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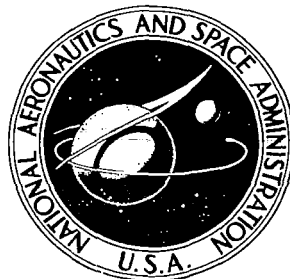
# METEOROLOGICAL ROCKET RESEARCH SINCE 1959 AND CURRENT REQUIREMENTS FOR OBSERVATIONS AND ANALYSIS ABOVE 60 KILOMETERS

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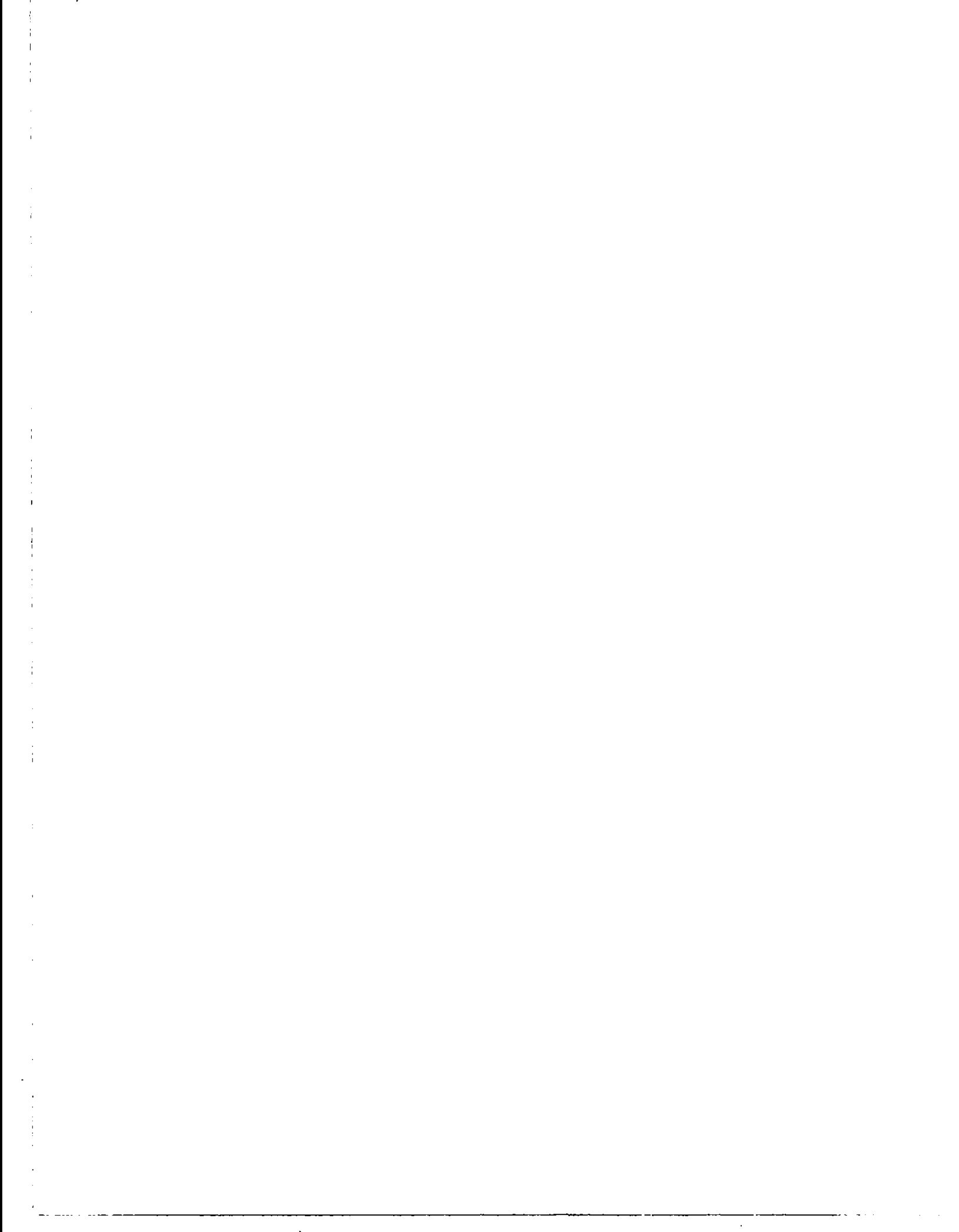
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# METEOROLOGICAL ROCKET RESEARCH SINCE 1959

# AND CURRENT REQUIREMENTS FOR OBSERVATIONS AND ANALYSIS

# ABOVE 60 KILOMETERS

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# ABSTRACT

A detailed survey is made of routine rocket soundings since 1959, yielding measurements of neutral parameters up to 60 km, and of special rocket soundings giving data to ca. 100 km. The distribution of soundings, of which only 21% have been taken in latitudes north of 40°N, is given by station and year for more than 30 rocket sites, including foreign locations. Observational accuracies are examined in sufficient depth to permit an evaluation of the broad validity of the measurements. The observational errors may be appreciable, depending on the conditions of measurement, yet the observations are/considered to efficiently delineate the broad atmospheric structure and circulation above radiosonde levels. Error contamination, however, may be critical in small-scale analysis.

