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MEASUREMENTS OF WINDS BY CHEMICAL RELEASES IN THE UPPER ATMOSPHERE

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ABSTRACT

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Upper atmospheric winds are of importance to the designers of space vehicles as well as to geophysicists. For this reason a number of organizations have begun to study winds above 80 kilometers by releasing into the upper atmosphere chemicals which luminesce either by the action of sunlight or by a reaction with naturally occurring molecules. Seventy-seven of these releases were studied in an effort to determine a statistical model for wind velocities between 80 and 200 kilometers at mid-latitude sites.

author

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AERO-ASTRODYNAMICS LABORATORY
RESEARCH AND DEVELOPMENT OPERATIONS

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SUMMARY

Upper atmospheric winds are of importance to the designers of space vehicles as well as to geophysicists. For this reason a number of organizations have begun to study winds above 80 kilometers by releasing into the upper atmosphere chemicals which luminesce either by the action of sunlight or by a reaction with naturally occurring molecules. Seventy-seven of these releases were studied in an effort to determine a statistical model for wind velocities between 80 and 200 kilometers at mid-latitude sites.

I. INTRODUCTION

Atmospheric winds are an important input to spâce vehicle design and performance studies. The responses of a vehicle to winds include deviation of the vehicle from its intended flight path, structural loads on the vehicle when subjected to wind shears, loads from control system responses to winds, and vibratory loads arising from excitation of resonances in structural modes, fuel sloshing in the tanks, and control systems with insufficient damping. Scoggins and Vaughan [1] have explained the necessity and problems of obtaining wind inputs for space vehicle design.

Meteorological data have provided statistical mean wind inputs for altitudes below 80 km [2]. Only recently, however, have enough wind data been accumulated to begin to form a picture of the wind structure above 80 km. Wind speeds of as much as 255 m/s and wind shears of 140 m/sec/km have been observed. In general, upper atmosphere winds are very random showing little order with altitude, season, time of day, etc. Some of the randomness has been attributed to turbulence of the upper atmosphere. Earlier reports by Roberts [3] and Ragsdale and Wasko [4] surveyed the upper atmosphere wind data then available; this report revises and amplifies these two earlier works.

The author wishes to thank Mr. W. T. Roberts, Space Environment Group, Aero-Astrodynamics Laboratory, MSFC, for his helpful suggestions and discussions of upper atmosphere winds. Gratitude is also expressed to Dr. H. D. Edwards and Mr. C. G. Justus, both of the Space Sciences Branch, Engineering Experiment Station, Georgia Institute of Technology, for their discussions with the author and their communication of unpublished wind profiles and recent results of turbulence investigations.

II. SOURCES OF UPPER ATMOSPHERE WIND DATA

A. TECHNIQUES OF MEASURING UPPER ATMOSPHERE WINDS

Early evidence of the existence of high velocity winds in the upper atmosphere came from observations of the movements of noctilucent clouds and persistent meteor trails. Whipple [5] has presented a summary of these early measurements. Ragsdale and Wasko [4] briefly surveyed the various techniques which have been used to determine upper atmosphere winds. Radio tracking of the ionization trails left in the wake of burning meteors and time sequence photographs of artificially produced chemiluminescent clouds are the techniques by which a large part of the wind data presently available have been produced. The radio-meteor technique provides a relatively inexpensive means of making a synoptic study of winds and can even be used in the daytime. A measure of the wind motion is obtained from observations of radio echoes from the drifting ionization left in the wake of a meteor as it burns up in the atmosphere. Unfortunately, the altitude range available for study is firmly established at 80 to 110 km. The radio-meteor technique also suffers seriously from a lack of spatial resolution. For example, altitude resolution is at best only ± 3 km [6].

The chemiluminescent trail technique overcomes many of the disadvantages of the radio-meteor technique, but at somewhat greater cost. Simultaneous photographs of an artificial cloud are made from two or more sites on the ground. These photographs are used to triangulate the position of the cloud, and a sequence of such photographs provides a picture of the wind motion. Early wind measurements using this technique relied on observations of the motion of identifiable features on the cloud; Justus et al. [7] have developed a means of tracking the position of long thin clouds which do not have recognizable features for triangulation.

The artificial clouds are placed aloft by ejection from small rockets. Winds at morning or evening twilight are indicated by the movement of sodium or cesium clouds which emit resonance radiation when illuminated by sunlight. Recently wind measurements [8] have been made at night using artificial clouds composed of chemicals which react with constituents of the atmosphere to give off light. With the ability to provide wind measurements through the night, the chemiluminescent trail technique begins to approach the spatial and temporal distribution made possible by the radio-meteor technique as a means of making a systematic study of upper atmosphere winds. The chemiluminescent trail method gives an altitude resolution of ±0.1 km; wind measurements are also possible at altitudes from 60 to over 200 km, depending on the chemical composition of the artificial cloud.

Other methods of high altitude wind measurement are of somewhat less value than the chemiluminescent trail or radio-meteor methods. The analysis of the anomalous propagation of sound from exploding grenades is useful only below 90 km. Interpretation of the drifting of ionization irregularities and sporadic E as neutral air winds is subject to some question. The data indicate only the motion of the ionization irregularities -- not necessarily the motion of the ionization itself, much less the motion of the neutral air. The true wind -- the motion of the neutral air -- and the geomagnetic field act to transport ionization with a velocity different from that of the true wind.

B. SOURCES OF WIND DATA USED IN THIS REPORT

Wind profiles from 77 chemiluminescent trail releases made from April 1956 to February 1965 are analyzed in Section III. Table I provides a list of the releases studied and gives pertinent facts about each [10-17]. Of the 77 chemical releases studied, 47 are from Eglin AFB, Florida (30° N), 27 from Wallops Island, Virginia (38° N), 2 from Holloman AFB, New Mexico (33° N), and 1 from Cape Kennedy, Florida (28° N); 10 are winter releases, 20 spring, 9 summer, and 38 fall. Altitudes range from 55 to 255 km, but a statistically significant sample is available only from 80 to 180 km. Throughout this report, altitude is given in kilometers, speed in meters per second, and wind direction is given as the direction of transport, the direction toward which the wind is blowing, in degrees east of north.

It should be realized that the author is analyzing upper atmosphere winds from a small sample and essentially only two mid-latitude locations. The uncertainties accompanying such an analysis should be kept in mind.

