Behavior of Smoke Trails, 30 to 70 km

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ABSTRACT

This preliminary study is concerned with proving the smoke trail as a usable tool in measuring total atmospheric motion, and developing a technique for the three-dimensional analysis of smoke trail data in the 30–65 km altitude region. The field experiment and data reduction techniques are explained. The trail is shown to be a reliable tracer of atmospheric motion and the analysis of only one trail indicates the rather startling fact that vertical motions are present at all altitudes sampled. Extreme vertical motions $> 5 \text{ m sec}^{-1}$ are present even in the thermally stable atmosphere below the stratopause.

1. Introduction

For well over a decade photography of artificial clouds or trails, reported in too many papers to reference herein, has been a major tool in atmospheric studies above 60 km altitude. Why then should this same tool not be good at a somewhat lower altitude for short periods of time with a greater accuracy and finer definition?

This was the premise of the Design Climatology Branch of the Air Force Cambridge Research Laboratories (AFCRL), when asked by the Air Force's aerospace vehicle designers to provide estimates of heretofore unmeasurable parameters of turbulence and organized wave structure in the 30–60 km (100–200 thousand feet) altitude region. The question was directed at atmospheric motions, be they eddies or undulations, that would appear as turbulence to advanced aerospace systems, such as hypersonic lifting reentry aircraft, flying at 10,000–20,000 ft sec⁻¹. Non-uniform atmospheric motion over horizontal distances up to 25 km are considered important.

2. Operational experiments

The field part of the ensuing experiment consisted of eight rockets, launched in pairs from the Eglin Gulf Test Range. The two rockets within each pair were launched simultaneously at a quadrant elevation (QE) of 84° in evening twilight from sites at A-11 and D-3 approximately 150 km apart. The field layout is shown in Fig. 1. Each rocket laid two 40-km long trails, one from 30–70 km on ascent and another upon descent through that layer. Thus, four spatially separated and nearly simultaneous trails were visible. Each trail was photographed from three of the four camera locations, sites # 1 through

4 on Fig. 1, for purposes of triangulation in fixing trail position. K-46 cameras using 5-inch Plus-x film were operated on a 15-sec cycle in which 0.7-, 1.5- and 5.0-sec exposures were taken. Only one of the exposures was picked for use in data reduction. Each camera was fixed and its look angle determined by photographing stars.

Trimethyl aluminum (TMA) was used to produce the smoke trails. Each rocket payload consisted of two canisters of TMA, one for each trail, mounted on a NIKE IROQUOIS rocket, the launch vehicle used in this experiment. Since the trail is not chemiluminescent at these altitudes, a photography window of approximately 15 min is available at twilight where the trail is sunlit against a dark sky background. Table 1 gives the dates of rocket launches and separation of trails at 45 km altitude.

TABLE 1. Horizontal separation (km) of trails at 45-km altitude and a quadrant elevation QE of 84°.

Trail	Date	A	Trail B	C
B	29 Nov 1967	85	—	—
	3 Dec 1967	73	—	—
	16 Dec 1967	50	—	—
	9 Dec 1968*	49	—	—
C	29 Nov 1967	85	17	—
	3 Dec 1967	96	35	—
	16 Dec 1967	100	58	—
	9 Dec 1968*	86	39	—
D	29 Nov 1967	133	74	58
	3 Dec 1967	137	92	60
	16 Dec 1967	143	109	57
	9 Dec 1968*	148	107	72

Trail Code

A Up trail from A-11 launch
 B Down trail from A-11 launch
 C Down trail from D-3 launch
 D Up trail from D-3 launch

¹ Some of this material was presented by the author at the Conf. on Composition and Dynamics of the Upper Atmosphere, Amer. Meteor. Soc., 7 November 1968.

* New launch facility at site A-15 replaced A-11 in the 9 December 1968 shot. A-15 is 9 km west of A-11 on Santa Rosa Island.

FIG. 1. Field layout of smoke trail experiment depicting launch facilities, camera sites, and planned trail positions.

3. Validity of trail motion

There has been skepticism as to the motions of rocket-released smoke trails in portraying true atmospheric phenomena at these high altitudes due to motion induced by rocket wake, method of release, energy of chemical reaction, etc. Several studies are available (Lettau;² Beaudoin *et al.*, 1967) that refute arguments that motions are self-induced; however, skepticism still exists.

