A Universal Procedure for Deploying Constant-Volume Balloons and for Deriving Vertical Air Speeds from Them

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ABSTRACT

A graphical method for flying any type constant-volume balloon at specified heights up to 500 m above mean terrain is described. The flight parameters, surface free-lift, and surface superpressure are determined from graphs whose only argument is the air temperature difference between balloon flight level and inflation shelter. Another graph corrects the flight parameters for any balloon other than the 150 cm tetroon by using the balloon's volume and volume ratio. Flight-level error is about 30 m per degree Celsius of flight-level temperature error in a normal lapse rate. The balloon will fly too low if the air temperature is warmer than estimated.

Instructions for constructing flight-parameter graphs for any particular constant-volume balloon are included along with an outline of the inflation theory. The mechanical details of correctly ballasting constant-volume balloons are given. Air ballast is used inside the balloon, thereby virtually eliminating impact dangers.

Vertical air speeds are estimated directly from a graph whose arguments are observed tetroon (150 cm) vertical speed and the tetroon's vertical distance from its equilibrium level. A correction graph allows the use of any other constant-volume balloon whose frontal area to volume ratio and drag coefficient are known.

Because of the tetroon's large drag coefficient (0.74), the tetroon's vertical speed itself may be used as first-order estimates of vertical air speed.

1. Introduction

The "constant-volume" balloon is an appropriate tool for investigating the kinetic and dynamic properties of the atmospheric boundary layer, in a Lagrangian context, at selected heights above the ground. Since not all constant-volume balloon users fly the same shape balloon, and since computing lift and superpressure for each flight can become tedious, this paper presents a simple method for computing balloon surface lift and for inflating and ballasting *any* constant-volume balloon for use as noted above.

The so-called constant-volume balloon actually changes volume slightly with changes of superpressure (excess of internal balloon pressure with respect to ambient pressure) because of the elasticity of the Mylar (or other material) envelope. Fig. 1 shows the superpressure-volume relationship for the two constant-volume balloons (tetroons) used by the Air Resources Laboratories (150 and 105 cm on a side with a Mylar skin thickness of 0.05 mm). This volume change with change of internal pressure causes the balloon-system (balloon plus all attachments) average density to change, so this density change must be considered when determining balloon buoyancy at the release level. The balloon is released with a system average density less than ambient density. Therefore, the balloon ascends until it reaches a level where balloon-system density equals the ambient atmospheric density. This is because the balloon-system density decrease with height is about one-fourth the rate of atmospheric density decrease. In the absence of vertical air motions (stable atmosphere) the balloon will float near the level for which it is ballasted. In convective conditions the balloon will tend to float at a slightly higher average elevation because there is no upper boundary to limit balloon excursions above its equilibrium float level while the earth restricts downward excursions of both air parcels and balloons.

The effect of density (volume) change with increasing superpressure in the balloon during ascent is shown in Fig. 2 where the schematic density lapse curves of a real balloon, a hypothetical truly constant-volume balloon, and the atmosphere are shown. The slight increase of balloon volume (density decrease) during ascent causes the real balloon to float at a higher level, for a given initial bouyancy, than would a truly constant-volume balloon. Since the real balloon expands slightly during ascent, its internal pressure (superpressure) does not increase with height as fast as atmospheric pressure decreases. As an example, in a normal lapse rate, superpressure increases during ascent in the 150 cm tetroon at about 0.6 the rate that atmo-

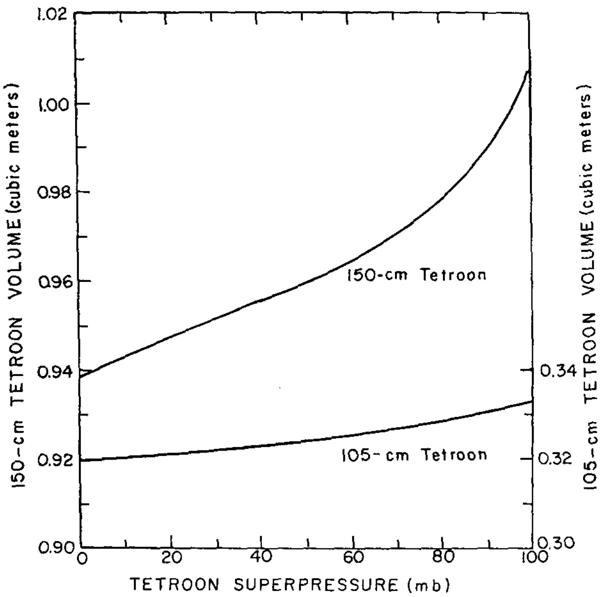

FIG. 1. The pressure-volume curves for the 150 and 105 cm tetroons used by the Air Resources Laboratories, NOAA. The Mylar skin is 0.05 mm thick.