III. WINDS AND WIND SHEARS FROM 77 CHEMICAL RELEASES

A. PROBABLE WIND SPEEDS

Figure 1 shows the wind profiles for evening twilight, 1910 CST, of May 21, 1963, at Eglin AFB, Florida (ref. 14). The sodium vapor trail extended over an altitude range from 68 to 140 km. This trail was selected as representative of upper atmosphere wind profiles because it possesses most of the features frequently seen in the profiles used in this analysis. These features are

1. Sudden changes in wind direction and magnitude with altitude, 80 to 120 km,

2. A dominant maximum of wind speed between 100 and 110 km,

3. Evidence of turbulence observed below 100-110 km, smooth trail above 110 km,

4. Slow variations in magnitude and direction with attendant low shears above 130 km, and

5. Occasional appearance of a second speed maximum at about 150 km.

The example shown in Figure 1 exhibits the first four of these features.

The statistics of the wind data from the 77 chemical releases are given in Table II and presented graphically in Figure 2. Mean and maximum observed wind speeds, and 50-, 75-, 95-, 99-, and 99.9-percentile winds are shown at five km altitude intervals. The percentile winds were computed on the basis of a Gaussian (normal) speed distribution. These statistics show the presence of the principal maximum at 105 km and the secondary maximum observed in some releases at 150 km. An identifiable principal maximum is observed in 54 of the 77 releases tabulated in this study; of the remaining 23 releases, 19 had observational difficulties which prevented the identification of a principal maximum. The averages of wind speed and altitude of the principal maximum are 114 ± 26 m/s (standard deviation) and 105.0 ± 4.5 km, respectively.

B. VECTOR WIND VARIATIONS

Roberts [3] has reported on vector wind behavior in an earlier paper that dealt exclusively with winds from 37 of the 77 chemical releases used in this study. His method of analysis was to make wind rose plots at 10 km intervals showing magnitudes and directions of the observed wind vectors at each altitude. These plots were then examined for diurnal and seasonal trends. Roberts was able to draw some conclusions from these plots, but in many cases, it could only be said that the wind exhibited great variability in speed and direction. The same type of analysis, this time at five km intervals, was attempted with wind data from the 77 chemical releases used in this study. Table III presents the results: directional trends and magnitudes according to season. The variability in wind speed and direction and lack of summer and winter data prevented more definitive statements.

C. SEASONAL AND GEOGRAPHICAL VARIATIONS

Seasonal and geographical variations in the magnitude of the wind vector can be seen from the wind data used in this study. Figure 3a compares the mean wind profile from "summer" (April-September) with that from "winter" (October-March); Figure 3b makes the same comparison for winds from Eglin AFB and Wallops Island. Differences in means from summer and winter are valid in the altitude ranges 96-104 km and 112-128 km because in these ranges the summer and winter data each have 40-60 percent population from each location. Similarly, the mean winds shown in Figure 3b for Wallops Island are made up of approximately 50 percent summer data and 50 percent winter data over the entire altitude range 80-140 km; mean winds above 88 km for Eglin consist of about 30-40 percent summer winds, 60-70 percent winter winds. Figure 3a shows that mean summer winds are 5-10 m/s greater than mean winter winds in the range 95-105 km, and 10-20 m/s greater from 110 km to at least 130 km. Mean winds from Eglin AFB are 5-15 m/s greater than those from Wallops Island in the ranges 90-95 km and 113-120 km; mean winds from Wallops Island exceed those from Eglin by 5-15 m/s in the ranges 102-110 and 123-135 km.

D. WIND SHEARS

Individual wind profiles generally exhibit sudden variations in speed and direction with altitude below 120 km. Above this altitude, speed and direction both vary slowly and smoothly with altitude. The region of high wind shears in the upper atmosphere thus extends from 80 to 120 km. Total wind shears of as much as 120 m/s/km over 1 km separation and 131 m/s/km over 1/2 km separation have been found in the chemiluminescent trail data used in this analysis. Greenhow and Neufeld [18] have reported a maximum shear of 140 m/s/km from radio-meteor data, while Blamont and Baguette [19] have observed an extreme shear of 140 m/s/km from four sodium vapor releases over Hammaguir, Algeria. The highest wind shears accompany the principal maximum (when it is observed) at 100-110 km. Above 120 km, shears are almost always less than 10 m/s/km and are usually on the order of 5 m/s/km.

These facts can be seen in Figure 4 where the means of wind shears from 30 chemical releases over Eglin AFB are presented [20]. Figure 4 also shows the frequency of observation of high and low shears in 10 m/s/km intervals. Kochanski, in an analysis [21] of wind data from 25 selected sodium vapor releases (23 of which were used in this study), has found empirically that the dependence of average wind shears on altitude separation, Δz, is logarithmic: for Δz of 1/2, 3, and 5 km, the value of mean wind shear at $\Delta z = 1$ km should be multiplied by 1.20, 0.75, and 0.66, respectively. Within a factor of two, wind shear data of Greenhow and Neufeld [18] and Ragsdale and Wasko [4] show this same dependence. Estimates of maximum wind shear to be encountered ($\Delta z = 1$km) are given in Table IV.

IV. TURBULENCE

A. EVIDENCE FOR THE EXISTENCE OF TURBULENCE

The trails of chemicals released into the upper atmosphere below about 110 km frequently show evidence of turbulence in that the artificial cloud is broken into a string of nearly spherical globules. These observations have been reported by Blamont and de Jager [22], Edwards et al. [13], and Groves [23]. The globules appear some two to three minutes after release, and persist, increasing in size, until they become so diffuse that they can no longer be photographed. A characteristic of this globular structure is that it stops at a certain altitude; there the trail exhibits an abrupt transition to laminar flow characterized by a smooth trail. The altitude of this transition, or turbopause, is observed to lie in the range 100-110 km. Edwards has found the average turbopause from chemical releases over Eglin AFB to be 106 km [24], while Blamont and de Jager [22] have observed a turbopause of 102 km in a single firing at Hammaguir, Algeria.