Further refutation is provided by Fig. 2, photographs taken at approximately 1, 2 and 4 min after release of two simultaneous trails as seen by the same camera. These motions could not have been self-induced. The trails are approximately 17 km apart. (Photographs have been retouched for reproducibility.) Note that even the small details in the features on each trail are reproduced in near symmetry throughout this 4-min time interval. The features must be due to atmospheric motions as mechanical or chemical mechanisms could not produce this symmetry in features. Lester and Tolofson (1964) also indicated almost exact similarity between three simultaneous smoke trails below 15 km altitude with maximum initial separation of about $1\frac{1}{2}$ mi (approximately $\frac{1}{10}$ that in Fig. 2). Their suggestion, that spatial wind variations within the troposphere may be quite small, can be extended into the stratosphere and mesosphere. Fig. 2 indicates that organized, relatively small structures exist at least over these 4 min of time and 17 km of space.

² Lettau, B., 1965; unpublished AFCRL study.

4. Computation of coordinate points from smoke trails

Obtaining x , y , z coordinate points from smoke trail photographs is a long and tedious process. Only a brief, simplified version of the procedure will be presented here.

For each selected time frame the image of the trail on the film from each of the three cameras looking at one trail is read sequentially from bottom to top (the trail being reproduced by a series of points) by an Oscar E. film reader. Each point of the trail read from a given camera defines an azimuth and elevation of that point on the trail from the particular camera site (the direction cosine of a ray from the camera site to the particular point on the trail). Since it is impossible to select a point on the trail which is optically identifiable in each of the films from each of the cameras, it becomes necessary to use a computer program which will, in essence, allow the computer to arbitrarily match rays to points on the trail from each of the three cameras.

The grouping of all the data from the three cameras simultaneously to determine the common rays is not feasible even by computer simply because of the magnitude of the computations. Hence, a search for possible pairings (matching) of rays from two cameras is made, first choosing one as a pivot or lead camera. The acceptable pairings between a lead station and a second station are found by seeking out the rays or lines-of-sight of the second station which lie in a plane defined by the line joining the stations and a line defined by a particular line-of-sight from the lead station. Fig. 3 shows such a particular sight line from the lead station designated L

FIG. 2. Simultaneous trails B and C photographed 29 November 1967 from camera site #1. Trails are separated by approximately 17 km and centered near 50 km altitude.

to point P, defining the plane PLS. A series of rays λ_x from a second station designated S to points X along the trail are examined until the planes XSL and PLS coincide. When two planes coincide, the pair of rays, one from the lead station and one from the second station, are considered possible correct rays to point P. The search of all rays from the second station is continued until all possible pairings with the lead station ray to point P is found.

The lead camera is then paired with the third camera in the same manner. The acceptable ray pairings obtained from each of the camera pairings with the lead define a set of ray candidates for the solution of point P. The second camera is now used as a lead using only the accepted set of rays obtained from the previous pairings. Each ray of the new lead is then paired with the rays from the third camera. This final pairing reduces the candidates to a minimum set of three rays, the lead

ray and one ray from each of the other two cameras, all directed at point P on the trail. This minimum set is then used in a conventional multi-station theodolite solution procedure that minimizes the errors of closure and obtains an optimum *position point* defining point P of the smoke trail in X, Y, Z space. No solution point is computed based upon two cameras only, as it is the final pairing with the third which eliminates the extraneous solutions.

Continuing the above procedure for position point solution for all the read points (rays) of the lead station yields a continuous series of trail position points which when connected by a line depicts the smoke trail in X, Y, Z space. Choosing one of the other two camera locations as the initial lead station and re-doing the whole coordinate point solution procedure yields a different set of solution points. The line connecting these points is coincident with that from the previous solution.

FIG. 3. Depiction of lines of sight from lead camera station L to point P on the smoke trail, and a second camera station S to points X along the trail.

5. Data accuracy

Some trouble acquiring exact camera orientation for the shots in 1967 was encountered due to problems with the time code on the film with the star image and with fuzziness in star images. When one or more cameras are not oriented exactly, the accepted error tolerances for ray pairings must be relaxed to insure that a solution is found for every point on the trail. With the relaxed tolerance there is more scatter in the trail position (error in solved position points) and careful editing of data is required to insure that false solutions don't occur.

