

status report on radar meteor wind and density measurements¹

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Abstract

Equipment developments under the AFCRL radar meteor trail project are reviewed. Winds and densities in the 80–100 km altitude region obtained at AFCRL, Eglin AFB, Stanford, and Durham are briefly compared with results from other radar meteor stations. A comprehensive list of over 40 meteor trail stations is provided.

1. Introduction

The radar meteor trail technique uses the Doppler shift of the signals returned from ionized meteor trails (which are embedded in the neutral atmosphere in the 80- to 100-km altitude region) to determine the winds; it uses the decay-rate of the signals from underdense meteor trails to compute the density of the neutral atmosphere. This method has been employed over the past 20 years in order to obtain these meteorological variables in the upper atmosphere. Even though returns from ionized meteor trails were obtained as early as 1928 (Heising, 1928), and though not unknown to radar operators during World War II, the first wind measurements were not made until the late 1940s by Manning *et al.* (1950) at Stanford University. Greenhow, operating at Jodrell Bank along with Lovell, Hall, Neufeld, and others began taking systematic measurements in the early 1950s; using five years of data, they were able to describe the wind circulation at these levels over England (Greenhow and Neufeld, 1960, 1961). Their analyses show that the diurnal and semi-diurnal variations of the winds were of the same order of magnitude as the mean winds and the turbulent components (which in these studies included gravity waves). Another group operating at Adelaide, Australia, under Elford began taking observations in the fifties, and it is still taking observations, providing the longest record of meteor trail data available for climatological studies.

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The Meteorology Laboratory of AFCRL began in-house research in this area in 1962 in order to provide meteorological support for aerospace vehicles operating in these high reaches of the earth's atmosphere. With emphasis on prediction, the equipment was designed to detect the large-scale features, such as tides and the major weather systems, and thereby excluded the fine-scale resolution required for delineation of individual gravity waves, which were, and still are, considered to be unpredictable. In the course of the project, advanced data handling techniques utilizing both on-line and off-line computers were developed to ease the data reduction bottleneck which had hampered all previous operations. The on-line computer was also used for design studies, and this information was incorporated in the design of the Stanford University Mark II system. The Mark II was recommended by the Inter Union Commission on Solar Terrestrial Physics (IUCSTP) as an international prototype at the IUGG 1971 Moscow meeting. An improved height measuring method developed under contract by the University of New Hampshire at Durham was also recommended by IUCSTP at the same meeting. The meteorological results obtained under this program at Eglin AFB, Stanford, Durham, and AFCRL are similar to results derived by other groups. However, possible latitudinal and longitudinal differences, as well as the existence of standing waves at these levels, seem likely and demand further investigations.

2. Winds and densities in the 80- to 100-kilometer altitude region

Meteors enter the earth's atmosphere with a speed of from 10 to 70 km sec⁻¹, the average speed being approximately 42 km sec⁻¹, and a trail of ionized atmospheric gases is left behind. This ionized trail is embedded in the atmosphere and hence becomes a tracer of the atmospheric motions at these levels. A typical trail is of the order of a few decimeters in diameter and approximately 15 km long. If the orientation of the trail is such that there is a specular reflection point (perpendicular point) on the trail as seen by the fixed antennas of the radar set (see Fig. 1), then the radar cross section becomes large enough to return a usable signal. The major part of the

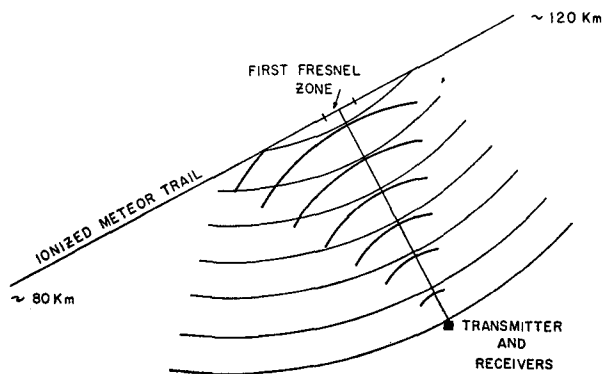


FIG. 1. Representation of radar waves reflected from an ionized meteor trail.

signal reflected back to the radar comes from the first Fresnel zone, which has a length of 1 to 4 km, depending upon the radar wavelength and the distance to the trail.

Most meteor radar systems operate in the 20- to 75-MHz band. The lower frequencies detect trails higher in the atmosphere and, with the same amount of power, detect a larger number of trails, but the lower frequencies are more sensitive to ionospheric features and require larger, more cumbersome equipment components.

The Doppler shift of the signal provides information on the radial component of the velocity of the specular reflection point relative to the radar set. In most cases the wind shears are not strong enough to move the specular reflection point along the trail at sufficient speed to mask the wind motions. If no other information is available concerning the position of the trail, then the elevation and azimuth angles of the beam center are used and a standard height between 95 and 99 km (depending on the characteristics of the radar) is assigned. The vertical velocity is generally assumed to be zero and the Doppler speed is divided by the cosine of the elevation angle to give the horizontal speed. Even though this method is very crude, it does provide climatological information on monthly mean winds, as well as diurnal and semidiurnal variations of the winds. Fig. 2 shows that over 60% of the returns at Stanford were in the narrow height interval, 97 ± 2.5 km.

To obtain a complete description of the horizontal winds, two antenna directions, at right angles to each other, are normally used. If range and elevation angle are also known, then the height of the specular reflection point can be computed, and the variations of the wind and height can be determined. Range can easily be measured to a few dekameters (or more accurately, if desired). The major difficulty is that of measuring the elevation angle to within 1° or better so that the height can be determined with an accuracy of 1 km or less.

If the horizontal beamwidth is fairly wide and if all trails are assumed to be on the same azimuth as the beam axis, then detected trails actually far from the beam azimuth will provide false wind information. For ex-

ample, if the antenna points north, if the wind is from the west at 100 m sec^{-1} , and a trail to the northwest is detected, then if no other azimuth information is available and all trails are assumed to be to the north, a wind of 71 m sec^{-1} from the north would be obtained, whereas the actual meridional wind component would be zero. This example points out the importance of using beams with narrow horizontal patterns, or of obtaining azimuth information for each trail so that the wind components can be calculated accurately.