This behavior of the artificial cloud has been attributed to the existence of turbulence in the upper atmosphere. However, there remains the question of whether the turbulence is ambient or is produced by the vapor ejection mechanism or the rocket's wake [25]. That the globular structure persists for a long time after ejection, that it is observed on both ascending and descending legs of a trajectory, and that the turbopause lies always around 105 km indicate that it is ambient turbulence, a real atmospheric effect.

B. FEATURES OF UPPER ATMOSPHERIC TURBULENCE

Turbulent flow is characterized by each component of the velocity being distributed irregularly, or aperiodically, in time and space, energy being transferred from larger to smaller scales of motion, and the mean separation between neighboring fluid particles tending to increase with time [26]. Energy is supplied by an external source to the largest eddies in the turbulent field; this energy is passed on to smaller and smaller eddies until it is finally dissipated as heat by the effects of viscosity in the smallest eddies. Energy must be continually supplied if the turbulence is to persist.

A primary effect of turbulence is to enhance mixing: in a mean horizontal (turbulent) flow, fluid elements transfer mass, heat, momentum, etc., vertically. Thus, in a stably stratified fluid such as the atmosphere above 90 km, the turbulence must do work against gravity in the process of a vertical transport of mass. This provides another term in the equation which balances the energy supplied with the energy dissipated [25]:

$$E_s = E_g + E. \tag{1}$$

Here E_s is the rate per unit mass at which energy is supplied to the turbulent field, and E_g and E the rates per unit mass at which energy is dissipated by buoyancy and viscous effects, respectively. Turbulence will not persist when E_s is less than the sum of E_g and E. In the atmosphere above 90 km, wind shear provides the only source of energy to maintain turbulence.

Upper atmospheric turbulence can be studied by both the radio-meteor and chemiluminescent trail techniques. When the radio-meteor technique is used, turbulent velocities are usually defined as the differences between instantaneous velocity measurements and the mean velocity measured over one hour [18].

Two definitions of turbulent velocities have been used in connection with chemiluminescent trail data. In one instance, Roper [27] defined the turbulent velocity at any altitude as the difference between the measured wind at that altitude and a polynomial fit to the wind data over the entire measured altitude range. Roper used a polynomial of degree n (integer) where

$$n \approx 1 + \frac{\text{total altitude range covered by data (km)}}{20 \text{ (km)}} . \tag{2}$$

This definition is subjective to a certain extent: one must choose n properly so that the polynomial does not assume any of the features of the turbulent motion. Edwards and Justus [24], having made all the calculations required to produce wind data from artificial cloud photographs, have defined turbulent velocities as deviations of instantaneous velocities from an average over the length of time the trail is observed. Others [11, 22, 28] have investigated turbulence by an examination of the diffusion characteristics of the artificial cloud.

C. OBSERVATIONS

1. Turbulent Velocities. Greenhow and Neufeld [18] have observed turbulent winds of r.m.s. velocity 25 m/s. They found no correlation of turbulent velocity with either mean hourly wind speed or altitude gradient of the hourly mean wind. Justus and Edwards report [20] from chemiluminescent trail data (92-108 km) that the characteristic velocity of the largest eddies in the turbulent field is 23-26 m/s. Roper and Elford [29], using the radio-meteor technique at the University of Adelaide, Australia, report similar results.

2. Size Scales. The globules which usually appear when chemicals are released below 100-110 km are spherical or nearly spherical. Optical observations of globule diameters [22, 24] show that they range in size from 70 m to 2.5 km. However, these dimensions do not necessarily indicate the size scales frequently used in the statistical description of turbulence.

The lower limit of eddy size at any altitude is set by the local kinematic viscosity at that altitude. Using standard turbulence theories (i.e., Ref. 25) Edwards [24], Greenhow and Neufeld [18], and Blamont and de Jager [22] have found the scale of the smallest eddies to be 5-40 m (size increases with altitude), 50 m, and 60 m, respectively.

The degree of correlation between two turbulent velocity components v_i and v_j measured at points $\vec{r}$ and $\vec{r} + \Delta\vec{r}$ separated by a distance $\Delta\vec{r}$ is given by the general double velocity correlation coefficient g_{ij} $(\vec{r}\,; \Delta\vec{r})$:

$$g_{ij}(\vec{r};\vec{\Delta r}) = \frac{\left\langle v_i(\vec{r})\; v_j(\vec{r}+\vec{\Delta r})\right\rangle}{\left[\left\langle v_i^2(\vec{r})\right\rangle\left\langle v_j^2(\vec{r}+\vec{\Delta r})\right\rangle\right]^{1/2}} \qquad i = 1,\ 2,\ 3 \tag{3}$$

where v_1, v_2, v_3 represent the three components of turbulent velocity, and the mean values are taken with respect to time over all velocities separated by a distance $\vec{\Delta r}$ [24, 25]. If the correlation coefficient is independent of location in space (as is frequently the case in the upper atmosphere), the notation involving the vector $\vec{r}$ may be dropped and the correlation coefficient written $g_{ij}(\vec{\Delta r})$. The scale of the largest eddies in a turbulent field is defined as the distance $L_0 = |\vec{\Delta r}_0|$ over which the correlation coefficient falls from its initial value at $\Delta r = 0$ to a value of zero at $\vec{\Delta r}_0$. Equation 3 can be further modified to give a vertical correlation coefficient $g_{ij}(\Delta z)$ which indicates the vertical scale of turbulence or any of several horizontal correlation coefficients, $g_{ij}(\Delta x)$, $g_{ij}(\Delta y)$, or $g_{ij}(\Delta h)$ ($\Delta h^2 = \Delta x^2 + \Delta y^2$), which indicate the horizontal scale of turbulence.

Greenhow and Neufeld [18], in calculating vertical correlation coefficients from radio-meteor data found the vertical scale of the largest eddies to be seven km; recent work by Justus and Edwards [20, 24] shows the same conclusion.

When Greenhow and Neufeld calculated the horizontal correlation coefficient, they found that it decreases from 1.0 to about 0.2, where it remains steady as horizontal separation is increased. From this they estimated that the horizontal scale of the largest eddies is on the order of 150 km. However, Justus and Edwards [20, 24] have found from the horizontal motion spectrum function of the turbulent winds and the horizontal correlation coefficient that the horizontal scale is only 10 km, indicating only slight anisotropy. This disagreement, which must be resolved, is discussed further in Section V.

