	107–137	1.213
		0755–0810	122–181	0.972			
277	86/6/23				1732–1747	78–122	1.354
	(1724)						
303	86/6/27	0522–0537	49–78	1.170	0527–0542	122–152	1.660
	(0539)				0542–0557	78–107	1.348
					0612–0627	49–78	1.123

Note: No sodar measurements were available for flights 320 and 340.

Brutsaert 1989) to adopt $d_0 = 5z_0$, so that (1) can be written as

$$V = \frac{u_*}{k}\ln\left(\frac{z - 5z_0}{z_0}\right). \tag{2}$$

A critical point in the application of (2) with measured wind velocity profiles is the determination of the height range over which it is valid. The choice of the height range affects the value of the resulting roughness length z_0; therefore the correct height range of (2) can be inferred from the value of z_0 which can be reasonably expected for the given terrain. In the Landes region some 65% of the area is occupied by pine forest in different stages of growth. The remainder of the region is occupied by clearings with fields under agricultural production, or with shrubbery and recent plantings, and by some housing nuclei and other settlements. The areal mean height of all these roughness obstacles ranges in the extreme between 4 and 15 m, so that the aerodynamic roughness has to lie between approximately 0.5 and 2 m. Accordingly, in the application of (2) with each radiosonde wind velocity profile, the largest number of points in sequence was selected that produced a value of z_0 between 0.5 and 2.0 m. As indicated earlier, (Parlange and Brutsaert 1989) this procedure was straightforward, as the inclusion of one or more points, above or below the chosen interval, would produce a value of z_0 that would be well outside the range $0.5 < z_0 < 2$ m, and thus not reasonable for the terrain conditions of the Landes region (see Fig. 2). The results regarding the value of the roughness z_0 and the range of the logarithmic layer derived from the radiosonde profiles are summarized in Table 2.

Application of (2) with V measurements over the logarithmic height range also allows the determination of the friction velocity u_*. It was observed in the analysis that once z_0 in (2) is fixed, the inclusion or omission of a point in the profile does not change the resulting u_* value appreciably. Thus, once z_0 is known, (2) provides an estimate of u_* which is relatively more robust than if z_0 is allowed to be a free parameter in the regression. At any rate, the values of u_* obtained by either procedure were very close. The values of u_* obtained by applying (2) with $z_0 = 1.2$ m [and thus (1) with $d_0 = 6$ m] for each of the neutral profiles are listed in Table 3. These values were found (Parlange and Brutsaert 1989) to be in good agreement with u_* values measured independently by means of the eddy correlation method; the correlation coefficient was $r = 0.96$ and the slope of the linear regression through

TABLE 2. Summary of results. Mean (±SD).

	Geometric mean roughness z_0 (m)	Height range of z (m)		Height range of $(z - d_0)/z_0$ for z_0 = 1.2 m & d_0 = 6.0 m	
		Lower	Upper	Lower	Upper
Lubbon Radiosonde	1.18 (±0.40)	86 (±22)	160 (±38)	67 (±18)	128 (±32)
Lubbon Sodar	1.11 (±0.23)	76 (±24)	136 (±43)	58 (±20)	108 (±36)
Estampon Sodar	1.19 (±0.29)	89 (±31)	137 (±36)	69 (±26)	109 (±30)

the origin was 0.98. As explained elsewhere (see also Brutsaert et al. 1989) these eddy corrrelation measurements were made on a 29 m mast, about 9 m above the forest canopy in the vicinity of Estampon by a research team from the Institute of Hydrology, Wallingford, Great Britain.

c. *Analysis of neutral sodar wind profiles*

The main objective of the sodar wind analysis was to obtain an additional assessment of the reliability of the results of the radiosonde wind analysis. Because two sodar systems were operated concurrently, potentially more wind profile data under neutral stability could be available than the 14 radiosonde profiles. Moreover, as atmospheric conditions usually changed slowly, in principle those profiles which preceded and followed the sodar measurements, corresponding most closely to the radiosonde release time, could also be used in the analysis. However, the actual number of usable profiles was much smaller. The sodar stations were not always in operation at the time of the radiosonde releases. Also, not all the available profiles were suitable for analysis, especially when they displayed too much scatter as a result of low signal reflectivity.

The time intervals of the sodar wind velocity profiles that were found to be suitable for the determination of z_0 are listed in Table 1. The analysis was carried out in the same way as for the radiosonde wind profiles. Thus, for each profile, by trial and error the largest height range was selected, over which linear regression by means of (2) produced a value of z_0 between 0.5 and 2.0 m. This procedure is illustrated in Fig. 2. The analysis was carried out separately for Lubbon and Estampon. The resulting height ranges, and the values of z_0 for each 15-minute profile, are listed in Table 1. The results of Table 1 are summarized in Table 2.