spheric pressure decreases with height. In general, superpressures which significantly exceed 70 mb in the larger tetroon and 100 mb in the smaller tetroon should be avoided because then the Mylar begins to "creep" and the balloons will not return to their original volume (hysteresis effect) when ambient pressure (and superpressure) is returned to its original value. An advantage of a smaller balloon, therefore, is that it can withstand a greater altitude range during convective activity, without reaching the "creep" stage of the Mylar skin.

2. Weigh-off and inflation procedure

If a series of balloons or tetroons is to be flown at the same elevation and with the same superpressure, all that basically is required to determine the correct free lift at the surface is knowledge of the temperature at flight level and in the inflation van (not the ambient surface temperature). For example, Fig. 3 shows that if one wishes to weigh-off a 150 cm tetroon for a flight 100 m above the ground (use the 100 m curve) with a flight-level superpressure of 40 mb, then if the temperature in the inflation shelter exceeds that at flight altitude by 2°C, the required surface free lift would be 5 g and the required surface superpressure 36 mb. For each degree error in estimating the temperature at flight level, the error in tetroon height is about 30 m, and in the sense that if the temperature is warmer than estimated the tetroon will fly too low.

Provision is also made in Fig. 3 for flying the 150 cm tetroon at 200, 300 and 500 m above the launch level. Please note that in these cases surface free lift and surface superpressure are given as functions of inflation shelter and flight-level temperature difference per 100 m. For flight levels between those shown by the traces in Fig. 3, one merely determines surface free lift and surface superpressure for levels bracketing the desired flight level and interpolates to get the desired values.

Fig. 3 is invalid if the available balloon does not have nearly the same volume (0.94 m^3) or pressure-volume relationship as the 150 cm tetroon. For such other balloons, the surface free lift and surface superpressure should be determined as specified for the 150 cm tetroon in Fig. 3; Fig. 4 can then be used with the available balloon's volume and its volume ratio (ratio of volume at 60 mb to volume at 10 mb superpressure, equal to 1.021 for the 150 cm tetroon). The conversion factor, found at the intersection of these values, is multiplied by the surface free lift obtained for the 150 cm tetroon. For example, the small tetroon has a volume of 0.32 m^3 and the ratio of the volume at 60 mb superpressure to that at 10 mb superpressure is 1.015. The conversion factor from Fig. 4 is then 0.38, and for the conditions of the case cited earlier the free lift would be 0.38×5 g, or about 2 g. It is important to note that no adjustment is needed for the surface superpressure.

Figs. 3 and 4 provide a simple, universal, constant-volume balloon flight computation system for nearly any balloon (tetroon, sphere, cylinder, etc.) within the

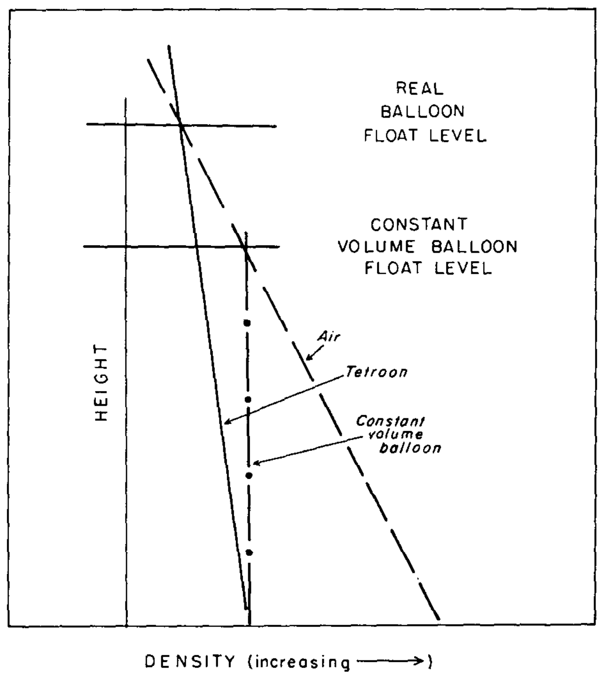

FIG. 2. Schematic diagram showing the density lapse with height of a real "constant-volume" balloon (tetroon), a (hypothetical) truly constant-volume balloon, and the atmosphere (air). The height at which total balloon system average density equals atmospheric density represents the equilibrium float level of the balloon system. As shown, a truly constant-volume balloon system would float at a lower level for a given initial system density and given volume.