3. Energy Balance. The terms E_s, E_g, and E in the energy balance Equation 1 can be evaluated by direct calculation from the turbulent wind velocities [24, 25]. In addition, measurements of cloud diffusion can give an estimate of E_s, the rate of energy supply per unit mass. After an initial expansion by molecular diffusion, the globules expand by turbulent diffusion according to

$$r^2 = \frac{4}{3} E_s t^3 \tag{4}$$

for a period of time equal to the time scale of the largest eddies. Measurements of globule growth by Blamont and de Jager [22] show that the rate of energy supply is about 0.007 watts/kg.

However, Justus and Edwards [24, 25] in applying standard turbulence formulas to measurements of turbulent winds find that E_s and E_g both vary slowly with altitude and have respective values of 0.4 and 0.35 watts/kg in the altitude range 90-110 km. They also find that E, the rate of energy dissipation by viscous effects, increases rapidly with altitude [20, 24]. It is this increase which is responsible for the abrupt turbulence cutoff at 100-110 km (Equation 1).

4. <u>Criteria for the Onset of Turbulence</u>. Any theory which seeks to explain upper atmospheric turbulence must satisfactorily predict the turbopause observed at 100-110 km. The oft-quoted Reynolds criterion, that flow will be turbulent when the Reynolds number

$$R_e = \frac{v\ell}{\nu} \tag{5}$$

is greater than 2000, is not presently suitable for application to upper atmospheric turbulence. In equation 5, ν is the kinematic viscosity, v is the flow velocity, and ℓ is the "pipe" diameter. Reynolds did not perform his experiments in a stratified, free atmosphere but in long straight pipes. Thus, when the Reynolds criterion is applied to upper atmosphere turbulence, one must ask for new definitions of flow velocity and "pipe" diameter. In addition, the kinematic viscosity above 90 km and the critical Reynolds number for a free atmosphere are not yet well known. Reasonable estimates of the factors in the Reynolds number (v and ℓ equal to the velocity and size scales of the largest eddies, for example) show that the Reynolds criterion is not satisfied above about 110 km [20, 22].

In the previous section, it was stated that the rapid increase in E with altitude is responsible for the turbulence cutoff. An upper limit to turbulence is that the altitude at which E becomes equal to E_s; above this altitude, turbulence cannot persist. The energy dissipation and supply rates as calculated by Justus and Edwards from turbulent winds satisfactorily predict the observed turbulence cutoff at 105 km. Depending on the method used to calculate E, their predicted values of the turbopause range from 104 to 109 km with an average value of 107 km [20, 24].

V. DISCUSSION

A. OBSERVATIONS OF ANISOTROPY IN TURBULENCE

It is difficult to reconcile the large horizontal scale, anisotropic eddies observed by Greenhow and Neufeld [30, 31] as turbulence. Such eddies have a time scale on the order of 100 min. If a fluid element is displaced from its equilibrium position, its restoring force produces a harmonic motion with a natural frequency ω_g, the Brunt-Väissälä frequency, given by

$$\omega_g^2 = \frac{g}{T}\left(\frac{\partial T}{\partial z} + \frac{g}{C_p}\right), \tag{6}$$

where T is the temperature, g is the acceleration of gravity, z is the altitude, and C_p is the specific heat at constant pressure [24, 25]. If the lifetime of an eddy is greater than $2\pi/\omega_g$, then it is possible to follow a fluid element through a complete gravitational cycle. But such a motion is too ordered to be true turbulence. Standard atmosphere tables allow the calculation of ω_g subject to a possible error of a factor of two. This calculation shows that motions with time scales greater than about 275 seconds at 90-110 km cannot be true turbulence. Time scales of the largest eddies as measured by Justus and Edwards [20] are in the range 300-330 seconds.

It now appears that a combination of tidal winds and internal atmospheric gravity waves may explain the features of upper atmospheric winds [21]. Hines [32] proposed gravity waves as an explanation for certain wind features observed by the optical and radio tracking of meteor trails.

A size scale of 150 km as observed by Greenhow and Neufeld begins to approach the size scale of the mean wind. Rosenberg and Justus [33] find that the mean wind remains correlated over a distance 400-1000 km in the north-south direction, and perhaps 10, 000 km in the east-west direction, which corresponds to a tidal mode. It seems more likely then that the large scale irregularities observed by Greenhow and Neufeld represent gravity wave perturbations on the tidal wind structure.

B. CIRCULATION IN THE UPPER ATMOSPHERE

Radio-meteor winds measured at only two locations, Jodrell Bank, England, and the University of Adelaide, Australia, have shown that some order can be found in the motions of the upper atmosphere. These studies [34-36] have found a prevailing, 24-, 12-, and 8-hour periodic wind component with the magnitude of each component varying with season. But a detailed picture of wind motion in the 80-100 km region above only 2 locations does not allow the formation of a general circulation pattern above 80 km for the entire planet. Wind data from chemiluminescent trails are adding to our knowledge of the upper atmosphere each year, but many more probes of the upper atmosphere will be needed before a reliable picture of its circulation can be formed.

A new technique has shown promise in reducing the cost of obtaining wind measurements from chemiluminescent trails. Instead of using rockets, the chemicals are placed aloft by projectiles shot from large guns. Several firings of a 16-inch smooth bore gun on Barbados have been very successful [37]. This reduction in cost, accompanied by a rapid recycling time for repeated firings, and the development of night-visible clouds, now enable the chemiluminescent trail technique to be used for a synoptic study of winds above 80 km.