The friction velocity values u_* of the sodar profiles were calculated like those of the radiosonde profiles, namely by linear regression of (2) for a fixed value of the roughness z_0 = 1.2 m. As mentioned above, this procedure is more robust than if z_0 is allowed to be a free parameter in the regression. In this way, even fairly noisy profiles could be used in the analysis. To allow comparison only the highest quality sodar profiles, measured around the time of the radiosonde releases, were used in the calculation. Quality was based on the reflectivity and on minimal erratic fluctuations in the profile. The resulting u_* values are listed in Table 3 together with the time interval and the height range of points used.

TABLE 3. Friction velocities u_* (m s^{-1}).

		Lubbon sodar			Estampon sodar		
Flight	Radiosonde u_*	u_*	Time (UTC)	Height range (m)	u_*	Time (UTC)	Height range (m)
156	0.57	0.56	0519–0534	78–107	0.51	0530–0545	78–122
157	1.11				0.82	1131–1146	93–181
203	0.78	0.65	1738–1753	63–181	0.64	1738–1753	63–181
221	0.32	0.17	1729–1749	49–152			
232	0.80	0.74	0800–0815	78–181	0.71	0801–0816	63–168
238	0.64	0.60	2336–2351	93–181			
239	0.41	0.32	0451–0506	78–107			
241	0.40	0.42	1749–1804	63–181	0.21	1732–1747	63–181
269	0.68	0.40	1723–1738	78–181	0.42	1710–1725	137–181
272	1.29	1.07	0740–0755	107–181	0.83	0758–0813	107–211
277	0.55	0.62	1709–1724	49–181	0.49	1732–1747	78–122
303	0.76	0.56	0537–0552	49–93	0.80	0527–0542	122–152
320	0.50						
340	0.36						

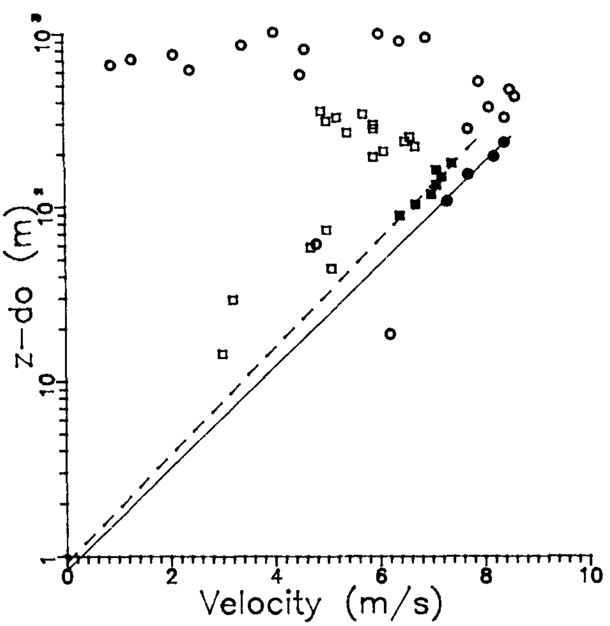

FIG. 2. Same as Fig. 1, but ordinate is logarithmic. The straight lines are the least squares regressions by means of (2) through the solid points; the solid points indicate the extent of the logarithmic layer.

3. Comparison of results

a. Surface roughness

The results of the determination of the roughness z_0 and of the height range of the logarithmic layer obtained by the radiosonde and by the sodar systems are summarized in Table 2.

It can be seen that the sodar roughness values are in excellent agreement with the value $z_0 = 1.18$ m obtained from the radiosonde wind profiles. The mean roughness derived from the sodar data at Lubbon, $z_0 = 1.11$ m is a little smaller than that at Estampon $z_0 = 1.19$ m. It might be tempting to attribute this to the fact that the Lubbon site is in a large clearing whereas the Estampon site is a mature pine forest; however, the difference in roughness is insignificant.

b. Extent of surface layer

As shown in Table 2, the lower limits obtained with the sodars closely agree with the limits obtained with the radiosonde, but the upper limits are lower than those of the radiosondes.

The lower level of the surface layer, variously called the merging or blending (Wieringa 1976) height, is probably the most important limit. It is the upper boundary of the transition layer, i.e., the roughness wake layer, in which local surface effects are felt. In contrast, in the surface layer the profiles reflect the regional impact of the surface on the boundary layer. In this respect, one of the most interesting results obtained with the radiosonde wind measurements is verified.

The agreement between the two sodars regarding the upper limit of the surface layer could be interpreted as pointing to an overestimation with the radiosonde wind profiles. On the other hand, the accuracy of a sodar typically decreases with distance from the acoustic source so that more scatter is generally found in the upper limit of the sodar wind profiles. The upper limit of the CRPE system is approximately 360 m. Breakdown of the sodar profiles in some instances restricted the upper height of application of (2). Thus, the estimate of the upper limit of the inner region by means of the sodar profiles is likely to be on the low side.

c. Friction velocity

The u_* values calculated from the wind profile data by means of (1) and (2) with $z_0 = 1.2$ m and $d_0 = 6.0$ m are presented in Table 3. In Fig. 3 the values calculated with the Lubbon sodar wind profiles can be compared with those obtained with the radiosonde profiles. In Fig. 4 the same comparison is shown for the Estampon sodar profiles. In both figures the correlation may be termed good, namely $r = 0.92$ for 11 data points and $r = 0.84$ for 9 data points. The reason that not all of the 14 neutral events could be used in the comparisons is that on a few occasions the sodar stations were not in operation (see Table 3). The respective slopes of the linear regression through the origin in the figures are 0.85 and 0.77. This may be an