The decay rate of underdense trails can be used to obtain information on the ambipolar diffusion coefficient at the height of the specular reflection. If the height of the underdense trail is known by other means, then the decay-rate can be used to measure the neutral atmospheric density. On the other hand, if the height is not known, then a standard-atmosphere density profile can be assumed and the standard-atmosphere height can be determined from the decay rate. Even though there are a number of serious theoretical and practical limitations to the determinations of these densities or density-heights, some useful climatological information can be obtained.

Because of the earth's rotation on its axis as it passes through the solar system debris, at most observatories there is a diurnal variation in the number of meteors that enter the atmosphere. Besides the season and time of day, the detection rate also depends on the antenna direction, beamwidth, power and receiver sensitivity. At our four sites, AFCRL, Eglin AFB, Stanford, and Durham, the maximum rate generally occurred near midnight and the minimum near 1500 local time. The maximum rate exceeded the minimum rate by a factor of

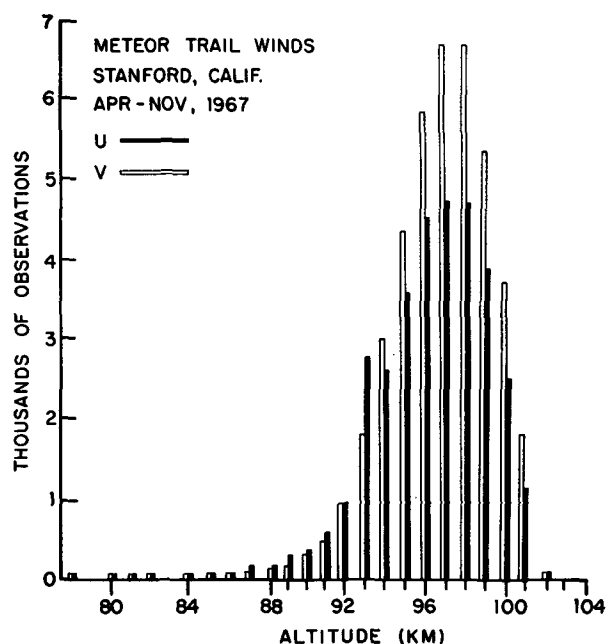


FIG. 2. Altitude distribution of meteor winds at Stanford, Calif., for the period April–November 1967.

2 or more. During most of the runs in 1970, approximately 1000 usable Doppler winds were obtained per day.

3. Equipment development

The AFCRL system and the Stanford systems were patterned after Greenhow's coherent pulse Doppler radar. The radial speed of the trail was determined from the Doppler shift, and it was necessary to have at least one half cycle of the Doppler in order to determine the Doppler frequency. Since the trails generally lasted for only a few tenths of a second, a large number of trails with low Doppler frequencies were eliminated because of the lack of definition of the Doppler frequencies. This appeared as a bias in the distribution of radial wind speeds, namely, decreasing the relative number of low radial wind speeds. However, Nowak (1967) remedied this by beating the returned signal with a signal 40 Hz above the transmitted signal, which gave an offset Doppler. This offset Doppler also removed the requirement for a second Doppler channel previously used to resolve the directional ambiguity.

The PB-250 computer incorporated into the AFCRL system was used for a number of different purposes. First and foremost, the computer controlled the radar set and temporarily stored the raw data for each pulse returned from the validated trail. The computer made a quick check, and if the data passed this check, then editing followed, and either the data were transferred to magnetic tape for later reduction on a large-scale computer, or the data were processed by the on-line computer, and the wind and height information printed on the computer typewriter. If the data failed the test, the system returned to the search mode.

A copy of the AFCRL radar system was constructed by the U.S. Army to be used in the on-line mode to provide real-time wind information at the White Sands Missile Range (Duff, 1972).

Because the computer had been placed as far forward in the system as permissible, it was possible to perform design studies on the system by changing the computer software rather than by changing hardware in the system. The information gained with this flexibility was incorporated into the second system built for AFCRL by Stanford University, the Mark II (Nowak, North, and Frankel, 1970).

The Mark II was a coherent pulse Doppler radar operating at 36.8 MHz ($\lambda = 8.14$ m). Elevations and azimuth angles were measured by the Clegg-Davidson (1950) split-beam (or amplitude-comparison) method. The system operated in an unattended mode, but the data tapes had to be changed every two or three days. The electronic circuits were all on printed circuit boards. An on-line computer was not used, but the raw data were recorded on IBM-compatible tape for subsequent reduction on a large-scale digital computer. This was the system recommended as an international standard by the IUCSTP at the 1971 meeting of IUGG in Moscow.

The Mark II was field tested at Eglin AFB, Fla., and two elevation and azimuth angle calibrations were made using a radio-beacon, first in a satellite and second in an aircraft (Barnes, 1972b).

The AFCRL system was moved to Durham, N.H., in 1967 and operated by the University of New Hampshire. The elevation and azimuth angle measuring subsystems were changed from the amplitude-comparison method to the phase-comparison method (Rudman *et al.*, 1970), and these subsystems were calibrated using the beacon in satellite OV1-17 (Frost and Clark, 1970; Clark, Glanz, and Frost, 1970). The phase-comparison (or interferometer) method gave more accurate results than the amplitude-comparison method, and it was also found that the phase method could be calibrated at ground level, which is a distinct advantage. It was also recommended by the IUCSTP at the same IUGG meeting that the phase-comparison method developed by the University of New Hampshire be used because of the demonstrated accuracy and ground level calibration capability.