Table I

CHEMICAL RELEASES YIELDING WIND DATA

Date	Reference	Time[1]	Season[2]	Site[3]	Altitude Range[4]	Remarks
4-11-56	10	PM	Sp	H	72-109	Data not used
11-26-57	10	AM	F	H	104-202	
8-17-59	10	AM	Su	W	140-220	
9-29-59	13	AM	F	E	108-118	
9-30-59	13	AM	F	E	119-129	
10-3-59	13	AM	F	E	101-115	
10-12-59	13	AM	F	E	98-104	
11-18-59	12	PM	F	W	94-163	
2-27-60	9	PM	W	W	64-104	
4-1-60	9	PM	Sp	W	68-104	
5-24-60	12	PM	Sp	W	84-169	
5-31-60	9	PM	Sp	W	90-103	
8-9-60	13	AM	Su	E	83.5	One altitude only
8-10-60	13	AM	Su	E	107-116	
8-13-60	13	AM	Su	E	74-78	
8-16-60	13	AM	Su	E	99-109	
8-17-60	13	AM	Su	E	111-123	
8-18-60	13	AM	Su	E	105-114	

Table I (Continued)

CHEMICAL RELEASES YIELDING WIND DATA

Date	Reference	Time[1]	Season[2]	Site[3]	Altitude Range[4]	Remarks
12-9-60	12	AM	F	W	90-138	
4-19-61	12	AM	Sp	W	92-154	
4-20-61	12	PM	Sp	W	81-165	
4-21-61	12	AM	Sp	W	82-162	
9-16-61	12	PM	Su	W	78-146	
9-17-61	12	AM	Su	W	96-172	
3-1-62	12	PM	W	W	71-126	
3-2-62	12	AM	W	W	65-127	
3-23-62	12	PM	Sp	W	59-140	
3-27-62	12	PM	Sp	W	80-118	
4-17-62	12	AM	Sp	W	76-191	
6-6-62	12	PM	Sp	W	56-137	
10-15-62	17	AM	F	E	90-117	
10-16-62	17	AM	F	E	91-107	
10-16-62	17	N	F	E	98-115	
10-17-62	17	AM	F	E	87-113	
10-19-62	17	AM	F	E	91-100	
10-22-62	17	AM	F	E	96-107	

Table I (Continued)

CHEMICAL RELEASES YIELDING WIND DATA

Date	Reference	Time[1]	Season[2]	Site[3]	Altitude Range[4]	Remarks
10-23-62	17	AM	F	E	105-114	
10-25-62	17	M	F	E	101-112	
10-25-62	17	AM	F	E	98-108	
11-1-62	17	AM	F	E	97-120	
11-5-62	17	AM	F	E	96-116	
11-7-62	12	AM	F	W	68-152	
11-13-62	17	PM	F	E	150-164	
11-15-62	17	N	F	E	107-122	
11-27-62	17	N	F	E	93-107	
11-30-62	12	AM	F	W	77-157	
12-3-62	15	PM	F	E	90-135	Four-in-one-night series
12-3-62	15	PM	F	E	95-135	Four-in-one-night series
12-3-62	15	N	F	E	95-135	Four-in-one-night series
12-3-62	15	N	F	E	90-115	Four-in-one-night series
12-5-62	12	PM	F	W	83-138	
12-6-62	17	M	F	E	89-108	
12-12-62	17	N	F	E	103-114	
12-14-62	17	N	F	E	89-126	

Table I (Continued)

CHEMICAL RELEASES YIELDING WIND DATA

Date	Reference	Time[1]	Season[2]	Site[3]	Altitude Range[4]	Remarks
2-20-63	12	PM	W	W	58-151	
2-21-63	12	PM	W	W	83-164	
5-15-63	17	N	Sp	E	96-113	
5-17-63	15	PM	Sp	E	70-170	Four-in-one-night series
5-17-63	15	N	Sp	E	95-130	Four-in-one-night series
5-18-63	15	M	Sp	E	95-115	Four-in-one-night series
5-18-63	15	AM	Sp	E	95-165	Four-in-one-night series
5-21-63	14	PM	Sp	E	70-140	
5-23-63	12	PM	Sp	W	81-205	
5-24-63	12	PM	Sp	W	84-170	
9-23-63	17	N	F	E	90-142	Up and down trail
9-25-63	17	N	F	E	90-117	
9-25-63	17	N	F	E	92-100	
10-1-63	17	AM	F	E	88-166	Up and down trail
1-22-64	16	M	W	W	89-113	
1-22-64	16	M	W	W	107-125	
5-18-64	17	M	Sp	K	93-123	
10-17-64	17	AM	F	E	87-140	Launched with 10-17-64 below

Table I (Concluded)

CHEMICAL RELEASES YIELDING WIND DATA

Date	Reference	Time[1]	Season[2]	Site[3]	Altitude Range[4]	Remarks
10-17-64	17	AM	F	E	88-152	Up and down trail
11-18-64	17	AM	F	E	93-140	
2-27-65	17	N	W	E	93-128	
2-28-65	17	M	W	E	90-132	
2-28-65	17	M	W	E	90-134	

---

[1]PM - Evening twilight

N - Cloud in darkness, before midnight

M - Cloud in darkness, after midnight

AM - Morning twilight

[2]W - Winter, December 22 - March 22

Sp - Spring, March 22 - June 22

Su - Summer, June 22 - September 22

F - Fall, September 22 - December 22

[3]H - Holloman AFB, New Mexico, 33° N

E - Eglin AFB, Florida, 30° N

W - Wallops Island, Virginia, 38° N

K - Cape Kennedy, Florida, 28° N

[4]In kilometers.

Table II

STATISTICS OF WIND DATA FROM 77 CHEMICAL RELEASES

Altitude (km)	Number of Observations	Mean Speed	Maximum Speed	Percentile Winds*				
				50	75	95	99	99.9
80	14	46	89	41	56	78	93	111
85	18	57	103	55	69	89	103	118
90	33	53	134	50	71	102	124	148
95	45	58	110	54	73	100	119	141
100	58	65	132	60	82	113	135	160
105	61	70	161	64	93	136	166	200
110	58	74	151	71	95	131	156	184
115	50	71	168	68	94	131	156	186
120	42	68	163	63	90	128	156	186
125	37	68	143	62	87	122	147	174
130	33	68	152	59	85	122	146	176
135	30	66	201	62	85	118	141	167
140	25	65	197	61	84	119	143	169
145	19	83	255	69	96	134	161	191
150	18	83	242	69	108	164	202	246
155	14	87	228	74	102	142	170	200
160	14	87	220	82	101	130	150	173
165	11	91	213	82	106	141	165	193
170	8	98	203	85	108	142	166	193
175	5	106	191	94	126	173	206	243
180	5	105	180	98	134	186	223	264

* Percentile winds computed using assumption of Gaussian speed distribution.