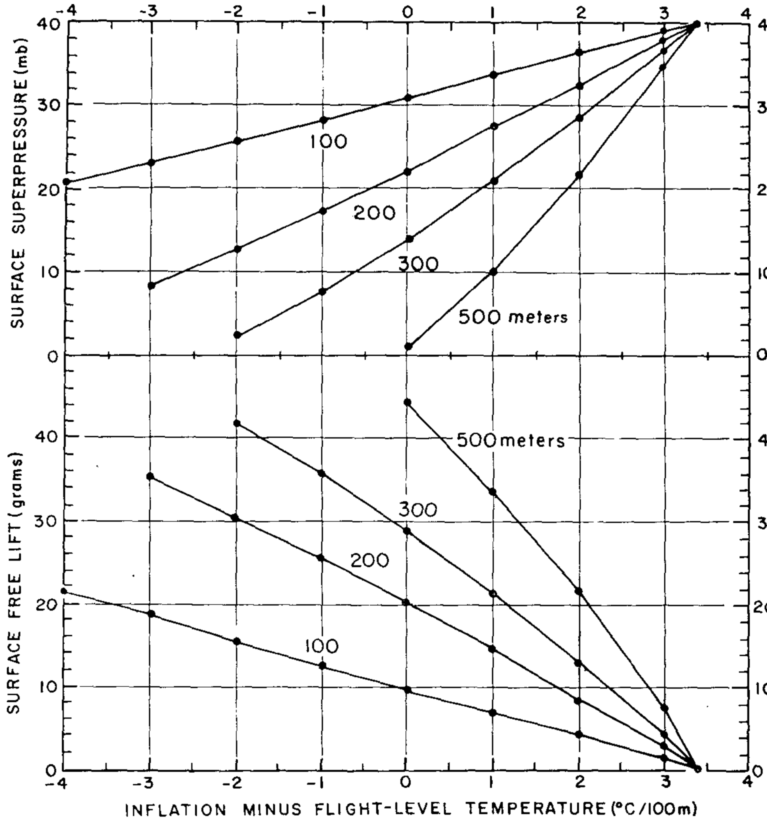

FIG. 3. Graph for computing surface free lift and surface superpressure for 150 cm tetroon for flight 100, 200, 300 and 500 m above launch level with a flight-level superpressure of 40 mb. Note that the difference between inflation-room temperature and flight-level temperature is normalized to a distance of 100 m.

height and temperature-difference limits shown in Fig. 3. The theoretical basis for construction of Fig. 3 is given in the Appendix.

The suggested inflation procedure involves attaching to the constant-volume balloon (tetroon) all items that are to be flown with it, as well as the gram weights equal to the calculated free lift, and then inflating with helium until the balloon barely floats (at this stage, the balloon will be only about half full). Next, air is added until the balloon is filled but has no superpressure (the advantage of such air "ballast" is that it is of no hazard to aircraft). The balloon is then again filled with helium until the required superpressure is attained. Interestingly enough for the tetroon, the mass added by superpressuring with helium is slightly overcompensated by the resulting lift due to expansion of the tetroon, but the small excess of free lift thus gained can be balanced with a few pieces of adhesive tape. Please remember that the weights attached to the balloon (equal to the calculated free lift) *must* be removed before releasing it. It is, of course, important to keep the inflation shelter temperature as even as possible during inflating and balancing of the balloon.