4. Data reduction, analysis, and presentation

In Greenhow's original work and in the work at Adelaide, the biggest bottleneck was that of reducing the filmed records taken of the oscilloscopes. A typical run at Jodrell Bank lasted for approximately five days, and the rest of the month was required to reduce the filmed data. For this reason, one of the first tasks at AFCRL was to incorporate an on-line computer into the system so that the raw radar data could be reduced automatically. As mentioned previously, the computer was placed as far forward in the system as possible. The output of the receivers went directly into A/D converters and from there into the computer buffer. The only decision made outside the computer was the requirement that n out of m pulses have returns within the same acceptable range bin. This was necessary because of the limited speed and storage of the computer and it helped to eliminate most of our problems with RF noise in the Hanscom Field area. Acceptable slant ranges were from 60 to 300 km. The range bins were 1.2 km deep, and it was usually required that 8 out of 12 pulses have targets in the same range bin for validation. The validation changed the sign-bit of the data-word in the buffer from positive to negative. This initiated the storage program which stored the information from that pulse, and from those pulses obtained within the next half second, in the computer memory for subsequent processing.

The PB-250 computer was not ideally suited for the task, but it was the only computer available. With the use of a fast delay line, double precision instructions, and one instruction which had been built into the PB-250 but had not been recognized by the manufacturer, it was possible to operate the complete system at a PRF of 488, which was close to our goal of 500 PPS (Barnes, 1965).

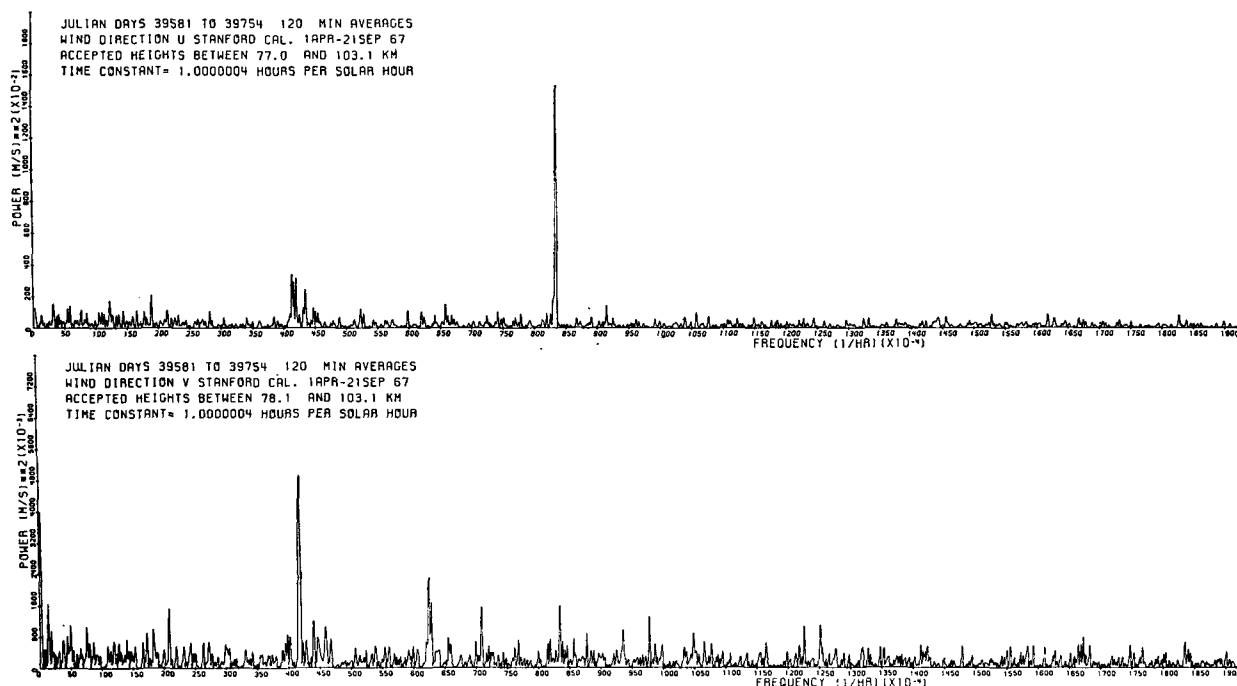


FIG. 3. Spectrum analyses of Stanford meteor wind data showing strong diurnal and semidiurnal periods (0.0417 and 0.0833 hr^{-1} , respectively).

Our usual mode of operation was to have the edited raw data recorded onto magnetic tape for later reduction at the AFCRL Computation Center. This was the most efficient means since it required only a few seconds to record the data on the tape and return to the search mode of operation. The small internal program which checked the raw data stored in memory for consistency took only a few milliseconds, but eliminated enough of the noisy trails so that one 2400-ft magnetic tape would last for one week instead of one day.

The data reduction programs used at the AFCRL Computation Center were first written for the IBM 704; the programs were updated continually with the modification of the radar system and utilization of new computers. The report by Glanz and Clark (1970) gives the most complete and most recently published version of this program along with flow diagrams. This version is used on the University of New Hampshire IBM 360. A later version including minor changes has been programmed for the AFCRL CDC 6600.

The output from these programs and from the programs which reduce the raw data from the Stanford systems consist of one card for each trail. Each card contains information on the date, time and place of observation along with the range, height, radial speed, elevation angle, azimuth angle, horizontal speed, decay-rate, density-height, and reliability information, when these parameters are available. The card format is the same for each of the systems except for the reliability information, which is included on the last part of the card and which varies from system to system.

Other radar meteor groups have changed, or are changing to automatic data reduction, and this now puts the pressure on the analysis of the data. It is at this point that the meteorologists should be able to use the data coming forth in order to make significant contributions to the understanding of this region of the upper atmosphere.

A spectrum analysis of the data taken at Stanford University for the time period 1 April through 21 September 1967 is shown in Fig. 3. The top diagram is for the west to east component, and the bottom diagram is for the south to north component of the wind. All data in the 77- to 103-km altitude region were utilized and 2-hr averages were taken to simplify the computations. The 12-hr semidiurnal period at a frequency of 0.0833 hr^{-1} shows up as a very strong spike in the zonal wind and is also evident in the meridional wind. The 24-hr diurnal frequency at 0.0417 hr^{-1} has approximately the same amplitude in both components. Note that the power scales are different for the two diagrams in Fig. 3. More detailed analyses of these and other data show that the diurnal and semidiurnal periods are more important than other periodic components of the wind.