The data to be presented are good but not as good as desired. To help insure accuracy the trail was reduced by using each of the three camera locations in turn as the lead station. The resulting three sets of position data were pooled and component plots X, Z and Y, Z made. For this preliminary analysis a smoothed line was fit by hand to the plotted data and all further analyses made from these smoothed component plots. The resulting trail was continuous through all time frames and, with a few exceptions, several coordinate point solutions per 100 m altitude define the trail position. The reproducibility of the trail with time is good but

FIG. 4. Trail B photographed 16 December 1967 from Fort Rucker Recreation area, camera site # 1, and Tyndall AFB, camera site # 4. The camera is looking south from Fort Rucker and west from Tyndall. Time is seconds after trail release.

FIG. 5. Winds for 16 December 1967. Central minute and 3-min winds are for 500 m layers derived from smoke trails.

the scatter about the smoothed trail is greater than optimum. The radius of error found from the theodolite solution procedure, in point solutions, varies from 1 m to ~ 250 m with a mean of 75 m. This is about twice that believed attainable with this set-up.

6. Preliminary data analysis

Position data for trail B (16 Dec. 1967) were reduced for the 1st, 2nd, 3rd and 4th minute time frames after trail release. Preliminary analysis consists of 1) computation of horizontal winds, 2) a three-dimensional study of the motion of selected reproducible features, and 3) shears through a major trail distortion.

Fig. 4 shows this trail for two different time frames as viewed from the north (camera site 1) and from the east (camera site 4). Note that the trail remains continuous even though horizontal displacements > 10 km occur in the upper part of the trail at 325 sec after release.

a. Horizontal winds

For each time frame, mean trail positions for 500 m thicknesses were computed and assigned the altitude of the mid-point. Using overlapping 500 m thicknesses, mean trail positions were obtained centered at each 250 m in altitude. From these, horizontal winds were computed.

For comparison, Fig. 5 shows these winds for the 3-min and central 1-min time intervals. Included are winds from a ROBIN, a falling 1 m Mylar sphere tracked by precision radar. ROBIN winds are computed by smoothing over a fixed time interval. Since the fall rate decreases, this corresponds to smoothing through a 3.3-km layer at 70 km and at 30 km altitude (Newell *et al.*, 1966). The ROBIN sounding was made approximately 5 min later in time and 100 km further east. The shear at 64.5 km in the trail winds is caused by the

abrupt jump in position data from the main trail to the upper sheared-off trail. (Trail configurations are explained in Section 5b.) No attempt was made to smooth through this large vertical distortion.

As expected, the 1-min winds show more detail than the 3-min winds. How much of this is real and how much is noise in the data has not yet been determined. The ROBIN winds are in good agreement with those of the smoke trail. The match is better in the zonal than the meridional components. The greatest differences occur in the upper part of the meridional component; however, these differences are not surprising due to the 100-km separation of the ROBIN and smoke trail.

A structure function analysis of this horizontal wind data for altitudes < 64 km gave dominate vertical wavelengths of approximately 7 and $3-3\frac{1}{2}$ km in both the zonal and meridional components. These are quite close to the 8.5- and 3.2-km values found over White Sands, from a series of ROBIN soundings (Boer and Mahoney, 1968).

b. Selected position data

Selected reproducible position data for two height intervals, the 60–70 km and the 45–50 km altitude regions, were analyzed for the four time periods. For simplicity only the 2nd and 4th minute trail positions are shown in Fig. 6. These labeled points are reproducible through the entire time period. When projected back to release time they produce the necessary straight line trail. Total velocities of each point due to the general air flow, turbulence, or undulations, whatever the case, were computed. These are the motions of the reproducible trail feature, not necessarily the direction of the TMA particle movement.

Table 2 gives the vertical component (m sec^{-1}) of wind velocities for each 1 min and, also, the 3-min time

FIG. 6. Selected reproducible position data for the 2nd and 4th minute trail position from trail B, 16 December 1967.

intervals, computed from the selected points. Table 3 gives the 3-min total velocities.

An initial look at the zonal component of trail movement as shown in Fig. 6 indicates the startling fact that the upper trail, points A-H, is shearing off at a rather rapid rate and descending, while the adjacent trail at Point I is progressing upward at a slower rate. In the meridional component the upper part is moving south and the lower trail north. Note also that the altitude of the start of the meridional and zonal shear is not the

same, i.e., point H is within the sheared-off upper trail zonally but remains in the northerly flow meridionally. From Table 2 it can be seen that the motion of the upper descending trail is not uniform, i.e., point B is progressing downward at a lesser rate than A, and point C moved up, down, and then up during the 3 min. The

TABLE 2. Vertical motion ($m \text{ sec}^{-1}$) from smoke trail B3.