In some instances, the inflation-shelter temperature is so high (summer conditions) that the inflation graph (Fig. 3), if extended, would call for negative balloon balance in the shelter. Here, weight must be added to go aloft with the balloon to get the correct float altitude. For this condition, the balloon system is first balanced, as outlined above, but *without* freelift weights, then the weight specified by the inflation graph is added before release. The so-weighted balloon will have positive buoyancy when taken outside the shelter where about 4 g free lift are gained for each degree Celsius of temperature drop between the shelter and the outside air. Since one milliliter of water weighs one gram, the easiest way to add specified weight to the balloon is to add a measured amount of water to a small plastic bag that has been attached to the balloon before balancing.

Once the balloon has been inflated and balanced for the existing flight level and shelter temperatures, no adjustment is needed if the shelter temperature changes before the balloon is launched. Experiment has shown that the balloon automatically adjusts surface free lift and surface superpressure to correspond with shelter temperature change so that the balloon will ascend to the intended flight level, provided that the flight-level temperature has not changed. Since the flight-level

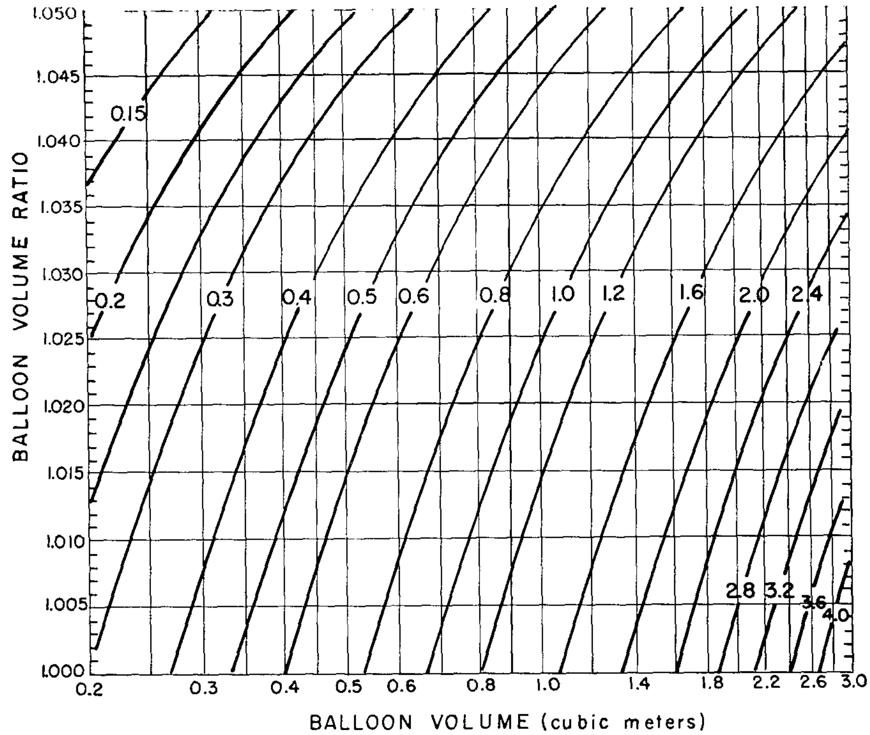

Fig. 4. Correction-factor graph for converting surface free lift for the 150 cm tetroon to that for any constant-volume balloon. The coordinates are the available balloon's volume and the volume ratio for superpressures of 60 and 10 mb. The free lift determined from Fig. 3 is multiplied by the correction factor found in the body of this graph.

temperature (density) is generally conservative, a moderate delay in launch can be tolerated without requiring further buoyancy adjustments to the balloon. When the temperature at flight level is changing rapidly, however, balloon altitude accuracy may be increased by estimating the flight-level temperature expected at launch time.

Under convective conditions, there is an advantage in flying the balloon with less than 40 mb flight-level superpressure (specified in Fig. 3) where possible, because it can then be carried higher in the atmosphere without causing the Mylar plastic to stretch permanently. To do so, subtract the same number of millibars from the surface superpressure as are subtracted from the 40 mb flight-level superpressure, but not more than the surface superpressure indicated in Fig. 3. For example, for flight at 100 m with a temperature difference of 1°C (adiabatic lapse), Fig. 3 calls for a 34 mb surface superpressure for a 40 mb flight-level superpressure. The balloon could be flown with a 20 mb flight-level superpressure by deducting 20 mb from the 34 mb surface superpressure indicated by Fig. 3.