Usually, for individual stations, the mean winds, diurnal and semidiurnal tidal winds, and diurnal density variations have been studied using fairly simple mathematical techniques (Greenhow and Neufeld, 1961; Roper and Elford, 1965; Müller, 1968; Lysenko *et al.*, 1969; Spizzichino, 1969; North and Frankel, 1972; Barnes, 1972c). The most sophisticated analysis was developed

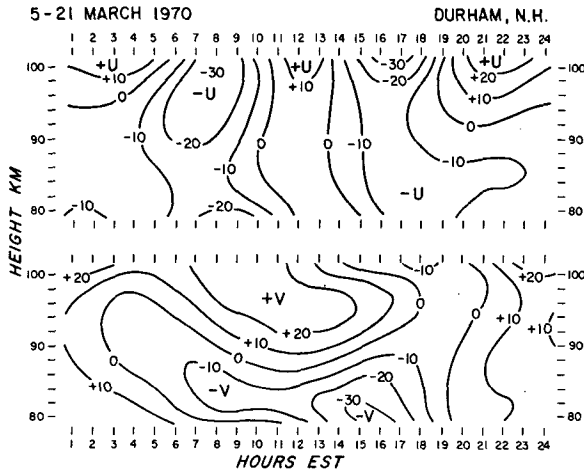


FIG. 4. Mean diurnal horizontal wind components for Durham, N.H., 5 to 21 March 1970, from a Groves-type analysis.

by Groves (1959) and has been programmed and documented by Roper (1965). Fig. 4 shows the analysis of some of the data from Durham, N.H., by Roper's program. This analysis is the best fit of the data to a model of the atmosphere which is variable, but includes the first few harmonics of the diurnal tide, and allows for vertical influence of the data. Another type of analysis, previously employed by Revah (1969), used two-dimensional autocorrelation coefficients that were then reapplied to the data to smooth the analysis. Unfortunately, many data throughout a small volume of the atmosphere are required in order that this type of analysis remain computationally stable.

5. Results from the AFCRL program

Table 1 lists the years that the radar systems obtained data under this program.

A run was made at Stanford University (Palo Alto), using a narrow-beam antenna field, specifically to investigate the diurnal variation of density. The results are shown in Fig. 5; they compare quite well with results obtained by Hall (1960) at Jodrell Bank some years previously. These results are based on the decay-rate, ambipolar diffusion, density relationship which includes a number of questionable assumptions as detailed by Barnes (1968) and by Barnes and Pazniokas (1972). On the other hand, the results are reproducible as seen in Fig. 5, and, as pointed out by Barnes and Pazniokas (1972), monthly mean wind profiles obtained using

TABLE 1. Years during which meteor data were obtained.

Station	Location	Years
AFCRL	42N, 71W	1964-1966
Stanford	37N, 122W	1965-1971
Durham	43N, 71W	1968-1970
Eglin AFB	31N, 87W	1969-1971

density-heights compare well with monthly mean wind profiles obtained using geometric heights acquired by trigonometric methods.

Because of the strong influence of the tides at these heights, the data were analyzed so as to obtain the *least squares* best fit to the equations

$$V(t) = V_0 + V_1 \cos \frac{2\pi}{24} (t-A) + V_2 \cos \frac{2\pi}{12} (t-B)$$

and

$$U(t) = U_0 + U_1 \cos \frac{2\pi}{24} (t-C) + U_2 \cos \frac{2\pi}{12} (t-D),$$

giving the wind in each of the two orthogonal directions, U and V , as a mean (subscript 0) plus a diurnal wave (subscript 1) and a semidiurnal wave (subscript 2) with maximum amplitudes of the individual waves at times A , B , C , and D . If less than 40 observations were obtained from one antenna direction during an observation period, the results for that antenna direction were not considered reliable. The decrease in reliability is primarily attributed to the presence of gravity waves at these levels, but it is also due to 1) the lack of altitude discrimination and 2) cross-wind components entering the calculations because of the wide antenna patterns, as explained in the foregoing.

In summer and in winter, the mean zonal flow was from the west, and the mean meridional flow from the summer pole. At the time of the equinoxes, the zonal flow was from the east and the meridional flow was not well defined. The semidiurnal tidal wind rotated in a clockwise direction for these Northern Hemisphere stations, indicating that the semidiurnal tide was propagating energy vertically upwards through the mesosphere into the thermosphere. The phase of the semidiurnal tide was fairly constant from one day to the next during the summer, exhibiting a gradual seasonal variation, but there were very rapid changes of the phase about the time of the equinoxes. These rapid phase changes did not seem to occur at the same time each year, but they did seem to be associated with the appearance of the zonal easterlies. According to the theory of Charney and Drazin (1961), it is during the period of the equinoxes

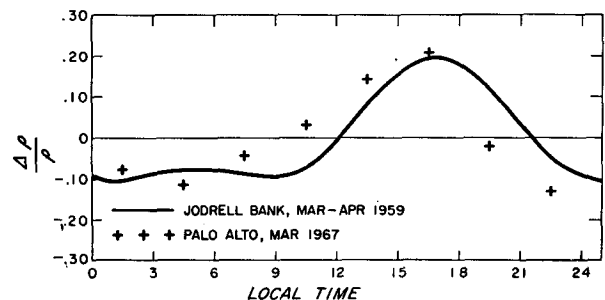


FIG. 5. Diurnal variation of atmospheric density at approximately 97 km as determined from the decay-rates of underdense radar meteor trails.

