AN INEXPENSIVE AND SIMPLE TECHNIQUE FOR MEASURING WIND VELOCITY IN THE LOWER 600M OF THE ATMOSPHERE

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ABSTRACT

An inexpensive and simple technique for measuring the average wind velocity in the lower 600 m of the atmosphere is proposed. The technique uses 30-g pilot balloons filled with helium. Final position of the balloon is measured by a clinometer and a compass--instruments which are readily available to forestry personnel. Sources of error are discussed and it is concluded that horizontal velocity determined by the suggested procedure is probably accurate to within 17 percent.

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INTRODUCTION

The relative importance of wind as one of the factors controlling forest fire behaviour is well known (Davis 1959). Success of prescribed burns and suppression of wildfires are often dependent on an accurate assessment of current and forecast wind velocities. Unfortunately wind velocities are highly variable, especially over forested terrain. The extrapolation from one location to other locations of a measured wind velocity often assumes homogeneity in the wind field which does not exist. Accurate forecasting of wind at specific locations is difficult to achieve owing to the general paucity of observations as well as to the complex nature of the fluid dynamic problem. Final recourse is usually made to empirical relationships in order to reduce the average forecast error. Although empirical techniques can improve standing on forecast skill-score tests, specific cases may still be handled rather poorly; hence, a mix of statistical and physical reasoning is the best approach to the forecasting problem. The net result of this dual problem of observing and forecasting winds is that there is no suitable substitute for on-site observations of wind velocity in those situations where accuracy is required. It is for this reason that fire researchers have recommended that a portable weather-observing station be designed (Nikleva *et al.* unpubl. rep.). Such a station was envisaged as having equipment for measuring both surface winds and winds aloft.

There are many techniques now available for measuring upper-air winds, but a time-honoured technique still often used consists of optical theodolites tracking a small free balloon ascending at a more or less uniform rate. This technique has the advantages of reasonable cost, reliable instrumentation and simplicity of data reduction. It suffers from poor spatial resolution of the wind field and from being restricted to reasonably fair weather. For special studies two or three theodolites are employed and simultaneous observations of balloon position obtained. The number of theodolites and observers required can be reduced so that for routine observations or when reduced accuracy is acceptable, a single theodolite is feasible.

Even though the single-theodolite technique is quite straightforward and relatively inexpensive in comparison with other techniques in vogue it is still not cheap or simple enough for use by untrained personnel. Theodolites cost between $1500 and $2000 each, and a rapid reduction of pibal flights requires the use of special plotting boards. Fortunately, for many forestry applications wind information is not required to very great heights. Within the friction layer (< 1000 m) an ascending pilot balloon is visible to the unaided eye and consequently the magnification provided by a theodolite is not necessary. This paper proposes that a clinometer and a compass such as those used by forestry personnel in cruising may be substituted for the single theodolite with the result that a simple and practical technique is available for measuring the average wind velocity through the lower atmosphere.

THEORETICAL CONSIDERATIONS

Geometry

Figure 1 depicts the geometry for the analysis which follows. The balloon is released by an observer at point O and after a time, t, a sighting is made on the balloon which is then at position B. This sighting consists of the angles ϕ and α, where ϕ is the elevation angle and α is the azimuth from B to O. Thus, α is the direction from which the wind is blowing.

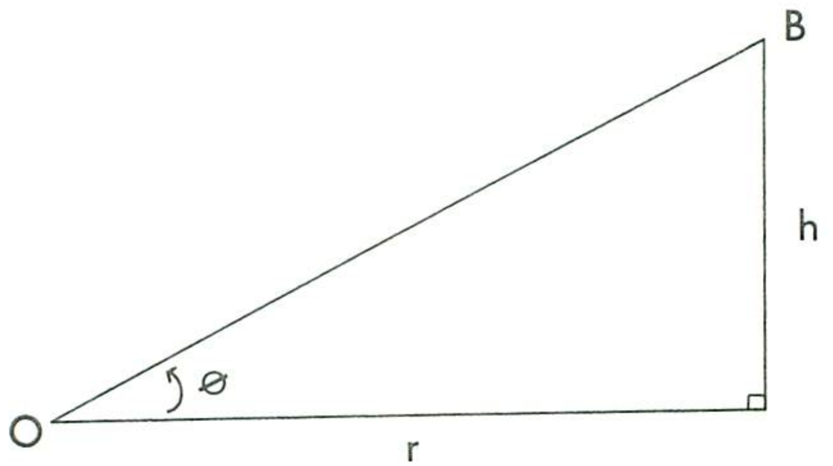

Figure 1. Geometry for calculating balloon displacement.