It is to be emphasized that all the diagrams (except Figs. 2 and 7) were carefully designed for accurate positioning of constant-volume ballons at specified heights above the launch level and are to be considered as operational devices. Balloon height deviations result chiefly from errors in flight-level and inflation-shelter temperatures.

3. Determination of vertical air velocity

The air trajectory meteorologist is often interested in vertical air motions along the constant-volume balloon track, and makes estimates of them by noting the balloon's vertical movements under the assumption of a fairly good correlation between air and balloon speeds. However, because of the buoyancy force acting to return the balloon (tetroon) to its equilibrium float surface, the balloon's vertical velocity is not usually that of the air in which it is embedded, i.e., the balloon "slips" relative to the ambient air. The direct estimation of vertical air motion, given the 150 cm tetroon's vertical motion and displacement from its equilibrium float surface, is provided in Fig. 5. As an example, a downdraft of 40 cm s^{-1} is indicated in Fig. 5 at the location of a 150 cm tetroon that is observed to be 300 m below its equilibrium surface and ascending at 20 cm s^{-1}. In addition, the tetroon slip-speed magnitude can be determined from Fig. 5 for displacements from equilibrium up to 600 m by reading the slanted speed isopleths at the intersection of the tetroon displacement and tetroon zero vertical speed coordinates.

Vertical air velocities can be determined from any

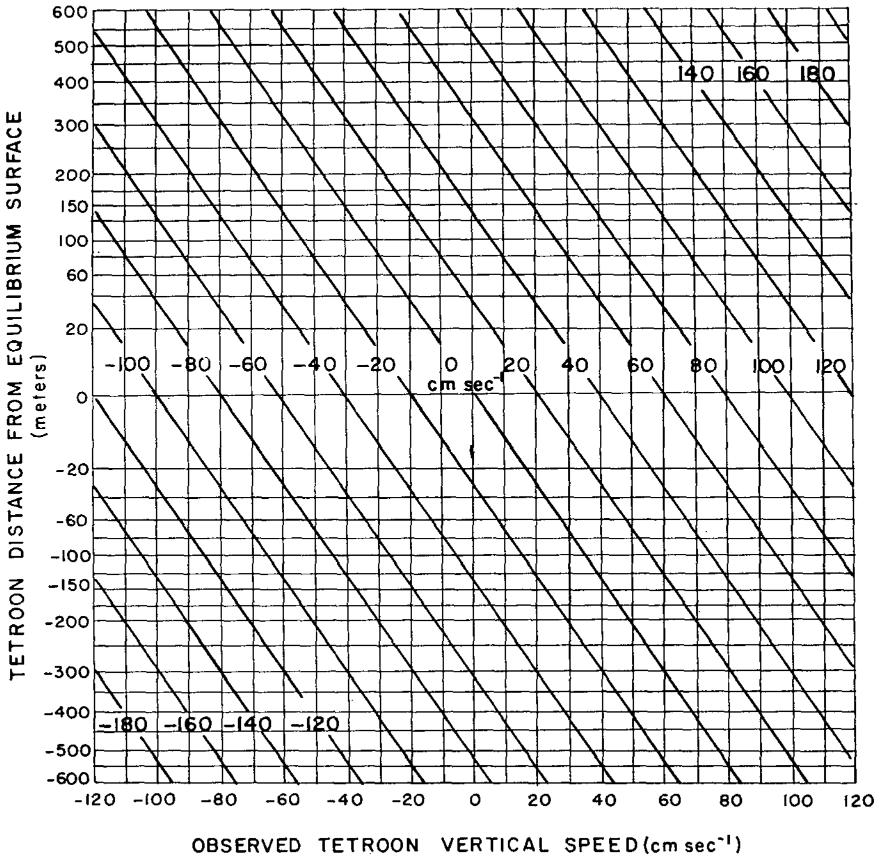

FIG. 5. Graph for estimating vertical air speed (slanting lines) from 150 cm tetroon vertical speed and the distance of the tetroon from its equilibrium float surface.