The number of special soundings (grenade, sphere, etc.) reaching levels higher than 60-70 km is an order of magnitude less than those made with small rockets. These special soundings, nevertheless, constitute the main empirical basis for recent knowledge of the neutral mesospheric structure. In view of their expense (several factors greater than the routine soundings), an economical and reliable technique is needed for measurement above 60 km, where various theoretical and a few practical problems demand attention. The latter include reentry analysis, ionospheric radio-wave absorption, and (indirectly) satellite orbital analysis, insofar as the thermosphere is influenced by the state of the mesosphere. Purely meteorological problems include explanation of the temperature gradient reversal at about 65 km, resolution of the vertical motion field, description of the full vertical structure of "stratospheric" warmings and their influence on the upper atmosphere, resolution of tidal and small-scale variations, and others. Finally, brief guidelines are offered for observational programs needed to solve the above problems.

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## INTRODUCTION

Historically, the upper limit of atmospheric investigations has been determined largely by the practical limits of the sounding techniques. A few decades ago the stratosphere was a remote region infrequently penetrated by pilot balloons. The introduction of the radiosonde and the use of radar for tracking upper air sensors, followed by improvements in equipment and techniques, led to the routine sounding of the stratosphere to about 100,000 ft, or 30 km, by the late 1950's.[1] From the observations, daily synoptic maps to 10 mb were prepared. Intensified stratospheric research was a natural consequence, not to mention investigation of tropospheric-stratospheric interaction.

Further stimulus was provided by the introduction of a meteorological network of rocket-sounding stations in 1959. From its modest beginnings the rocket network has grown to more than 30 stations providing quasi-synoptic coverage over a substantial portion of the globe (Figure 1a). The approximate height range sounded by small rockets is shown in Figure 1b; also depicted, schematically, are the amounts of observational data obtained by various sounding techniques. The practical height limit of the most commonly used rockets is about 55 to 60 km. Again, as with research at the higher radiosonde altitudes, the general availability of rocket observational data to about 60 km has resulted in new areas of investigation. A continuous series of synoptic maps at several levels based on rocket data has been undertaken, affording three-dimensional views of the atmospheric structure (Finger et al., ref. 2).

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[1]
Balloon ascents may significantly exceed 100,000 ft and under specially controlled conditions may substantially overlap the height domain of meteorological rockets. A remarkable record has been set, for example, by the meteorological group at Berlin Free University, who in recent years have attained mean heights exceeding 35 km and on June 9, 1966 reached a record height of 51.4 km (168,604 ft) (Scherhag, ref. 1).
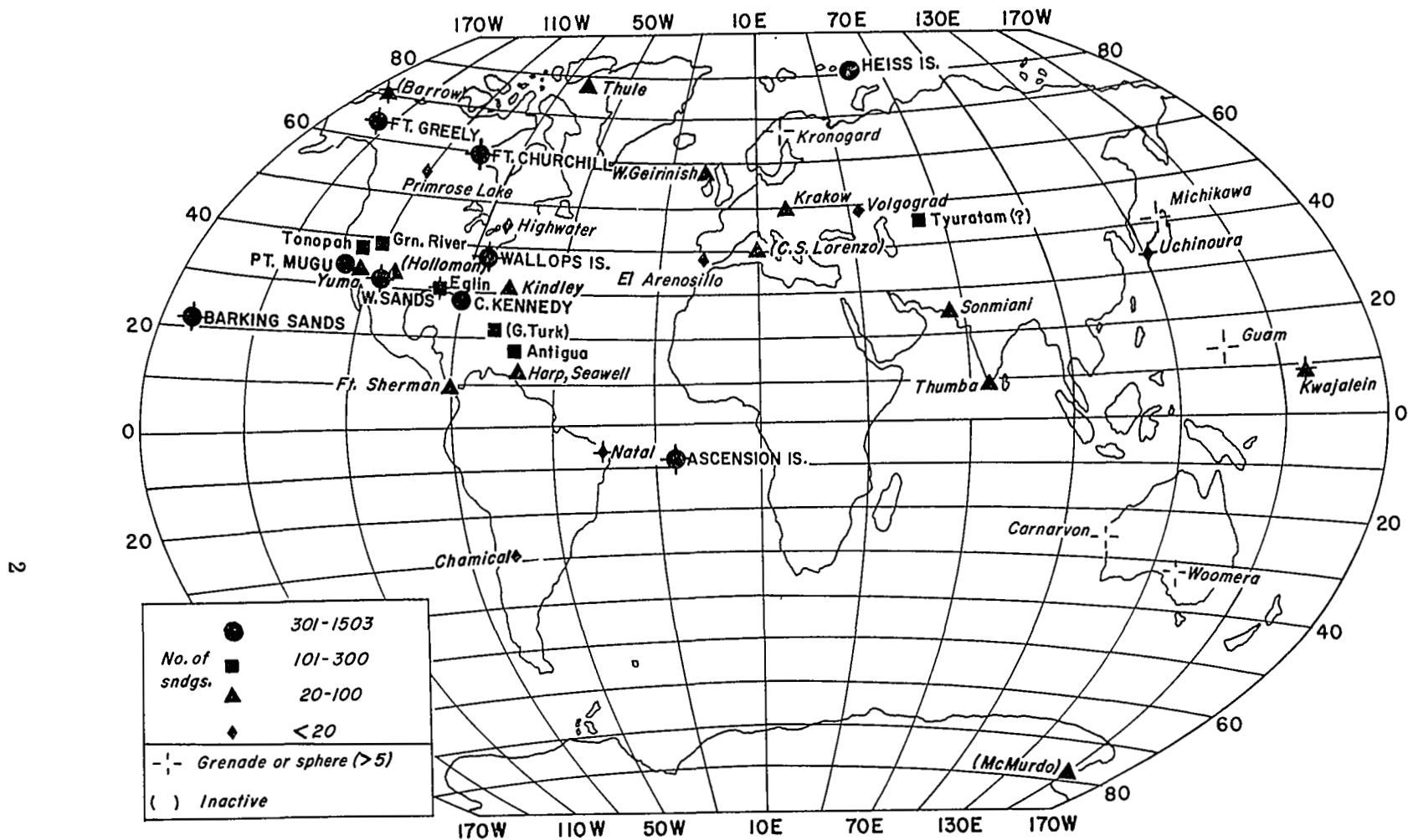
*Principal Meteorological Rocket Sites*