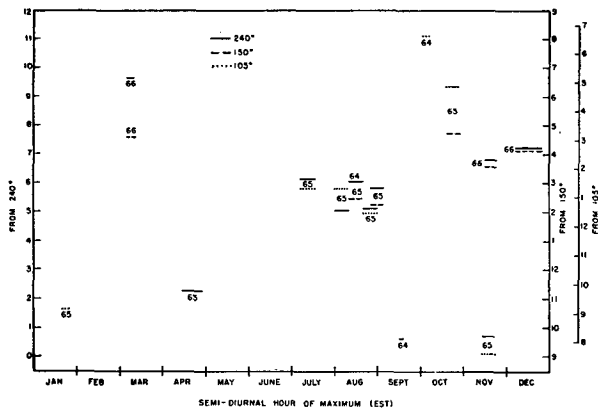


FIG. 6. Hour-of-maximum of the semidiurnal tidal wind from meteor trail observations taken at AFCRL in 1964, 1965, and 1966.

that the thermal structure of the upper atmosphere becomes such that the long wave energy, which is normally trapped in the lower atmosphere (troposphere and stratosphere), can penetrate *in force* into the upper atmosphere.

Seasonal variations of the phase of the semidiurnal tide at AFCRL are shown in Fig. 6. The months are given along the horizontal axis, and the hour of maximum along the vertical. Three scales are provided, one for each of the wind directions. The scale on the left is for winds from 240° which are plotted as solid lines. The scale on the inside right is for winds from 150°, plotted as dashed lines. The two dotted line values were obtained from the winds blowing from 105°; for these the scale is at the outer right. Associated with each plotted value or pair of plotted values is a number designating the year. If the semidiurnal tidal wind vector rotates at a constant rate, then the 240° and 150° values for a particular period should be near each other on the diagram.

For comparison, Fig. 7 shows data from Jodrell Bank and Sheffield, both located in England at approximately 53N. The Jodrell Bank data, designated by G, were taken between 1953 and 1958 (Greenhow and Neufeld, 1961), whereas the Sheffield data, designated by S, were taken from August 1964 through July 1965 (Müller, 1968). The scales are the same as those used in Fig. 6 except that the hour-of-maximum scales have been shifted one hour to allow for the fact that azimuths of the AFCRL antennas were 240° and 330° rather than 270° and 360°. This allows an exact superposition of the two figures for comparison purposes.

The diurnal tidal wind is not so well defined as the semidiurnal tide, even though there is evidence that on individual days, or for as long as a week, the amplitude of the diurnal tide will often exceed the amplitude of the semidiurnal tidal wind. On two occasions at AFCRL, the diurnal wind rotated counter-clockwise. This could be interpreted as a downward propagation of energy by this one component of the wind. Roper, in a private

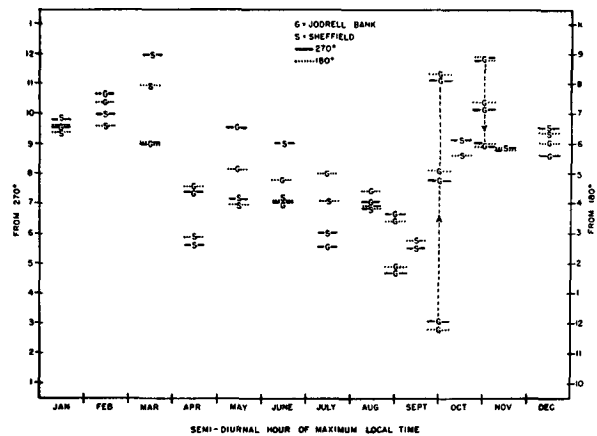


FIG. 7. Hour-of-maximum of the semidiurnal tidal wind from meteor trail observations taken in England at Jodrell Bank, 1953-1958, and at Sheffield, 1964-1965.

communication (1971), has noted similar reverse rotations in the Australian data; examples can also be found in the published Russian data (Lysenko *et al.*, 1969). Barnes and Pazniokas (1972) suggested that this might be overreflection, as defined by Jones (1968), with the excess energy coming from the mean winds, but this now seems to be an unlikely explanation since the maximum mean zonal winds are an order of magnitude too small to interact with the diurnal tide. A more likely explanation is that this is the result of the combination of two or more of the different diurnal modes operating at the same time. In all cases where the reverse rotation was observed, the sum of the energy in the diurnal and semidiurnal winds was propagated upward.

The data were also used to search for other tidal periods such as the 6- and 8-hr periods. The 6-hr period was shown to be not significant, and the 8-hr period, even though it did, on a number of occasions, rise above the noise level, was so small that it was dropped from our routine analysis programs. A long period of data from Stanford was used in a search for sidereal and lunar periods without any success. The diurnal and semidiurnal tides were removed from the data and correlations made with A_p , K_p , and the 10-cm solar radiation, but without significant correlations (Barnes, 1969).

Questions have arisen as to whether the meteor trail technique and the chemical-release, rocket-trail method measure the same movements in the upper atmosphere. Theoretical investigations by MacLeod (1966) and by others have shown that the motions of the ionized particles in the 80- to 120-km altitude region should be controlled by the motions of the neutral winds in the atmosphere at these levels. Actual comparisons of the two techniques were made at Eglin AFB (Barnes, 1972b) in December 1969 and November 1970, with the meteor observations approximately 150 km north of the rocket trails. There was very poor correspondence between the nearly instantaneous rocket winds and the appropriate monthly mean meteor winds calculated from the 30-day,

best fit, mean, diurnal, and semidiurnal components. However, reasonable comparisons of the winds did exist for those cases where the individual meteor observations were within one hour of the rocket trail observations. On the other hand, the small-scale space and time variations found by Rosenberg (1972) from seven trails deposited within ten minutes and tens of kilometers of each other would indicate that the mean observed chemical winds taken south of Santa Rose Island should not be extrapolated the 150 km to the north, to the center of the region of the atmosphere where the meteor trail observations were being taken.