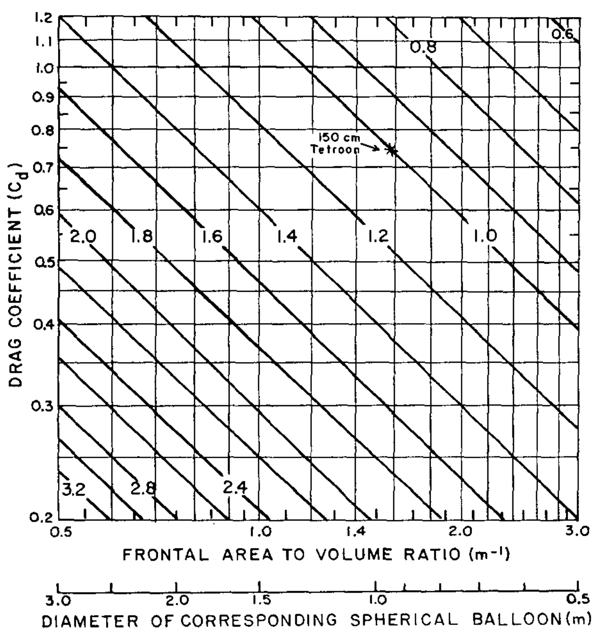

FIG. 6. Graph for converting the slip speed of the 150 cm tetroon to that for any constant-volume balloon. The coordinates are frontal area to volume ratio and drag coefficient. The slip speed determined from Fig. 5 is to be multiplied by the factor found in the body of this graph. The size range of spherical balloons corresponding to the range of frontal area to volume ratios presented is shown at the bottom for comparison. The 150 cm tetroon has a conversion factor of 1.0.

constant-volume balloon by the use of a slip-speed correction factor from Fig. 6 whose arguments are the balloon's frontal area[1] to volume ratio and the drag coefficient. The 150 cm tetroon has a frontal area to volume ratio of 1.59 m^{-1} and a drag coefficient of 0.74 (Hoecker, 1973) giving it a factor of 1.0 in Fig. 6. For a balloon with a different frontal area to volume ratio and drag coefficient, for example 1.7 m^{-1} and 0.50, respectively, and for the same conditions noted above, obtain the computed vertical air speed from Fig. 5 and use the relation: slip speed = air speed (Fig. 5) − balloon speed (observed), or slip speed $= -40-20 = -60$ cm s^{-1}. Fig. 6 is then entered with the available balloon's frontal area to volume ratio (1.7 m^{-1}) and drag coefficient (0.50) to find the slip-speed correction factor ($\sim$1.2). The following relation is then applied: corrected air speed = slip speed × correction factor + balloon speed, or, corrected air speed $= -60\times1.2+20 = -52$ cm s^{-1}. Note that Fig. 6 indicates smaller slip speeds for smaller balloons, hence smaller ballons give slightly better response to vertical air motions provided the drag coefficient is invarient.

Although computed for the standard atmosphere, Fig. 5 gives less than 4 cm s^{-1} air speed deviation for either adiabatic or isothermal lapse rates for a balloon displaced 600 m from its equilibrium float surface.

[1] The area projected from the balloon along its vertical motion axis onto a plane perpendicular to that axis.