Figure 1a. Location of principal meteorological rocket sites. Station symbols indicate number of soundings with small rockets, through 1966. Stations with less than 20 soundings have generally been omitted unless there was evidence of increased activity after 1966. Gun-probe sites are included. Main grenade and sphere sites are shown. Several locations where vapor trail, pressure gage, etc., measurements have been obtained are not included.
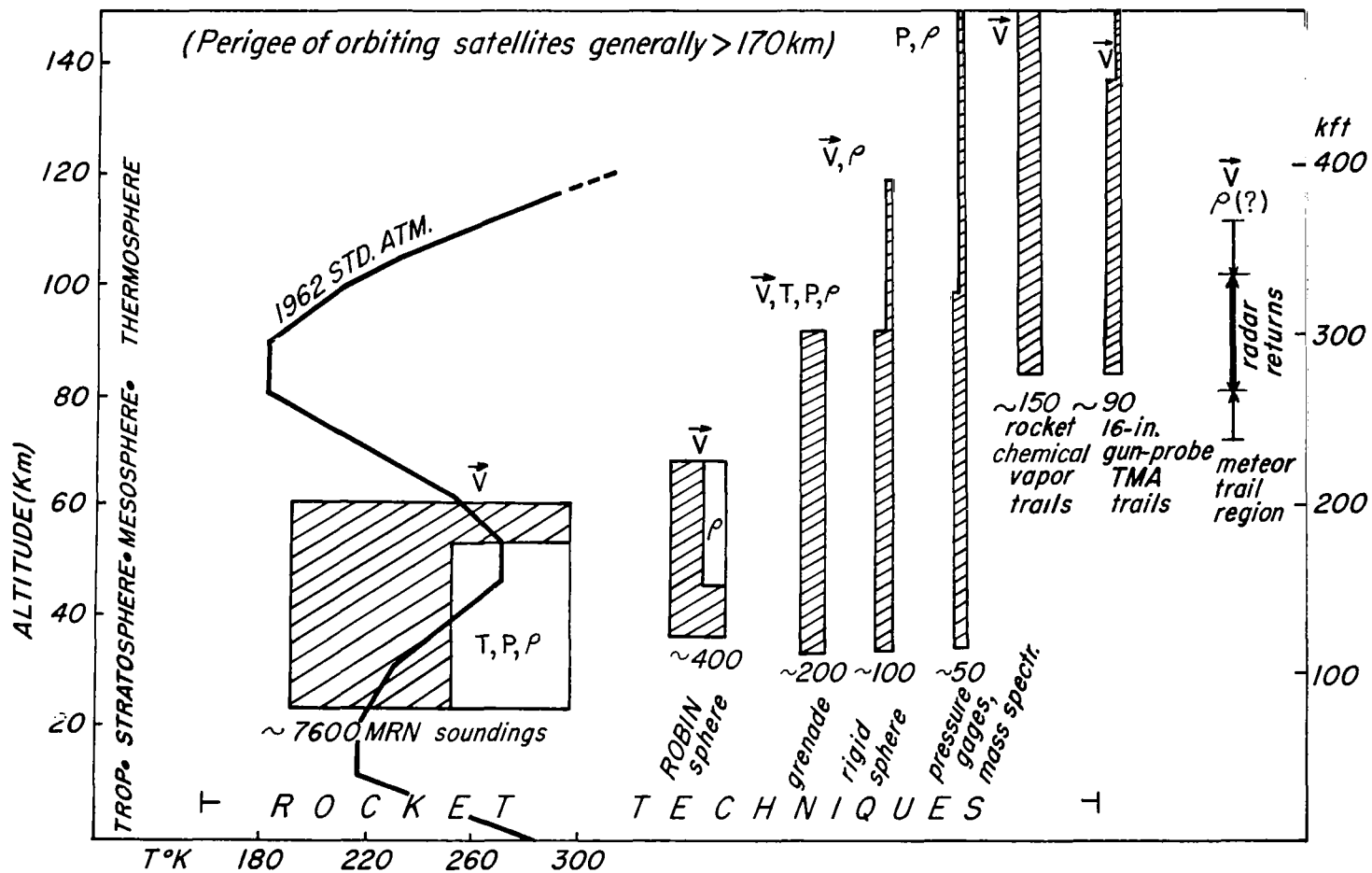
Figure 1b. Schematic representation of approximate number of soundings by various techniques, through 1966. MRN block includes ~100 5-inch gun-probe wind soundings and ~200 "operational" ROBIN sphere soundings. Soviet pressure gage soundings are not included and ionospheric techniques for deducing neutral parameters are not represented. For methods covered, representative height ranges are shown, but some measurements extend beyond the indicated heights. Meteor observations are plentiful; derived air densities are of low accuracy.

The research has been spurred on by discovery of new problems as well as new facts and to some extent also by the practical need for environmental information in the solution of certain space vehicle reentry problems (Sissenwine, ref. 3).