Lloyd *et al.* (1972) recently reported similar comparisons taken in October 1969 in Australia, where the distance between the chemical (Woomera) and meteor (Adelaide) trails were of the order of 450 to 600 km. Their results were similar to ours, showing a distinct lack of comparison between the individual TMA rocket wind profiles and the appropriate 15-day mean meteor wind profile. Contrary to our results, the meteor wind profiles from data collected half an hour on either side of each of the rocket flights did not agree with the TMA trail results. This paper (Lloyd *et al.*, 1972, p. 787) concluded, however, ". . . the inference that radio meteor measurements do not measure the same physical quantity as TMA trails is presently unacceptable." The authors suggested that the measured wind differences were due to a decrease of the horizontal correlation distance to 600 km or less during the time of the equinoxes when the circulation patterns at these levels change rapidly. This raises the question as to what horizontal correlation distances should be expected in this altitude region of the atmosphere.

As mentioned previously, the meteor data do not show evidence of tides with periods less than 8 hr. At a latitude of 35° , a 6-hr wave would have a half wavelength in excess of 4000 km, so, if only tides of 6 hr or longer operate at these levels, one would expect very good correlation at 600-km separation. High level weather maps for the upper stratosphere show long wave, planetary scale features with half wavelengths in excess of 1000 km, and, except for disturbed events such as sudden warmings, do not show evidence of horizontal correlation distances decreasing to less than roughly 1000 km. This is attributed to the normal structure of the lower atmosphere filtering out the shorter wavelength, baroclinically unstable wave disturbances, as explained by Charney and Drazin (1961). Because they have large horizontal correlation distances, the tides and the planetary scale weather systems would seem to be eliminated as possible causes of these poor comparisons.

Both the meteor and rocket trail data show that the winds in this altitude region of the atmosphere are very irregular. Greenhow and Neufeld (1960) investigated the irregular component of the wind and found that the correlation went to zero in 105 min, and the rms velocity of 25 m sec^{-1} gave a horizontal scale size of 150 km. Roper (1966) used the Adelaide meteor data for the

13 months December 1960 through December 1961 and found that the monthly rms velocity and horizontal scale-size values ranged from 23 m sec^{-1} and 50 km to 40 m sec^{-1} and 200 km. These results imply that the differences between Woomera rocket wind profiles and Adelaide meteor wind profiles obtained within ± 30 min were due to these mesoscale irregular wind components and the spatial separation of the observations. The closer spacing is thought to be the reason for the reasonable comparisons obtained at Eglin AFB.

A subsequent comparison was conducted at Eglin AFB in May 1971, and the data contained substantially improved information on the location of the individual meteor trails. Even though the data have not been analyzed, from the geometry it is clear that the closest separation cannot be less than 65 km. Further comparisons should be made with much smaller horizontal separation of the measuring regions, but, as pointed out by Barnes (1972b), some separation of the observation volumes is necessary so that the meteor radar will not be saturated by reflections from the rocket trails.

It is interesting to note that these mesoscale irregularities may be considered as gravity waves since they have velocities and dimensions that satisfy the equations of motion of the internal gravity wave spectrum. Observational and theoretical investigations have shown that most gravity waves observed in the mesosphere originate in the troposphere and propagate upwards at shallow angles. Perusal of the Charney-Drazin (1961) model reveals that gravity waves were specifically excluded by their modeling assumptions.

6. On-going and future meteor trail work

There are two areas of work which are actively being pursued at the present time. The first is the improvement of the individual sets in order to obtain increased data-rates and to improve the accuracy of the location of the trails above the surface and relative to the radar system. The second is an attempt to obtain global coverage in order to investigate latitudinal variations, longitudinal variations, synoptic variations, standing waves, and the general circulation of the atmosphere in the 80- to 100-km altitude region.

For the AFCRL systems, the data-rates were too small, the atmospheric volume too large, and the position definition was not accurate enough to investigate the individual gravity waves, which constitute a major component of the variability of the meteorological parameters at these levels. Fig. 8 is an example of the definition which is available from the meteor trail technique when the equipment is designed to detect small scale features. The observations were taken at Garchy, France, during the Leonid meteor shower, when the number of meteors entering the atmosphere increased more than one hundredfold over the normal rate. Similar small scale features have been observed at Garchy in other cases and by the systems at Adelaide, Australia, and Havana, Ill.

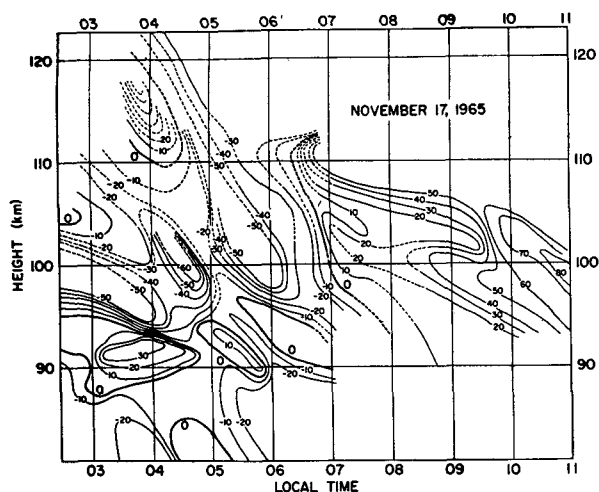


FIG. 8. East-west component of wind velocity (m sec^{-1}) as a function of height and time (Revah and Spizzichino, 1968).

Recent improvements in radar detection capabilities should be applied to detect the less dense meteor trails and thereby increase the normal data-rates. The interferometer technique developed by the University of New Hampshire could be improved to provide more accurate positional information by using additional antennas. This is being done with the Havana system currently undergoing relocation at the University of Illinois. One would expect that most of the equipment advances would come from advances initially made in other types of radar systems. For example, the interferometer technique was an adaptation of some radio astronomy work, and the signal-to-noise improvements in the Stanford systems were due to the application of pulse-coding techniques.

The Global Radio Meteor Wind Studies Project (GRMWSP) was proposed by the Steering Committee of Working Group 10 of IUCSTP in January 1970, and, at the 15th General Assembly of IUGG in Moscow in August 1971, the organization of GRMWSP was consolidated in Working Group 6 of Commission VIII of IAGA. Dr. Robert G. Roper, of the Georgia Institute of Technology, USA, and Dr. André Spizzichino of CNET, France, were appointed coordinators. The purpose of the project is to provide a clearing house for the exchange of data among the participants and with other interested parties. From time to time a schedule of preferred operating intervals is proposed, in the belief that simultaneous observations on a world-wide basis will lead more quickly to realistic global models of the meteorological conditions that prevail in the 80- to 100-km altitude region of the upper atmosphere. There are about two dozen meteor stations participating in the project at the present time, including three in the Southern Hemisphere and nine in the USSR.