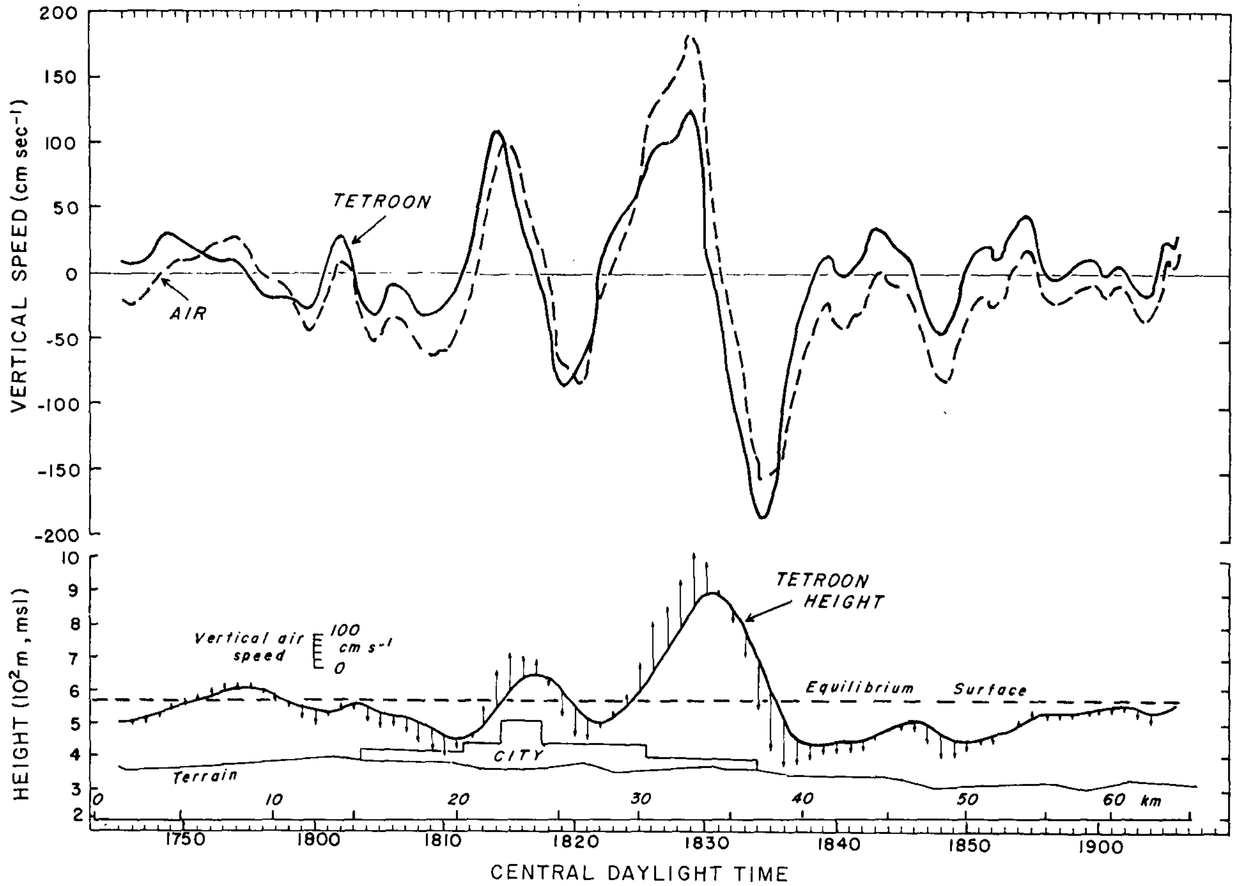

FIG. 7. Tetroon-derived vertical air speeds (vertical arrows) along a tetroon trajectory as it crosses an isolated urban area (Oklahoma City) on 28 September 1971. The traces at top show the comparison between tetroon vertical speed (solid line) and the vertical air speed derived from Fig. 5 (dashed line).

Obviously, the lapse rate is of little consequence in deriving vertical air speeds from balloons. Fig. 5 was constructed from the drag formula $V=(2D/\rho A C_d)^{\frac{1}{2}}$, where D is the static drag force, ρ the air density, A the tetroon frontal area (14 900 cm^2), and C_d the form drag coefficient (0.74), with the numbers in parenthesis applying to the 150 cm tetroon. It was assumed that external accelerations on the tetroon were of a low order and the buoyancy force balanced the static drag force.

To obtain vertical air speeds from the constant-volume balloon or tetroon, an equilibrium float surface must be established for each flight. The average tetroon height (after reaching apparent equilibrium) has generally been used but should the observed average flight level be higher than the real equilibrium surface, as may occur on strongly convective days, the downward air motions derived from Fig. 5 will be too large. The most uncertain feature in estimating vertical air motion from vertical balloon motion involves determination of the equilibrium float surface. This is particularly true in variegated or hilly terrain where the equilibrium surface may vary in height.

Other reasons for uncertainty of equilibrium surface height would be cooling and warming of the entire low-level layer of air with resulting raising and lowering, respectively, of constant-density surfaces. Mostly occurring at sunrise, sunset, or in air flowing from land to sea, etc., these changes will affect balloon height. Countering these effects would be cooling and warming of the balloon resulting in increasing and decreasing balloon density in phase with ambient atmospheric density trends. The magnitude of the above noted balloon corrective-density changes is not known, however. The experimenter should not always blame the inflation system for every marked displacement of a constant-volume balloon from its assigned altitude, but look for the causes as discussed above.