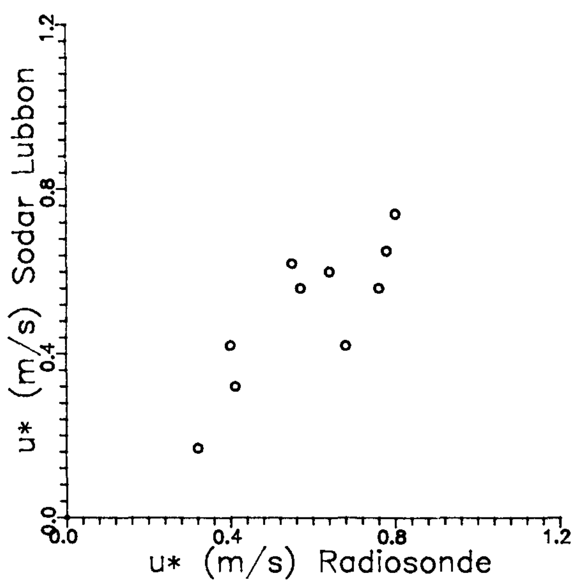

FIG. 3. Comparison of the u_* values derived from the wind velocity profiles measured by the radiosonde system with the u_* values derived from the wind velocity profiles measured by the sodar system at Lubbon. The u_* values are obtained by means of (1) or (2) for $z_0 = 1.2$ m and $d_0 = 6.0$ m. The correlation coefficient is $r = 0.92$.

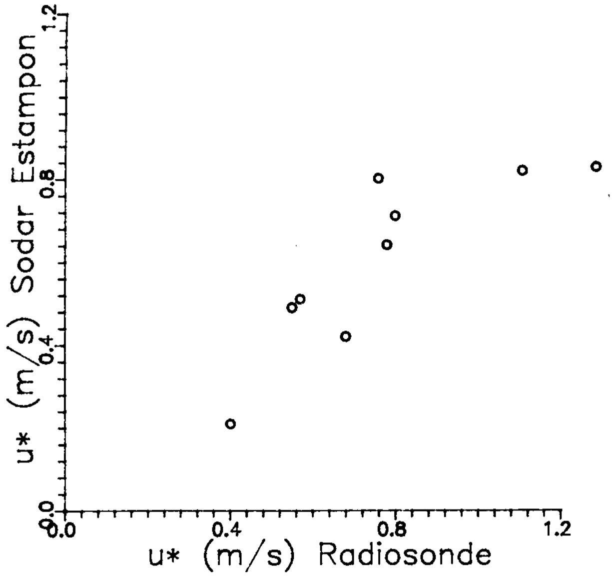

FIG. 4. As in Fig. 3, but with the u_* values derived from the wind velocity profiles measured by the sodar system at Estampon. The correlation coefficient is $r = 0.84$.

indication either that the radiosonde profiles tend to overestimate the surface shear stress or conversely that the sodar profiles tend to underestimate it.

Actually, that the radiosonde wind profiles would have overestimated the surface shear stress, does not appear likely. As noted above, in an earlier study (Parlange and Brutsaert 1989) the values of u_* obtained from the radiosonde profiles were shown to be in good agreement ($r = 0.96$) with u_* values measured independently by means of the eddy correlation method on a 29 m mast near Estampon. The slope through the origin was 0.98. Moreover, recently Keder et al. (1989) have shown that for strong wind conditions a sodar-measured velocity tends to be smaller than those measured with other instruments; thus the associated friction velocity is also likely to be smaller. It must be noted, however, that only few neutral events could be tested here, so that no general conclusions may be made.

4. Conclusions

The question, can radiosonde wind profiles capture sufficient information to characterize the surface layer of the boundary layer has only partly been answered. In general, the results of the analysis of the measurements with the two sodar systems and with the radiosonde system were in good agreement. The surface roughness values and the lower limits of the surface layer were nearly the same. However, although the values of the friction velocity are well correlated, on average the sodar results are a little smaller than the radiosonde values; also the upper limits of the surface layer derived from the sodar observations are lower than those derived from the radiosonde measurements. Clearly, both measuring systems have their limitations, and care must be taken in the analysis of wind profiles with either type of sounder. Although it can be argued that radiosonde profiles are not adequately time averaged, the present findings indicate that it is not unreasonable to use radiosonde data in similarity studies, at least under neutral conditions.

Finally, the good agreement between the results obtained from measurements taken at locations up to 5 km apart again supports the idea that the surface layer, as defined in this paper (see Table 2), reflects transport phenomena at the regional scale. In other words, both the roughness z_0 and the surface shear stress values u_* are characteristics of upwind fetches involving scales on the order of 10^4 m or more.

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