Table III

WIND VECTOR BEHAVIOR WITH SEASON*

Altitude* (km)	Spring (Mar. 22-June 22)	Summer (June 22-Sept. 22)	Fall (Sept. 22-Dec. 22)	Winter (Dec. 22-Mar. 22)
80	Varies in speed and direction	Insufficient data	Insufficient data	Tends to blow to northeast
85	Varies in speed and direction	Insufficient data	Insufficient data	Tends northeast
90	Varies, but has easterly component	Insufficient data	Varies, Insufficient data	Varies in direction, but winds > 60 m/s blow to northeast
95	Varies, from north to south, but has easterly component	Insufficient data	Varies, but frequently has easterly component	Varies in direction, but winds > 60 m/s blow to northeast
100	Varies, from north to south, but has easterly component	Sparse data, but tends to northeast	Varies, but frequently has easterly component	Varies in direction, but winds > 60 m/s blow to northeast
105	Varies, from north to south, but has easterly component	Insufficient data	Varies, but strong winds (> 60 m/s) blow to south and west	Varies in direction, but winds > 60 m/s blow to northeast
110	Varies, from north to south, but has easterly component	Insufficient data	Varies, but strong winds (> 60 m/s) blow to south and west	Varies in direction, but winds > 60 m/s blow to northeast

* Also see Roberts [3] for altitudes above 140 km.

Table III (Concluded)

WIND VECTOR BEHAVIOR WITH SEASON*

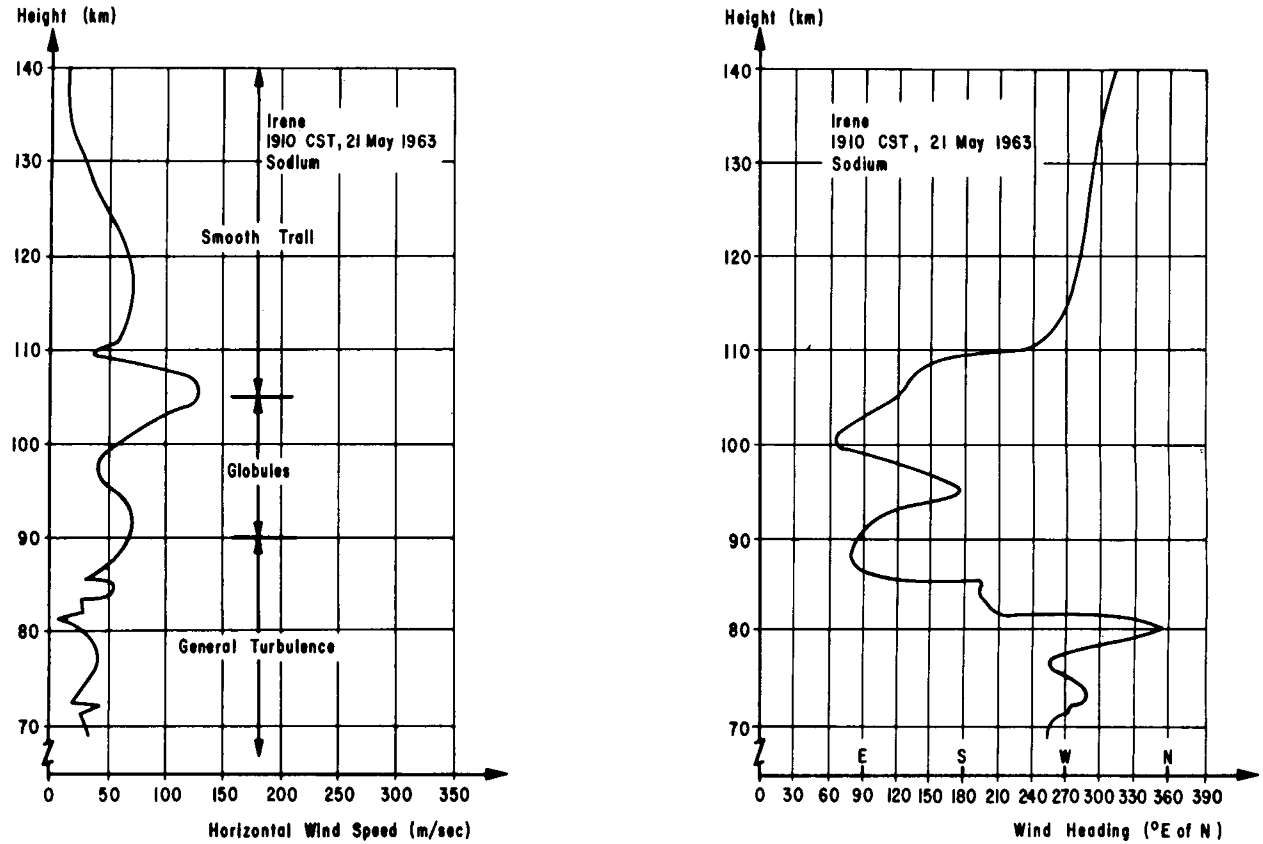
Altitude* (km)	Spring (Mar. 22-June 22)	Summer (June 22-Sept. 22)	Fall (Sept. 22-Dec. 22)	Winter (Dec. 22-Mar. 22)
115	Varies, from north to south, but has easterly component	Sparse data, but tends to southwest	Varies, but strong winds (> 60 m/s) blow to south and west	Varies in direction, but winds > 60 m/s blow to northeast
120	Varies, from north to south, but has easterly component	Sparse data, but tends to west	Varies, but strong winds (> 60 m/s) blow to south and west	Varies, but has strong (> 75 m/s) westerly component
125	Varies, from north to south, but has easterly component	Insufficient data	Varies, but strong winds (> 60 m/s)	Varies, but has strong (> 75 m/s) westerly component
130	Varies, from north to south, but has easterly component	Insufficient data	Varies, but strong winds (> 60 m/s)	Varies, but has strong (> 75 m/s) westerly component
135	Varies, but frequently has strong southerly component	Insufficient data	Varies in direction, but has strong (> 75 m/s) southerly component	Varies, but has strong (> 75 m/s) westerly component
140	Tends to blow to the south	Insufficient data	Varies in direction, but has strong (> 75 m/s) southerly component	Insufficient data

* Also see Roberts [3] for altitudes above 140 km.