An example of vertical air speeds derived from observed tetroon vertical speeds is shown in Fig. 7, along with the tetroon's time-height track as it floated across Oklahoma City (Angell *et al.*, 1973) and the flat, surrounding terrain. Derived vertical air speeds are depicted to scale as vertical arrows along the height trace and as the dashed curve at the top of the figure. For comparison, the tetroon's vertical speed (solid line) is also shown at the top of Fig. 7. Note the strong vertical oscillations induced in the air flow by the city in contrast to the minor "waves" over the nearly flat terrain. Interestingly enough, the largest wave amplitude was downwind of the city center. Attention is called to the significant downward air motion with a slowly rising tetroon between 1838 and 1842 CDT and, conversely, the upward-moving tetroon indicating zero vertical air movement near 1844 and 1853.

It is important to note from Fig. 7 that while the difference between vertical tetroon speed and air speed determined from Fig. 5 is fairly large in isolated instances, in general the tetroon itself gives a reasonably good overall picture of the variation in vertical velocity along the trajectory (compare the upper solid and dashed traces in Fig. 7). Consequently, unless one is interested in precise estimates of vertical air speed at specific points in space, it is permissible to use the vertical tetroon speeds as first-order estimates of vertical air speeds, particularly in view of uncertainties in determining the real equilibrium float surface. It has been found that the tetroon does a better job in delineating the vertical air motion (higher tetroon to air speed ratio) when the amplitude of the vertical oscillation is large and the period of oscillation is small.

APPENDIX

Derivation of Balloon Surface Superpressure and Free Lift Relationship

To fly the constant-volume balloon, or tetroon, at a selected altitude and flight-level superpressure, the appropriate surface superpressure (ΔP_s), surface free lift (L_s), and surface volume (V_s) of the tetroon must be computed. The tetroon inflation computations are based on Charles' and Boyle's gas laws, and were developed for the tetroon by Delver and Booth (1965). Eq. (A1) is the general gas law:

$$P_1V_1/T_1=P_2V_2/T_2, \qquad \text{(A1)}$$

where P is pressure, V volume and T Kelvin temperature. The pressure inside the tetroon is atmospheric pressure (P) plus superpressure (ΔP), so (A1) can be written

$$(P_s+\Delta P_s)V_s/T_s=(P_f+\Delta P_f)V_f/T_f, \qquad \text{(A2)}$$

where subscripts 1 and 2 in (A1) are replaced by s (surface) and f (flight-level) respectively. After rearrangement Eq. (A2) becomes

$$(P_s+\Delta P_s)V_s=(P_f+\Delta P_f)V_fT_s/T_f. \qquad \text{(A3)}$$

All of the factors on the right side of (A3) can be measured, specified or estimated, and P_s on the left side is known (measured). Needed are ΔP_s and V_s, but V_s is uniquely related to ΔP_s by the experimentally determined pressure-volume curve (Fig. 1) for the size of balloon (or tetroon) being used, so there is basically only one unknown.

Therefore, from a table of ΔP vs V for the particular balloon being used, values for these parameters are tried in the product, $(P_s+\Delta P_s)V_s$, until it equals the right side of (A3). When (A3) is balanced, one has the correct surface superpressure (ΔP_s) for launch and the correct V_s for computing surface free lift (L_s). Surface free lift is found by subtracting the lift equation for conditions at flight level (zero net lift), $L_f=0=\rho_fV_f$ $-$system mass, from the lift equation at launch level, $L_s=\rho_sV_s-$system mass, giving $L_s=\rho_sV_s-\rho_fV_f$. Here, ρ is the air density, and system mass includes the mass of the envelope, helium, ballast, target, etc. If, as may happen, the product $(P_s+\Delta P_s)V_s$ is greater than the right side of (A3), even when using $\Delta P_s=1$ mb, a greater flight-level superpressure and larger V_f are required. These new estimates are used to reevaluate the right side of (A3), and then, trial values of ΔP_s, and V_s must again be used in $(P_s+\Delta P_s)V_s$ as outlined above.

Graphs similar to Fig. 3 can be constructed for a given type of balloon by computing several points for one flight altitude and for different temperature lapse conditions. The simplified inflation procedure that requires only one argument, the temperature difference between flight level and inflation shelter, for determining the balloon's surface free lift and surface superpressure, results from the high correlation between pressures in the surface layers of the atmosphere, the nearly constant pressure decrease with height, the use of a constant height difference between flight and launch levels, and the quality control in manufacture that gives uniform pressure-volume characteristics among a set of Mylar balloons.

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