It is natural to ask, then, if the process of raising the altitude limit of meteorological investigation will be perpetuated. May we some day expect to have routine meteorological soundings throughout the mesosphere and perhaps part of the thermosphere? The important contribution already realized with medium or large rockets is recognized; however, the great expense of the rockets and the complexity of data reduction for some of the experiments (e.g., by the rocket grenade method) appear to make them impractical for routine meteorological use. From a purely instrumental point of view, considerable difficulty in extending routine measurements upward is anticipated. Yet much work is being done to improve the accuracy of present-day meteorological rocket measurements at the higher levels and new means of reliable and direct sounding to higher altitudes are being sought.

For the purpose of this report it will be assumed that the necessary means for routine soundings to higher altitudes will be found. The report will concern itself basically with the requirements for such observations. It is recognized that only a small percent of the solar energy affects the upper atmosphere directly (see discussion of electromagnetic spectrum by Craig, ref. 4, p. 155); yet there are strong reasons for the study of the upper atmosphere, some of which will be discussed in due course.

The plan of this report is to survey first the accomplishments made possible with the aid of meteorological rocket results, despite certain limitations in the data. Attention will then be directed to some of the problems of the region from 60 to 120 km, in order to ascertain the need for routine observations in this domain. The report will close with broad remarks on the desired space and time distribution and accuracy of the observations.


## SCOPE AND LIMITATIONS OF METEOROLOGICAL ROCKET SOUNDINGS


A meteorological rocket sounding, broadly defined, is one which provides measurements of atmospheric properties. By such a definition observations by a wide variety of rockets and sensors might be connoted, even to including, say, an experiment involving a large rocket equipped to measure the earth's magnetic field at extremely high altitudes. A narrower definition will be followed, namely, a meteorological rocket sounding is one which provides measurements of neutral properties (principally temperature, pressure, density and motion) in easily repeatable soundings. A further breakdown will be made into routine and special soundings.

Routine soundings may be distinguished from special soundings by their relatively small cost (from several hundred to slightly more than two thousand dollars[2]) and relative ease of data reduction. Examples of these are rocket soundings made with chaff, parachutes, and thermistors. Examples of special soundings are those obtained by the rocket grenade and falling sphere methods. ROBIN sphere soundings, although routinized in several respects, will be considered as special soundings. Measurements of trails of chemicals released from rockets, insofar as these aid in determining neutral motions and turbulence, could be regarded as special meteorological soundings, although they may have been carried out by experimenters working in other geophysical disciplines.

An exciting innovation has been the use of gun systems to launch routine meteorological and special high atmosphere probes (Boyer, ref. 9; Murphy et al., ref. 10). A mobile 5-inch gun system was used successfully at Wallops Island, Virginia in October 1963 and from late 1965 this system, which fires a fin-stabilized projectile containing chaff or parachute, has yielded large numbers of wind soundings to 60 km at several locations. A fixed 16-inch system has been used at Barbados, W.I. and Yuma, Arizona to generate tri-meythl aluminum (TMA) trails at 90 to 140 km or higher. In 1967, meteorological instrumentation for obtaining measurements of other variables with the gun systems was still under development. A few successful temperature soundings at altitudes to 50 km have been reported (Murphy and Bull, ref. 11).

By far the largest number of measurements has come from routine meteorological soundings, in particular from soundings made by the collection of stations known as the Meteorological Rocket Network (MRN). These

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Cost is strongly a function of the rocket-sensor combination used. Representative cost of the Arcas system, which is capable of carrying a 12-lb. instrument and telemetry package from sea level to 65 km, is $2100. Cost of the Loki system, which carries a smaller payload to 60 km, is about $1100. (See Frank, Carten, and Biedenbender, ref. 5, for a detailed cost breakdown and discussion of the possibilities for cost reduction.) Advantages and disadvantages of the Arcas and Loki have been analyzed by Kays and Olsen (ref. 6). Rather different cost data apply to gun systems used for launching probes; for the 5-inch system, used frequently in recent years, Boyer (ref. 7) estimates a flight hardware cost of $400 per flight. In contrast to the foregoing, soundings made with medium and large rockets involve a base cost from about $6000 to many times this amount. An excellent survey of medium and large rockets used for atmospheric research has been made by the Space Science Board (ref. 8).

measurements, which commonly extend to an altitude of about 60 km, will be described first. A brief account will then be given of special soundings exceeding this altitude.

Rocket Network Soundings

Distribution of soundings. - Developments in the Meteorological Rocket Network since its inception in October 1959 have been documented by Webb et al. (refs. 12-14). The term, "North American," often used in the early years of the network, was dropped as far-flung stations were added to the list of rocket-launching sites. The USAF network, which includes distant stations on foreign soil at Ascension Island (8°S) and Thule, Greenland (78°N) (Giraytys and Rippy, ref. 15) became an important contributor to the MRN. Other countries have initiated meteorological rocket programs (Groves, ref. 16; Bettle, Spurling, and Schmidlin, ref. 17), not to mention an active program carried out by the Soviet Union since 1957 (Quiroz, ref. 18). Thus it is not surprising that much discussion was devoted to the concept of a global meteorological rocket network (GMRN) at a Seminar on the Stratospheric Circulation held in London in mid-1967, under the auspices of the Committee on Space Research and the World Meteorological Organization. At this time, more than 30 stations were launching or had launched rockets repetitively for meteorological purposes (Table 1).

The total number of observations by the end of 1966 was approaching 8,000 (Table 2). This total and the total number of launching sites, however, may be highly misleading if synoptic requirements are under consideration. To begin with, the total number of stations obtaining soundings on any one day is typically only a small fraction of the total possible.[3] Moreover, temperature data are acquired on only a portion of the flights. The number of

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[3]
   Initially, the firing schedule recommended by the Meteorological Working Group (MWG) committee called for "workday" firings for one month in each season. The schedule was altered in May 1961 to Monday, Wednesday, and Friday year-around and in 1965 increased to daily firings throughout the year. Throughout the history of the rocket network, local noon has been the recommended time of firings. These objectives have been only partly fulfilled, owing to special requirements, as well as logistic limitations, at the individual sites. The dispersal of observation times has been sufficiently great to enable Reed, McKenzie, and Vyverberg (ref. 19) to infer, by stratifying the measurements according to the time of day, estimates of the diurnal variation of the wind.