Table 2 lists radar meteor stations which have contributed or have been designed to contribute information on atmospheric winds and/or densities. Meteor patrol

stations, designed to provide meteor rates, and forward scatter links, specifically designed for communications, have been excluded except where they have contributed to the meteorology of the high atmosphere. Some other radars undoubtedly have taken meteorologically useful observations but have not been brought to our attention. The listed radar characteristics are for the periods of most significant data or for the most recently operating equipment.

Newell and Dickinson (1967) have reviewed the possible application of data from a global meteor wind network. Such a network would relate the global motion fields in the upper mesosphere and lower thermosphere to the global motion fields in the atmosphere below 80 km and allow examination of the changes produced in ionospheric parameters (such as RF absorption) by changes in the motion field. The data could also be used to examine several aspects of the general circulation of the lower thermosphere and upper mesosphere, including such items as the conversion between tidal kinetic energy and the mean zonal kinetic energy, and the association between the meteor level winds and densities, and the atmospheric densities at satellite levels.

Due to the spatial and time diversity of the presently available observations, it is doubtful that the existence of the standing waves postulated by Newell and Dickinson (1967) could be confirmed. One of the objectives of GRMWSP is to reduce the time diversity of the observations, but additional stations are needed to provide more equally spaced longitudinal coverage. Better latitudinal coverage is required to adequately sample over the complete globe and to provide data for empirical confirmation of the theoretical models published by Lindzen and Blake (1971) and others concerning the various tidal modes present in the upper atmosphere. In particular, additional stations are needed on the half of the earth's surface included between 30N and 30S.

Theoretical models of the thermosphere from 100 to 300 km are based primarily on the absorption of solar UV energy in this region but they are fitted to the satellite drag measurements taken in the upper part of this region. It is found that these models agree with the observations between 200 and 300 km, but the fit becomes worse as the 100-km level is approached. One of the reasons for this is that the lower boundary of most of these models is taken around 100 km, and initially the lower boundaries were taken as static boundaries. Recent models (Chandra and Stubbe, 1970) have attempted to include the propagation of energy from below (for instance, by including diurnal variations of density and temperature at the lower boundary) to improve the lower parts of the models. From the success of the theoretical models at the higher levels, any information about the state of the atmosphere at the 100-km level would be of assistance in forecasting the state of the atmosphere in the lower 100- to 200-km region. Therefore, it is recommended that diurnal wind and density variations be included in any such models, and that the

model be nonlinear and dynamic, in order to provide a more realistic description of the atmosphere. The amount of turbulent energy dissipated in the meteor region plus the kinetic and potential energy transported upward through the top of the meteor region should be utilized in any such models. In particular, information from the meteor trail region should help to improve the forecasts of density variations which, in turn, would improve prediction of the decay of orbital elements of satellites and other space vehicles.

Studies by MacLeod (1966) and others have shown

that there is a connection between wind shears and the sporadic E layers at the same altitude in the ionosphere. The E_s, E, and D layers are of special interest because of radio communications. In the D and E regions, the neutral atmosphere motions dominate the flow and carry along the charged particles. Therefore, before the D and E regions can be understood, the movement of the neutral atmosphere at these levels will have to be described.

High altitude or large-yield nuclear explosions, or nuclear-powered space vehicles disintegrating on entering the earth's atmosphere, can deposit large amounts of

TABLE 2. Radar meteor trail stations.