Point	1-min intervals			3-min interval
	1st	2nd	3rd	
A	-10.8	-11.7	-10.8	-11.1
B	-4.2	-6.7	-5.0	-5.3
C	+2.5	-7.5	+0.8	-1.4
D	-4.2	-5.8	-2.5	-4.2
E	-3.3	-7.5	-0.0	-3.6
F	-7.5	-4.2	-0.8	-4.2
G	-7.5	-2.5	-1.7	-3.9
H	-12.5	-11.7	-15.8	-13.3
I	+2.5	+3.3	+5.0	+3.6
J	+2.5	-8.3	+16.7	+3.6
K	+4.2	-10.0	-2.5	-2.8
L	-1.7	-1.7	-4.2	-2.5
M	+3.3	-4.2	+4.2	+1.1
N	+3.3	-8.3	+5.0	-0.0
O	-0.0	-1.7	-4.2	-1.9
P	-5.0	-3.3	-0.0	-2.8
Q	-13.3	-12.5	-16.7	-14.2
R	-9.2	-10.8	-10.0	-10.0
S	-1.7	-0.8	+0.8	-0.6
T	-1.7	+0.8	+1.7	+0.3

TABLE 3. Total wind velocity vectors from smoke trail B3.

Point	Initial location (m)			Wind vectors		
	Altitude	West	South	Azimuth* (deg)	Elevation* (deg)	Magnitude (m sec ⁻¹)
A	67450	57650	34800	272	-10	62.1
B	67250	57650	34750	278	-5	56.6
C	66250	57800	35150	279	-1	58.5
D	65450	58050	35200	278	-4	58.2
E	65550	58400	35400	277	-4	55.6
F	65000	58400	35300	281	-5	45.3
G	64200	58550	35700	285	-4	50.5
H	63150	57350	34700	253	-17	44.6
I	64350	60300	35350	252	6	31.2
J	62100	60050	34250	241	6	31.9
K	62100	60250	34600	239	-6	26.8
L	55450	60700	36500	210	-7	19.5
M	56250	60500	35250	214	2	25.5
N	56200	60250	34750	217	0	27.8
O	51600	60000	35600	228	-5	22.9
P	52500	59750	35200	214	-5	30.1
Q	50050	59000	35450	245	-16	52.8
R	50300	59250	35550	245	-12	46.7
S	49450	58750	36600	250	-1	37.8
T	48450	58800	36250	245	0	42.9

* Azimuth and elevation are degrees from north and the horizontal, respectively.

TABLE 4. 500-m vertical and horizontal shear vectors through major distortion of smoke trail B3.

Height (m)	Vertical (deg) (sec ⁻¹) Southeast limb		Horizontal (deg) (sec ⁻¹)		Vertical (deg) (sec ⁻¹) Central limb		Horizontal (deg) (sec ⁻¹)		Vertical (deg) (sec ⁻¹) Northeast limb	
1st minute										
64250	9	0.0173	28	0.0103	*	*	*	*	*	*
64000	11	0.0185	34	0.0199	10	0.0285	11	0.0042	-12	0.0350
63750	6	0.0098	29	0.0204	18	0.0167	22	0.0065	-1	0.0016
63500	2	0.0037	22	0.0196	31	0.0571	30	0.0071	-2	0.0071
63250	*	*	*	*	*	*	55	0.0135	1	0.0052
2nd minute										
64500	-3	0.0082	17	0.0089	*	*	*	*	*	*
64250	3	0.0089	19	0.0113	-8	0.0191	2	0.0056	-5	0.0068
64000	8	0.0231	29	0.0125	-8	0.0107	-3	0.0071	-2	0.0059
63750	-4	0.0167	35	0.0133	-5	0.0060	-4	0.0058	-3	0.0053
63500	-13	0.0590	30	0.0134	-5	0.0059	-5	0.0062	-1	0.0025
63250	-4	0.0489	27	0.0098	-7	0.0084	-8	0.0056	-3	0.0050
63000	-1	0.0023	33	0.0132	-5	0.0068	-9	0.0051	-3	0.0050
62750	-5	0.0131	31	0.0176	28	0.0480	-10	0.0045	-4	0.0060
62500	*	*	*	*	*	*	23	0.0047	-7	0.0106
3rd minute										
64750	7	0.0167	15	0.0027	*	*	*	*	*	*
64500	5	0.0173	24	0.0034	-4	0.0071	24	0.0203	-31	0.0425
64250	-6	0.0112	24	0.0032	-10	0.0153	26	0.0144	-6	0.0060
64000	-3	0.0048	28	0.0037	-14	0.0203	20	0.0098	1	0.0016
63750	16	0.0379	35	0.0046	-10	0.0149	11	0.0045	3	0.0024
63500	-2	0.0034	55	0.0055	-6	0.0086	7	0.0029	1	0.0016
63250	-19	0.0350	39	0.0079	-2	0.0068	4	0.0013	3	0.0032
63000	-1	0.0122	38	0.0080	-1	0.0053	2	0.0008	1	0.0047
62750	2	0.0068	39	0.0092	-3	0.0050	2	0.0006	3	0.0059
62500		0.0016	43	0.0116	-5	0.0047	-4	0.0001	5	0.0082
62250	—	0.0034	44	0.0142	2	0.0034	-8	0.0013	4	0.0101
62000	3	0.0164	40	0.0178	47	0.0683	-6	0.0008	3	0.0068
61750	*	*	*	*	*	*	36	0.0051	3	0.0066