TABLE 1. Number of small-rocket and gun-probe soundings published in MRN data reports (PART A) and notes on sounding activity at stations not included in MRN reports (PART B).

| PART A | | | 1959 | 1960 | 1961 | 1962 | 1963 | 1964 | 1965 | 1966 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Antigua, B.W.I. | 17N | 62W | | | | | 5 | 39 | 100 | 84 | 228 |
| Arenosillo, Spain | 37N | 07W | | | | | | | | 13 | 13 |
| Ascension I. | 08S | 14W | | | | 13 | 19 | 95 | 149 | 167 | 443[a] |
| Barking Sands (Kauai), Hawaii | 22N | 160W | | 8 | 0 | 61 | 63 | 83 | 70 | 106 | 391[b] |
| Cape Kennedy, Fla. | 28N | 81W | | 59 | 47 | 223 | 236 | 188 | 276 | 235 | 1264 |
| Eglin AFB, Fla. | 30N | 87W | | 15 | 0 | 63 | 1 | 3 | 20 | 37 | 139[c] |
| Eleuthera I. | 25N | 76W | | | | | | | 1 | 0 | 1[d] |
| Eniwetok, M.I. | 11N | 162E | | | 13 | 0 | 0 | 0 | 0 | 1 | 14 |
| Ft. Churchill, Can. | 59N | 94W | 9 | 56 | 25 | 19 | 0 | 39 | 110 | 109 | 367[e] |
| Ft. Greely, Al. | 64N | 146W | | 16 | 40 | 29 | 55 | 158 | 149 | 216 | 663 |
| Ft. Sherman, C.Z. | 09N | 80W | | | | | | | | 42 | 42[f] |
| Grand Turk I. | 21N | 71W | | | | | 2 | 43 | 115 | 82 | 242[g] |
| Green River, Utah | 39N | 110W | | | | | | 36 | 53 | 34 | 123 |
| Harp, Seawell, W.I. | 13N | 60W | | | | | | 4 | 37 | 39 | 80[h] |
| Highwater, Can. | 45N | 72W | | | | | | | | | [i] |
| Holloman AFB, N.M. | 33N | 106W | 4 | 13 | 26 | 0 | 0 | 0 | 0 | 0 | 43[j] |
| Kindley, AFB, Bermuda | 32N | 65W | | | | 13 | 6 | 0 | 0 | 10 | 29[k] |
| Kwajalein, M.I. | 09N | 168W | | | | | 7 | 24 | 5 | 7 | 43[l] |
| McMurdo, Antarctica | 78S | 165W | | | | 9 | 11 | 0 | 0 | 0 | 20[m] |

| TABLE 1 (Continued) | | | 1959 | 1960 | 1961 | 1962 | 1963 | 1964 | 1965 | 1966 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Point Barrow, Alaska | 71N | 157W | | | 8 | 0 | 0 | 0 | 0 | 0 | $8^n$ |
| Point Mugu, Calif. | 34N | 119W | 14 | 79 | 86 | 106 | 201 | 161 | 165 | 198 | 1010 |
| Primrose Lake, Can. | 55N | 110W | | | | | | 2 | 0 | 0 | $2^o$ |
| San Nicholas I., Calif. | 33N | 119W | | | | | | 1 | 0 | 5 | 6 |
| San Salvador I. | 24N | 74W | | | | | 4 | 10 | 0 | 0 | $14^p$ |
| Tartagal, Argentina | 23S | 64W | | | | | | | | 12 | $12^q$ |
| Thule, Greenland | 77N | 69W | | | | | | 8 | 0 | 38 | 46 |
| Thumba, India | 09N | 77E | | | | | | | | 1 | $1^r$ |
| Tonopah, Nev. | 38N | 117W | | 39 | 18 | 9 | 5 | 5 | 17 | 10 | 103 |
| Uchinoura, Japan (Kagoshima) | 31N | 131E | | | | | | 2 | 0 | 5 | $7^s$ |
| Vandenberg AFB, Calif. | 35N | 121W | | | | | | | | 1 | 1 |
| Wallops I., Va. | 38N | 75W | | 47 | 72 | 92 | 102 | 107 | 136 | 139 | $695^t$ |
| W. Geirinish, Scotland | 57N | 07W | | | | | | | 23 | 31 | 54 |
| White Sands, N.M. | 32N | 106W | 11 | 60 | 198 | 195 | 252 | 290 | 253 | 244 | 1503 |
| Yuma, Ariz. | 33N | 114W | | | | | | | | 38 | $38^u$ |

[a]ROBIN spheres to late 1964. Also, recent grenade program. [b]Also recent sphere program. [c]Complete ROBIN data 1960-62 available on magnetic tape. [d]Inactive 6/65. [e]Also grenade, sphere programs. [f]Increasingly active 1967. [g]Inactive 12/66. [h]Gun-probe station; both 5-in. and 16-in. gun results included. [i]Gun-probe station, active 3/67. [j]Inactive 6/61. [k]Intermittent operation. [l]Special sphere series included. [m]Inactive 10/63. [n]Inactive 8/61. Recent grenade program. [o]Active again 5/67. [p]Inactive 12/64. [q]Eclipse series 11/66. [r]23 firings 7/64-7/66; data published in Indian journal. [s]Also other soundings, including grenades. [t]Also grenade, sphere programs. [u]Gun-probe station; both 5-in. and 16-in. gun results included.