Name	Location	Status *	Frequency MHz	Peak power	Pulse, μ sec	PRF	Remarks
Hayes Island	81N 55E	S	33.5	75 kW	20	500	IQSY, September 1965–February 1966
Heiss Island	80N 38E	S	33.5	75 kW			
College	65N 148W	R	30.2	750 W	CW		Side bands: 30.2 MHz $\pm$ 390 Hz Second set: 41 MHz, 100 kW, CW
Tomsk	57N 85E	S	30.0	50 kW	5	600	IGY, IQSY
Gorkiy	56N 44E	U	36.9	75 kW	10	500	
Kazan	56N 49E	R	36.6	60 kW	Pulse		Previous set: 72 MHz, 120 kW, 10 μ sec, 50 PPS
Moscow	56N 38E	U	33.	100 kW	10	500	First part of IQSY
Obninsk	55N 37E	R	24.0	75 kW	20	500	IQSY, September 1965–February 1966, December 1968
Kühlungsborn	54N 12E	U	32.55	40 kW	30	500	Comparisons with ionospheric drifts
Sheffield	54N 1W	R	24.8	20 kW	30	300	Second set: 36.3 MHz, 200 kW, 30 μ sec, 450 PPS
Jodrell Bank	53N 2W	SN	36.3	100 kW	20	150	
Bracknell	51N 1W	R	36.3	200 kW	30	450	
Eindhoven	51N 5E	U	40.				Under construction
Kiev	50N 31E	R	34.5	20 kW	10	500	IGY, IQSY Previous sets, 75 MHz and 31.2 MHz
Kharkov	50N 36E	R	36.9	100 kW	11	500	IGY, IQSY, April 1960–March 1961
Breisach	48N 8E	S	27.136	20 kW	100	66	27.046 MHz, 300W, CW
Garchy	47N 3E	R	29.79	5 kW	CW		29.7968, 29.7976, and 29.7920 MHz
Pullman	47N 117W	P					Copy of the Mark II, under construction
Majaki	46N 30E	U					IGY station, Odessa State University
Ottawa	45N 74W	S	32.22	100 W	CW		32.22, 39.22 and 49.98 MHz, used for decay-rate studies
Simferopol	45N 34E	U					IGY station
Bologna	44N 11E	P	40.	5 kW	10	140	Frequency variable from 38 to 45 MHz
Florence	44N 11E	SN	39.5	15 kW	16	150	No Doppler
London	43N 81W	P	40.	100 kW	CW		Forward scatter
Durham	43N 71W	S	36.8	30 kW	40	488	Moved from AFCRL in 1967, computer controlled
Frunze	43N 73E	R	38.3	45 kW	12	200	IQSY
Millstone	43N 71W	S	440.	2 MW	1000	60	Also 300 MHz
AFCRL	42N 71W	SN	36.8	30 kW	40	488	1964–1967. Also 73.2 MHz, 50kW, pulse Computer controlled
Havana	40N 90W	SN	40.92	3 MW	5	750	Moved to Urbana in 1971
Urbana	40N 88W	P	40.92	3 MW	5	750	
Dushanbe	39N 69E	S	37.4	80 kW	6.5	500	IGY, IQSY. Also 73 MHz, 50 kW, 10 μ sec, 100 PPS
Accomack	38N 76W	N	36.8	300 W	CW		
Stanford	37N 122W	SN	30.14	5 kW	10	300	28-bit, coded pulse Mark II operated here before move to Eglin
Ashkhabad	37N 59E	S	33.7				
Atlanta	34N 84W	R	32.5	1.7 kW	CW		32.5 MHz $\pm$ 360 Hz
Tokyo	35N 139E	P	37.46	10 kW	10	300	
Kyoto	35N 136E	R			Pulse		Copy of Mark II
White Sands	33N 106W	S	32.8	50 kW	40	500	Computer controlled, designed after AFCRL set
Eglin	31N 87W	SN	36.8	5 kW	10	300	Mark II, 28 bit, coded pulse: effective peak power 70 kW
Kingston	18N 77W	S	36.40	20 kW	35	100	Double pulses separated by 35 μ sec
Mogadishu	2N 45E	S	36.9	30 kW	40	500	August–October 1968 Russian set
Gan	1S 73E	P	36.3	200 kW	30	450	Proposed location of Bracknell set
Adelaide	35S 139E	R	26.773	1.5 kW	CW		27.540 MHz, 65 kW, 8 μ sec
Christchurch	44S 173E	R	27.12		Pulse		
Molodezhnaya	68S 46E	S	33.	35 kW	Pulse		Russian set
Mawson	68S 67E	SN	34.1	5 kW	15	750	Australian set

* Status: N = No longer operating; P = Proposed; R = Regular operation; S = Some data available; U = Unknown.

radioactive material in the upper atmosphere. The rate of settling of the radioactive particles passing through the meteor region depends upon the amount of turbulence in this region. This turbulence has been shown by Roper (1966) to be a function of the time of day and of season, and it probably also varies with latitude and longitude. Hence this turbulence, as a function of time, season, latitude and longitude, should be included along with the mean atmospheric circulation at these levels in any high altitude fall-out models. The climatology of this turbulence would also have applications to missiles staging at these altitudes.

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news and notes

JAM editor is appointed NOAA associate administrator



Dr. Edward S. Epstein has been appointed Associate Administrator for Environmental Monitoring and Prediction, National Oceanic and Atmospheric Administration. Dr. Epstein is currently editor of the *JOURNAL OF APPLIED METEOROLOGY* and Chairman of the Department of Atmospheric and Oceanic Science at the University of Michigan. He is succeeding Dr. Richard W. Hallgren at NOAA (see *BULLETIN*, **54**, 450).

Dr. Epstein graduated from Harvard College in 1951 and received an M.B.A. from Columbia University Graduate School of Business Administration. From 1953–1957, he served as an Air Force officer, performing research. In 1954 he received a Master of Science degree from Pennsylvania State University, and in 1960 received his Ph.D. from that institution. His affiliation with the University of Michigan began in 1959 and he has headed the Department of Atmospheric and Oceanic Science since 1971. Dr. Epstein has broadened the scope of the department to include studies of aeronomy and planetary atmospheres.

In addition to his work at the University of Michigan, he served as consultant to the Assistant Secretary of Commerce for Science and Technology from 1962 to 1964, and from 1968 to 1969 as a visiting scientist at the Meteorology Institute, University of Stockholm. He is a Fellow of the American Meteorological Society; a trustee of the University Corporation for Atmospheric Research; and chairman of the budget and program committee of the National Center for Atmospheric Research; panel member on committees of the National Science Foundation and the National Academy of

Sciences-National Academy of Engineering; and a member of the American Geophysical Union, the American Statistical Association, and the Royal Meteorological Society. Dr. Epstein is a certified consulting meteorologist. He will be resigning his post as editor of the *JOURNAL OF APPLIED METEOROLOGY*.

Effects of air pollution on solar radiation studied

Dr. James T. Peterson and Edwin C. Flowers of NOAA's Environmental Protection Agency report from the meteorology laboratory near Durham, N.C., that urban air pollution reduces the amount of solar radiation by several percent and that increased cloudiness over the city further reduces the amount of incident energy. In a study conducted in the St. Louis area from mid-July to mid-August 1972, the meteorologists took simultaneous solar radiation data at two sites—one downtown and one 30 miles southwest of the city. Radiation measurements were then compared to study the effect of pollution in the urban atmosphere when clouds were not a factor.

On the average the city received about 2–3% less solar energy because of particles in the atmosphere. The depletion in the ultraviolet wavelength averaged 6–7%. The cumulative total energy received at the city during the 28 days was 6.5% less than at the country location. The difference in ultraviolet wavelengths was 8.5%. The results indicate more cloudiness over the city.

Measurements at both sites include direct and global solar radiation in several intervals, atmospheric turbidity at 0.38- and 0.50-micron wavelengths, and the scattering coefficient and mass of aerosols.

Conducted simultaneously with METROMEX (Metropolitan Meteorological Experiment) in St. Louis, the experiment was a pilot for identifying the best sites for a larger Environmental Protection Agency measuring network of air pollution and meteorological parameters to be deployed there during the next five years.

(More news and notes on page 924)