Table IV

MAXIMUM EXPECTED WIND SHEARS, 80 TO 180 KM

Altitude Range	Maximum Expected Wind Shear ($\Delta z = 1$ km)
80 - 90 km	110 m/s/km
90 - 110	150
110 - 120	110
120 - 130	60
130 - 140	30
140 - 180	15



(a) Magnitude of the Horizontal Component of the Wind (m/sec)

(b) Azimuth of the Horizontal Component of the Wind (°E of N)

FIG. 1. WINDS FOR EVENING TWILIGHT, 1910 CST, 21 MAY 1963, AT EGLIN AFB, FLORIDA

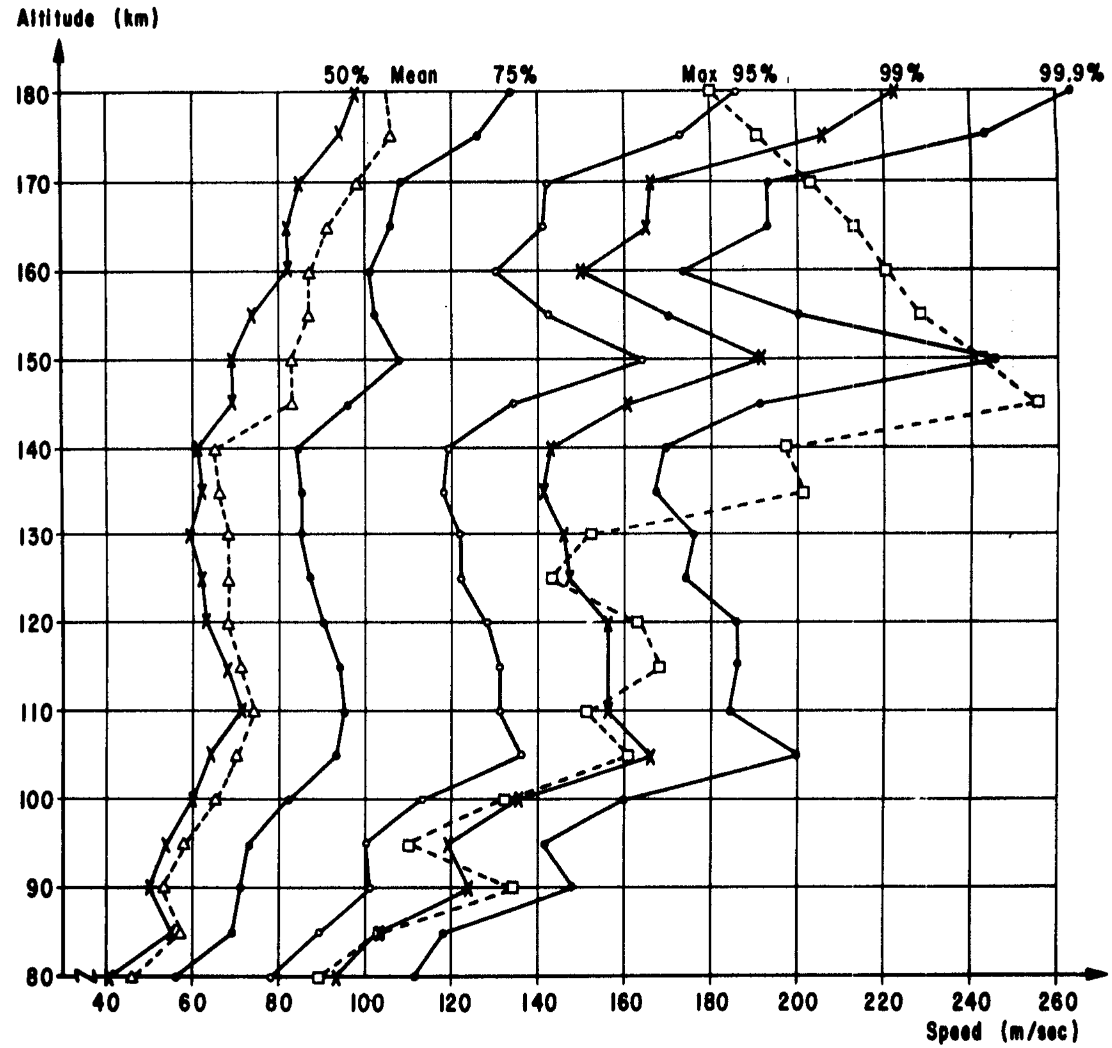