* No trail for shear evaluation.

vertical motion regime in the sheared-off upper trail differs markedly from that in the adjacent lower trail.

The trail distortion in the 45–50 km region, shown in Fig. 6, is more pronounced in the meridional plane. Points R and Q move north and descend in altitude. Above 63 km the descending motions are moving to the south. The zonal motion in the 45–50 km level, although much less in magnitude, is in the same direction as levels > 60 km. The trail below this distortion, depicted by points S and T, shows nearly horizontal movement.

Vertical motions of identifiable features L–P, lying in the altitude zone between the two distortions shown in Fig. 6, are also shown for comparative purposes in Table 2. These vertical motions as well as those of features J and K oscillate in sign with a wavelike behavior but with varying amplitudes and periods.

It should be noted from Table 3 that the direction of the 3-min motion from the horizontal ranges from +6° to -17°, further evidence of the magnitude and variability of the vertical motions. It is virtually impossible to make direct altitude comparisons of vertical motion and shear magnitudes due to the complexity and spatial extent of the trail. However, the altitude regions of strong vertical motions measured in the distortion in Fig. 6 can be compared with wind profiles in Fig. 5.

From this comparison it can readily be seen that the vertical motions above 61 km are in a region of relatively strong shear. This tendency is also present but is not as obvious for the vertical motion region < 50 km.

While the driving force is not known, the affinity of large vertical motions to wind shear together with the oscillatory nature of some of the motions, are indications that prime consideration must be given to gravity waves. However, there is no assurance that the driving force for the vertical motions in the two altitude levels studied is the same.

c. Shears through a major distortion

Horizontal wind velocities were computed by comparing 500 m mean position data for each 250 m altitude for regions of the major distortion shown in Fig. 6. For example, 500 m position data for section G–H is compared with “like data” for each time period for those portions where altitudes match; similarly, in the H–I and I–J regions.

From these horizontal vector winds, vertical and horizontal vector shears were computed for the comparable regions. Table 4 gives the vector shears for each of the 1-min time intervals; vertical shears as great as 0.068 sec⁻¹ and horizontal shears of 0.02 sec⁻¹ occur.

7. Summary and conclusions

Even though this paper is a preliminary analysis of only one smoke trail and definite conclusions are not possible, some interesting conjectures can be made.

1) Vertical motions are present at all altitudes. The magnitude varies but large values occur both above and below the stratopause. Descending motions are more prevalent and are greater in magnitude than ascending motions. Extreme motions are certainly larger than 5 m sec^{-1} and probably exceed 15 m sec^{-1} .

2) Regions of greatest vertical motion seem to occur in regions of high wind shears.

3) There are adjacent altitude layers in which overall direction and magnitude of the vertical motions are different.

4) Although no temperature soundings are available it must be assumed that vertical motions below the stratopause, roughly 50 km, are within a thermally stable atmosphere.

5) The exact reproduction of even the small-scale features seen on the two side-by-side trails implies that these vertical motions are not extremely localized. Duration and spatial extent of these vertical motions is as yet unmeasured. However, it also seems unlikely that motions directed as much as 17° to the horizontal would persist for any great distance or length of time.

6) While the driving force for these vertical motions is undetermined, gravity waves are the most probable cause. Also, the possibility that these motions could be related to the time of sampling, evening twilight, has not been eliminated.

A complete analysis of the data from the entire experiment is now being undertaken with the aid of the Department of Meteorology of the Massachusetts Institute of Technology. Hopefully, enough information will be obtained to answer the many questions raised by this preliminary analysis.

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