The balloon is assumed to rise at a constant rate, w, so that after a time, t, the balloon is at height, $h = wt$. If we let v be the average horizontal velocity over t, the horizontal projection of the slant distance OB is given by $r = vt$. From Figure 1 it follows that $r = h\cot\phi$ and, substituting, we have $vt = wt\cot\phi$, which simplifies to

$$v = w\cot\phi. \tag{1}$$

Note that equation (1) does not contain t as a variable. The quantity t will enter only insofar as it determines the depth of the layer over which the average horizontal velocity is being measured.

Many clinometers measure the slope, s, in percent rather than or in addition to ϕ. Now,

$100 \tan \phi = s$, and therefore

$$\cot \phi = \frac{1}{\tan \phi} = \frac{100}{s}.$$

Hence, equation (1) may also be written as

$$v = 100 \frac{w}{s}. \tag{2}$$

Error analysis

a) Theory

If differentials of equation (1) are taken, the relative error in determining the horizontal velocity is given by

$$\frac{dv}{v} = \frac{dw}{w} - \frac{\csc^2\phi}{\cot\phi}\, d\phi,$$

which simplifies to

$$\frac{dv}{v} = \frac{dw}{w} - \frac{2d\phi}{\sin 2\phi}. \tag{3}$$

Assuming that the elevation angle can be determined to better than 0.5 degrees, the second term on the right-hand side of equation (3) remains less than 5% for ϕ greater than 10.2 degrees. For a standard rate of rise of 3.1 m sec^{-1} (10.17 ft per min) (Berry *et al.*1945) this implies from equation (1) that the error in estimating v is less than 5% for v less than 17.2 m sec^{-1} (38.6 miles per hour). However, the relative error contributed by errors in measuring ϕ is generally much less than errors resulting from the assumption that the rate of rise of the balloon is a constant.

Factors leading to a variability in the rate of rise are considered in the Appendix. It is concluded that variation in a pilot balloon's rate of rise occurs both during flight and from one occasion to another, primarily as a direct result of variations in resistance to the motion of the balloon through the air. These variations depend upon ambient turbulence levels as well as other factors, but are essentially stochastic in nature. Hence, rates of rise need to be determined by actual measurements. Statistical inferences can be drawn from the results.

(b) Measured values

During July, 1973 double theodolite observations of pilot balloon flights were made over a predominantly jack pine (*Pinus banksiana* Lamb.) forest near Peshu Lake Ontario (46.8 N 83.3 W). A total of 33 usable flights were obtained. Data were processed on a remote computer terminal using a program written in APL360. Procedures were essentially the same as those given by Thyer (1962).

Figures 2a to 2c are frequency distributions of vertical velocity results for the layers 0 to 300, 300 to 600 and 0 to 600 m. Notice that the distributions are markedly skew. Although a χ^2 test accepts these distributions as normal at the 5% level, a skewness test rejects them as normal at the 5% level. (Figures 3a to 3c show the same results assuming a logarithmic distribution (i.e., $\log_{10} w$ versus frequency). These distributions are acceptable as normal at the 5% level by both the χ^2 and skewness tests. Thus, measured values for the rate of rise of pilot balloons form a log-normal distribution.

For the surface-to-600-m layer the mean value for $\log_{10} w$ was found to be 0.528 with an estimated population variance of 0.00633. Thus, 50% confidence limits (Spiegel 1961, p. 159) are given by

$$\log_{10} w = 0.528 \pm 0.6745\sqrt{0.00633}$$

$$= 0.528 \pm 0.054$$

Taking anti-logarithms of these confidence limits yields a mean rate of rise of 3.4 m sec^{-1} (11.15 ft per min) with a probable error in the order of 12%. If the elevation angle ϕ is assumed to be determined to within 0.5 degrees, it follows from equation (A2) that the total probable error in w is in the order of 17%.