TABLE 1 (Continued)

PART B

| | | | |
|---|---|---|---|
| Salto di Quirra, Sardinia | 40N | 09E | Series of ROBIN soundings, spring 1964, published in German Weather Service report, 1965, under U.S. Army contract. |
| Chamical, Arg. | 30S | 67W | 25 soundings in 1966-67 published in EXAMETNET Data Report Series issued by NASA |
| Heiss I., USSR | 81N | 58E | Key Soviet station, >300 soundings 1957-66; early soundings have been published (ref. 18); later soundings appear in Soviet rocket data reports. |
| Krakow, Poland | 50N | 20E | Vital rocket program dating from ca. 1965. |
| Natal, Brazil | 06S | 35W | 31 soundings in 1966-67 published in EXAMETNET series. |
| Tyuratam, USSR | 46N | 63E | Apparent "mid-latitude" Soviet site, 200 soundings 1957-66(ref. 18). |
| Volgograd, USSR | 49N | 44E | Near Kapustin Yar; 84 soundings in 1967. |

Note: Table 1 does not include sites which have not had small-rocket or gun-probe programs. For information on ship firings and on soundings with medium or large rockets see data catalogues issued by World Data Center A for Rockets and Satellites, Wash., D.C. Grenade and sphere soundings are discussed separately later in this report. For information on plans for small rocket programs abroad, see Groves (ref. 16).

Also omitted are two inactive stations for which precise information could not readily be found, namely, Keweenaw, Michigan (47N, 88W), where several rockets were launched in 1964; and Johnston I. (17N, 170W) where the Air Force obtained a number of wind soundings early in the history of the MRN.

TABLE 2. Number of meteorological rocket soundings, 1959-66, yielding specified data[a]

| | WIND | WIND (Cum.) | TEMP. | TEMP. (Cum.) | RATIO T/W | TOTAL NORTH OF 40°N | FRACTION OF TOTAL |
|---|---|---|---|---|---|---|---|
| 1959 | 38 | | 0 | | | 9 | |
| 1960 | 392 | 430 | 95 | | 0.24 | 72 | 0.18 |
| 1961 | 533 | 963 | 147 | 242 | 0.28 | 65 | 0.12 |
| 1962 | 832 | 1795 | 105 | 347 | 0.13 | 48 | 0.06 |
| 1963 | 969 | 2764 | 162 | 509 | 0.17 | 55 | 0.06 |
| 1964 | 1298 | 4062 | 422 | 931 | 0.33 | 207 | 0.16 |
| 1965 | 1679 | 5741 | 939 | 1870 | 0.56 | 282 | 0.17 |
| 1966 | 1902 | 7643 | 1241 | 3111 | 0.65 | 395 | 0.21 |

[a] As published in Data Reports issued by the Meteorological Working Group (White Sands Missile Range, N. Mex.) to 1966; and by the World Data Center A for Meteorology, Asheville, N.C., since July 1966.

soundings yielding wind data is nearly equivalent to the total number of soundings. From Table 2 it may be seen that in 1960-61, only one out of every 4 soundings gave temperatures; by 1965, the ratio had significantly increased to more than 0.5. Another important consideration is the areal distribution of the data. With southern missile sites (e.g., White Sands, N. Mex.; Cape Kennedy, Fla.) being the most active firing locations, the distribution has been heavily biased in favor of latitudes below 40°N. As recently as 1966, only 1 out of every 5 soundings was being obtained north of 40°N (last column, Table 2). The tropical regions have also had sparse coverage, and it was not until 1966, when rocket stations were added at Ft. Sherman, C.Z. and Natal, Brazil, that spatial analysis became feasible in very low latitudes (Quiroz and Miller, ref. 20).

Sensors, parameters, and effective altitudes of measurement. - A variety of rocket-sensor combinations has been used. The wind is determined typically from radar tracking of a descending parachute or chaff, ejected from the rocket at apogee. The relative advantages of chute and chaff have been discussed at length (e.g., Belmont et al., ref. 21). The lightweight chaff is useful at high altitudes, but disperses quickly, providing a poor radar target at the lower altitudes. Chutes have a fast initial fall rate (Figure 2) and thus provide only a coarse measure of the wind at the higher altitudes. According to ref. 21, chaff increased in popularity in 1963. The trend has been reversed, however, and a representative sample of soundings in 1965-67 (Table 3) shows only 1 out of 7 wind soundings as having been obtained with chaff. It may be noted that combined chaff-chute soundings have also been attempted. Gun probe measurements have already been mentioned.

The temperature sensing element used for most of the stations is a 10-mil semiconductor bead, coated to minimize the heating effect of incident solar radiation. Thermistor mounts of various designs have been developed in an effort to minimize error from several unwanted heat sources. The main difference among some of the sensors in Table 3, from a meteorological viewpoint, has to do with the immediate environment of the thermistor. The Arcasonde 1A arrangement has been heavily favored over the others, but the search for an ideal sensor continues. The accuracy of the telemetered information will be discussed below.