FIG. 2. MEAN, MAXIMUM, AND PERCENTILE WINDS FROM 77 CHEMICAL RELEASES, 80 TO 180 KILOMETERS

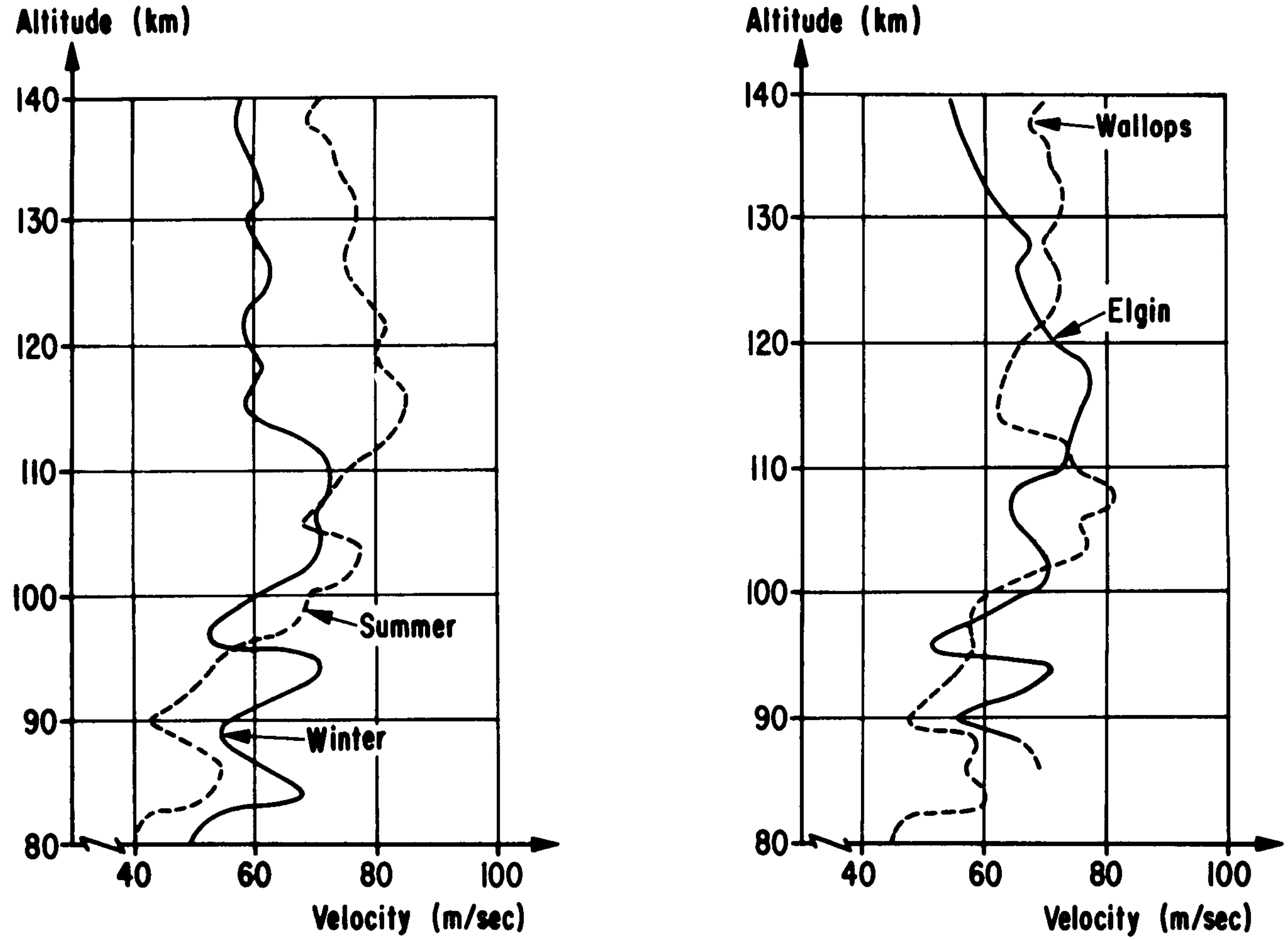


FIG. 3. SEASONAL AND LOCATIONAL DIFFERENCES

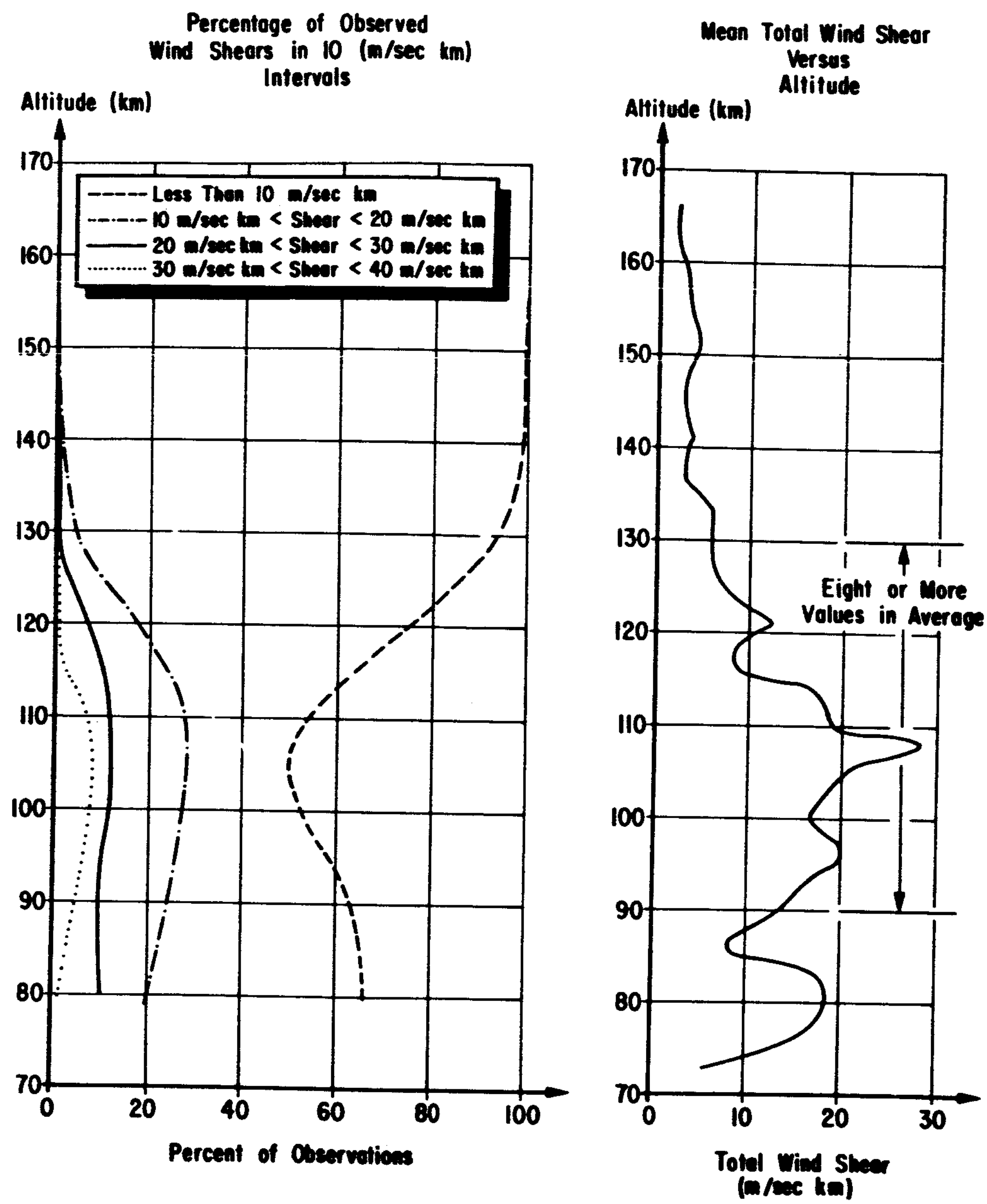


FIG. 4. WIND SHEARS FROM 30 CHEMICAL RELEASES
OVER ELGIN AFB, FLORIDA

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MEASUREMENTS OF WINDS BY CHEMICAL
RELEASES IN THE UPPER ATMOSPHERE

By

Hugh Wilson Morgan

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