SUGGESTED PRACTICAL PROCEDURE

The following steps are suggested as a practical routine for obtaining winds in the lower 600 m:

(a) Fill the pilot balloon with helium using a standard filling mechanism (for example, Atmospheric Environment Service of Canada, Cat. No. 0026-0422 Type B).

(b) Release the balloon from a location with a reasonably unobstructed view of the sky.

(c) After 1-3 minutes[1] have elapsed measure the vertical angle ϕ in terms of the slope, s, in percent by means of the clinometer. If s exceeds 150% or if the clinometer does not have a slope scale, the angle ϕ will have to be read in degrees and cot ϕ determined from a table. (A small table of values of

[1] For times shorter than 1 minute estimated values of the horizontal velocity of the balloon may be somewhat low owing to strong vertical shear which normally exists over forested terrain. A longer time interval results in a better estimate of winds aloft but the balloon may be readily lost to the unaided eye if a period of much more than 3 minutes has elapsed.

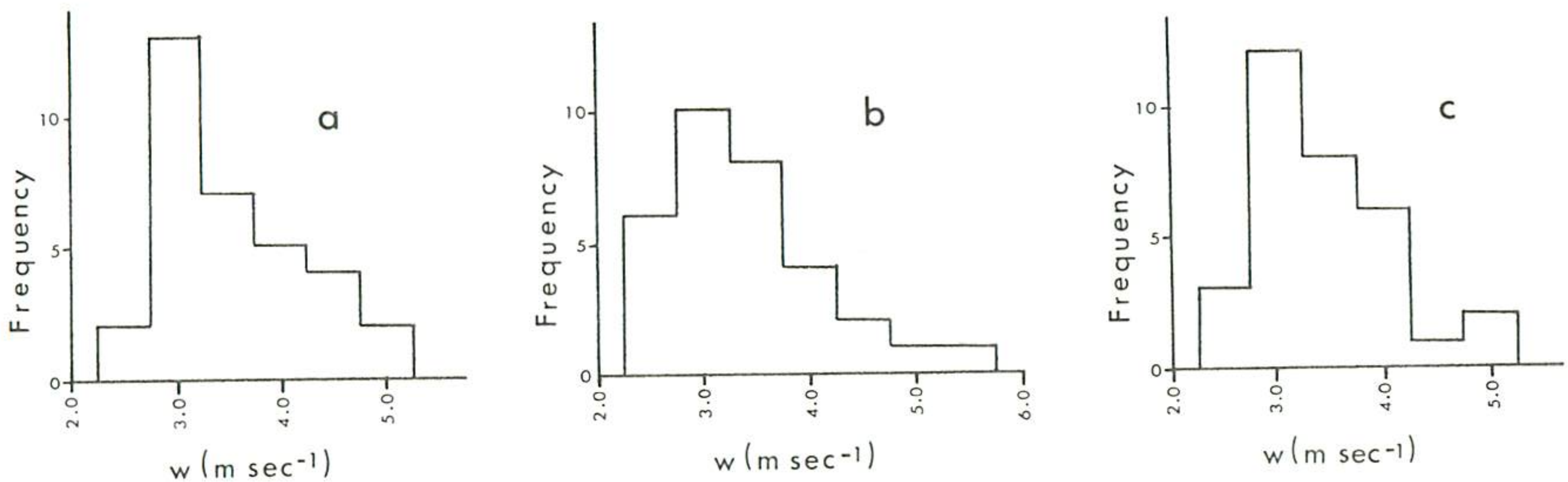

Figure 2. Frequency distributions for pilot balloon rates of rise at Peshu Lake, July, 1973 for the layers (a) surface - 300 m, (b) 300 - 600 m, and (c) surface - 600 m.