The maximum altitude of useful data may be several kilometers below rocket apogee, as the ambient temperature and wind are not measured immediately after ejection of the sensors. The wind sensor normally remains somewhat under the influence of the rocket trajectory in its first seconds of descent, and a method for correcting for this effect has been suggested (Eddy et al., ref. 25; Kays and Olsen, ref. 26). The bead thermistor is under the influence of a variety of heat sources, of which aerodynamic heating due to fast descent is probably the leading factor above about 55 km.
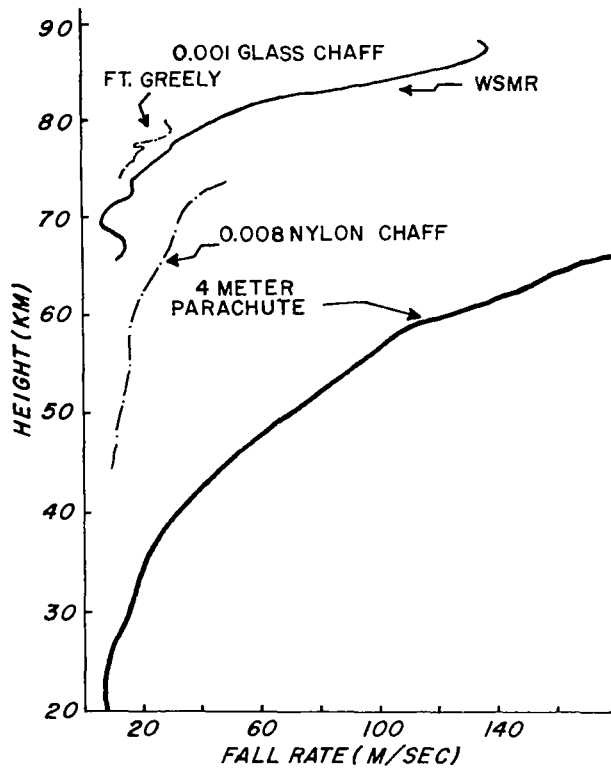
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Figure 2. Representative fall rates of various wind sensors (adapted from
Kays and Olsen, ref. 6).

TABLE 3. Number of MRN soundings classified by type of sensor[a] used, based on sample consisting of alternate months in period July 1965-June 1967.

| PARAMETER MEASURED | SENSOR | N |
|---|---|---|
| a. Wind | Chute | 2197 |
| | Chaff | 367 |
| | Sphere | 18 |
| | Ballute | 15 |
| | Chaff and Chute | 2 |
| | Chute (gun-probe)[b] | 92 |
| | Chemical trail (gun-probe)[b] | 13 |
| | Chaff (gun-probe)[b] | 6 |
| b. Temperature | Arcasonde 1A | 543 |
| | HASP (WOX 1A) | 24 |
| | Deltasonde | 21 |
| | Datasonde | 20 |
| | Resistance wire | 18 |
| | STS | 14 |
| | "Experimental" | 13 |
| | DMQ-9 | 7 |
| | Metrosonde | 2 |
| | Echosonde (Japanese) | 1 |
| | Sphere | 1 |

[a]
  See Webb (ref. 22) and Kays and Olsen (ref. 6) for distinctions among the different sensors and sondes.

[b]
  Five-inch gun system used with chute or chaff (Boyer, ref. 7); 16-inch system used for chemical trail measurements. The latter yield wind data for very high altitudes, typically 90-140 km (Murphy, ref. 23; Murphy and Bull, ref. 24; Murphy et al., ref. 10). Chaff, spheres, and telemetry packages have been used experimentally with 7-inch systems.

Table 4 gives an idea of the distribution of maximum altitudes for which data are published. It has been the usual practice to omit data at altitudes where the sensor is judged to be still under the influence of the rocket trajectory. Thus the altitudes given for the wind are the effective maximum altitudes of reliable data. (Data for White Sands, N. Mex. are a special case. Altitudes reached at this station are often higher than at other stations owing to (1) its high station elevation and (2) the introduction of wind corrections according to the method of Eddy, ref. 25, at the higher altitudes.) With regard to the temperature data, 55 km must be regarded as the approximate maximum altitude of reasonably reliable data, despite the possibility of improving the data through the use of correction techniques suggested by various investigators (see below). In short, 65 km for the wind, and 55 km for the temperature are considered the practical maximum altitudes reached routinely in meteorological rocket soundings. This is not to underestimate the potential of special series of observations taken under more controlled circumstances. Bollerman and Walker have recently reported (ref. 27) successful low-cost wind soundings to 90 km with specially designed (Cajun-Dart) rocket vehicles.

The same conclusion regarding the temperature applies to derived values of pressure and density. Values for these variables are found by integration of the hydrostatic equation, using initial pressure and height values from radiosonde data near the lowest point in the rocketsonde temperature profile. The pressure profile is usually obtained first, and then densities are found from the equation of state. In the first years of the rocket network it was left to the rocket data users to determine the pressure and density. Thiele (ref. 28) and Quiroz, Lambert and Dutton (ref. 29) compiled and statistically analyzed such data. In September 1962, computer-processed values of pressure and density became a regular feature of the rocket data publications (which from that month on were issued on a monthly, rather than seasonal basis).

Experimentation with temperature sensors other than the bead thermistor mentioned above has led to the routine use of tungsten wire resistance thermometers by the British at West Geirinish, since early 1965, following developmental efforts which began in 1963 (Almond, ref. 30; Farmer, ref. 31), and by the Soviets since 1957 (Quiroz, ref. 18). The Soviets have used a combination of several thermometers placed internally at varying distances from the surface of the separated nosecone (which descends suspended from a parachute). They also use two pressure gages to measure in two ranges of pressure. The density can then be determined directly from pressure and temperature data. Several hundred such soundings have been obtained at a number of land and ocean sites. In view of their high repeatability, we might consider the Soviet soundings as routine meteorological rocket soundings, despite the fact that considerable mathematical manipulation is required to convert the measurements to ambient values of temperature and pressure.