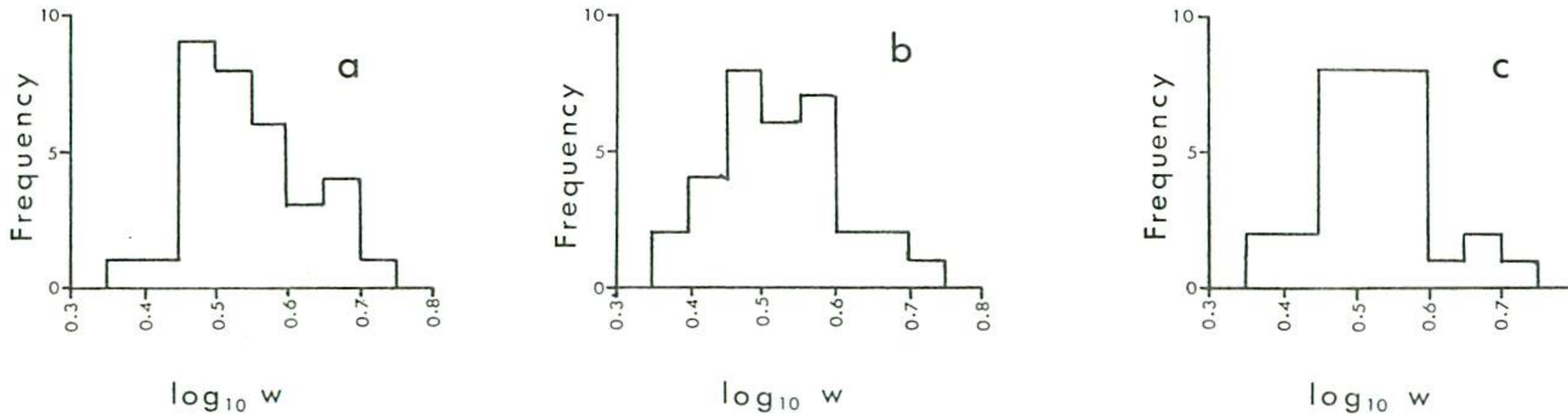

Figure 3. Frequency distributions of the logarithms of pilot balloon rates of rise for the same data as in Figure 2.

cot ϕ for selected values of ϕ may be taped to the inside of the clinometer case to assist in this calculation.)

(d) Immediately sight on the balloon with the compass and take a reading, α, which is equivalent to the back bearing from the balloon to the observer. This may be accomplished by aligning the orienting arrow with the south end of the compass needle. The angle α is the average direction from which the wind is blowing.

(e) If the angle ϕ has been measured in terms of the slope, s, use the formula

$$v[\text{m sec}^{-1}] = 340/s \qquad (4)$$

or

$$v[\text{miles per hour}] = 760/s \qquad (5)$$

to obtain the average horizontal wind velocity.

If ϕ has been read in degrees, use

$$v[\text{m sec}^{-1}] = 3.4 \cot\phi \qquad (6)$$

or

$$v[\text{miles per hour}] = 7.6 \cot\phi. \qquad (7)$$

CONCLUSIONS

An inexpensive and simple technique is available for measuring the average horizontal wind velocity in the lower 600 m of the atmosphere. The technique uses 30-g pilot balloons filled with helium. Final position of the balloon is measured by a clinometer and a compass--instruments which are readily available to most forestry personnel. The time interval over which the observation is taken need not be determined accurately except insofar as it determines the depth of the atmosphere to which the resultant average wind velocity pertains. Overall accuracy of the technique is probably in the order of 17%.

Within the lower 600 m of the atmosphere the technique is only slightly less accurate than the single theodolite technique, with both procedures suffering from the same major source of error. This major source of error is the assumption that the rate of use of the balloon is a constant. In fact, the rate of ascent of pilot balloons is quite variable, both during flight and from one flight to another. This variability in rate of ascent is caused by a non-constant drag coefficient.

Results from pilot balloon flights made during July, 1973 over a jack pine forest suggest that the rates of rise of pilot balloons within the surface-to-600-m layer of the atmosphere from one occasion to another are distributed in a log-normal fashion with a mean of 3.4 m sec^{-1} and a probable error in the order of 12%.

Because the procedure proposed in this paper is suggested as a practical approach, the author would appreciate feedback on impressions of the usefulness of the technique from any districts that test the procedure in the field.

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APPENDIX

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From principles of dynamic similarity it can be shown (Middleton and Spilhaus 1953, p. 170) that the rate of rise of a balloon is given by a formula of the form

$$w = \frac{bL^n}{(L + B)^{1/3}}, \qquad \text{(A1)}$$

where B is the weight of the balloon plus load (if any) and L is the so-called free lift (i.e., the weight that the inflated balloon and load will just support without sinking or rising). Values for the constants b and n must be determined by experiment. For pilot balloons $n \cong 0.5$ and $b \cong 1.46$ when w is in units of m sec^{-1} and helium is used as the inflating gas. In actual fact the complete equations describing a balloon's response are quite complex (Fichtl 1972), but for averaged velocities over an appreciable depth of the atmosphere, the simplified reasoning resulting in equation (A1) is acceptable.

By taking differentials of equation (A1) the relative error in rate of rise resulting from filling procedures and balloon weight variability is given by

$$\frac{dw}{w} = dL\left(\frac{1}{2L} - \frac{1}{3(L + B)}\right) - \frac{dB}{3(L + B)}, \qquad \text{(A2)}$$

where n is assumed equal to 0.5. For latex pilot balloons typical values are $B \cong 32$ g, $L \cong 144$ g, and maximum likely values are $dL \cong 5$ g, $dB \cong 1$ g. Substitution into equation (A2) yields $\left|\frac{dw}{w}\right| \sim 0.01$; that is to say, normal filling procedures and variability in balloon weight will not likely contribute more than 1% to the variability in the assumed rate of rise.

Changes in ambient air density with height and differences between balloon temperature and ambient air temperature will also result in variations in the rate of rise. However, such variations will generally be less than 1 or 2% in the lower 600 m of the atmosphere (Middleton and Spilhaus 1953, p. 172).

In the derivation of equation (1) it was assumed that the drag coefficient is constant both with altitude and from one occasion to another. The drag coefficient, C_d, is defined by

$$F_d = \frac{1}{2} \rho \, C_d w^2, \qquad \text{(A3)}$$

where F_d is the drag force on the balloon and ρ is the density of the air. However, the drag coefficient is a function of the Reynolds number, Re, defined by

$$Re = \frac{wD}{\nu}, \tag{A4}$$

where D is the diameter of the balloon ($D \cong 0.68$ m) and ν is the kinematic viscosity of air ($\nu = 1.5 \times 10^{-5}$ m^2 sec^{-1}). If one plots C_d versus Re, then for spheres placed in wind tunnels, C_d is relatively constant below some critical value $(Re)_c$ and drops abruptly as Re increases beyond $(Re)_c$. For smooth balloons in the atmosphere the transition is not quite so abrupt at $(Re)_c$ and C_d is not so constant as $(Re)_c$ is approached (Scoggins 1965). For balloons with $D < 1$m, $(Re)_c \sim 2$ to 3×10^5. Furthermore, $(Re)_c$ depends to some extent upon ambient turbulence levels. MacCready (1965) found that small balloons ($D < 1$ m) tend to have a relatively constant C_d. However, substituting typical values in equation (A4) gives a Reynolds number of 1.4×10^5, a figure which is uncomfortably close to the critical Reynolds number for smooth balloons. One concludes, therefore, that variation in a pilot balloon's rate of rise occurs both during flight and from one occasion to another primarily as a direct result of variations in the drag coefficient.

Aerodynamically induced lift forces result in horizontal oscillations superimposed on the average path of the balloon (Fichtl *et al.* 1972). These oscillations affect only the fine scale resolution of the wind field, however, and are not significant for wind velocity determinations over intervals of time greater than 20 seconds (Johnson 1965, Barnett and Clarkson 1965).

A final source of variation in the rate of rise of a balloon is the presence of vertical motions of the air itself. In general, sinking motions are negligible, except in the vicinity of obstacles. Updrafts are a more serious problem and if a balloon is observed entering the base of a cumulus cloud, then data from the flight are suspect. Two or three flights with consistent determinations should be used to confirm results if the presence of vertical air currents is suspected.