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TABLE 4. Number of soundings reaching indicated altitudes, based on sample of published data for June and December 1966.

| MAXIMUM ALTITUDE (km) | TEMP. | | | WIND | | |
|---|---|---|---|---|---|---|
| | J | D | Total | J | D | Total |
| <50 | 16 | 12 | 28 | 16 | 15 | 31 |
| 50-55 | 15 | 14 | 29 | 13 | 44 | 57 |
| 55-60 | 24 | 14 | 38 | <u>84</u> | <u>58</u> | <u>142</u> |
| 60-65 | <u>39</u> | <u>30</u> | <u>69</u> | 29 | 21 | 50 |
| >65 | 14 | 2 | 16 | 15 | 5 | 20 |
| Total | 108 | 72 | 180 | 157 | 143 | 300 |

TABLE 5. Error in density determined from ROBIN falling-sphere soundings [after Engler, ref. 37, Table 1 (inflated balloon)]

| Tracking Radar[a] | RMS Error | | |
|---|---|---|---|
| | 60 km | 50-60 km | 50 km |
| A | 3.5% | 3% | 3.5% |
| B | 7% | 9% | 15% |

a
A-type radar defined as radar with angular error of 0.4 mil (one mil equals 0.056 deg). Example: FPS-16. B-type radar has angular error of 1.5 mil. Example: MPS-19.

For many years, pressure gages have been used with large rockets to obtain measurements to 100 km and above (Ainsworth, Fox, and LaGow, ref. 32; Spencer, Bogess, and Taeusch, ref. 33; Theon and Horvath, ref. 34). Their use with small meteorological rockets has great appeal, but it is only recently that United States experimenters have shown the feasibility of such measurements (Thiele and Beyers, ref. 35).

Accuracies. - The subject of accuracy is extremely complex. Errors are associated with the choice of sensor, the sensor fall rate, method of tracking, interval over which the raw data are smoothed or averaged, the radiation environment of the sensor (in the case of temperature elements), and finally the structure of the atmosphere itself. A simplified presentation of error information, therefore, may be misleading. To illustrate, a document issued by the Meteorological Working Group (ref. 36) lists a 3.0% accuracy at 250,00 ft (76 km) and a 2.0% accuracy at 120,000 ft (36 km) for densities derived from the tracking of a rigid ROBIN sphere. A detailed analysis by Engler (ref. 37), however, shows a strong dependence of the error on the type of radar used and the height domain of measurement, as indicated in Table 5. Thus the reader must refer to the various detailed error analyses published to obtain as true a picture as possible of the error configurations. This discussion will therefore provide only a broad view of the observational accuracies, sufficient to evaluate the overall variability deduced from rocket sounding data in relation to the observational error.

Wind: Factors contributing significantly to wind error are the influence of the rocket trajectory on the sensor path (important only a few kilometers below apogee), poor target response (due, for example, to excessively great fall rate), and radar tracking inaccuracy. Unfortunately, the problem is complicated by dependence of the target response and tracking error on the ambient conditions. Errors tend to be magnified in case of large vertical wind shear. Thus a static set of accuracy values will not convey complete error information.

Table 6 provides error estimates made by various investigators. The impressions received from these error statements and from related background sources are as follows:

1) For sensors no longer under the influence of ballistic motion imparted by the rocket, but falling fast (fall rate greater than 50 mps), an overall accuracy of about 10 mps is the best that can be hoped for. According to Kays and Olsen (ref. 26), application of a fall rate correction may reduce the error to 5 mps.

TABLE 6. Wind Error Information

| Sensor | Comments on Errors |
|---|---|
| Chaff, foil | Error standard deviation ~5 mps due to target inhomogeneity; s.d. ~4 mps due to positioning (tracking error); estimated standard error in total wind vector, ~12 mps (Smith, ref. 38). Uncertainty in wind speed ~8 mps or 10% of speed, whichever is greater (Smith and Vaughan, ref. 39). Estimated standard error in total wind vector is 10 mps under optimum conditions (Rapp, ref. 40). |
| Parachute, 4-m | Target response generally considered acceptable for fall rates 10-50 mps. Tracking error for FPS-16 and Mod II radars estimated at 3 mps or less (JSAG, ref. 41), for 1-min. averaged winds. For fall rate of 70 mps and wind shear of $0.02 \ sec^{-1}$, Lally and Leviton (ref. 42) estimated wind accuracy at 10 mps. Winds considered accurate within 5 mps below 60 km after applying corrections which account for rate of descent from approximately 70 km (Kays and Olsen, ref. 26). |
| ROBIN falling-sphere | Rms error is 1 to 6.5 mps (radar tracking error), depending on altitude, inflation state of balloon, and data curve-fit used (based on error table published by Engler, ref. 37); for FPS-16 radar. For other radars larger error is expected. |

2) With a good radar and fall rates less than 50 mps, an accuracy of 3 mps is achievable for coarse wind averaging (e.g., 1-minute averages). An illustration of differences attainable from fine-scale reduction and relatively coarse averaging is given in Miller, Woolf, and Finger (ref. 43).

3) Since the error is a function of the ambient wind shear, static error values should be taken only as approximations.

4) For sensors under the influence of the rocket ballistic motion, wind correction factors have been published by Eddy et al. (ref. 25). Kays and Olsen (ref. 26) claim to have found verification of the validity of the Eddy corrections on the basis of a comparison of "corrected" parachute-given wind data with wind profiles derived from nearly simultaneous chaff observations. Fair agreement was found (within ~15 mps), although in view of the small sample of soundings compared by these authors, further investigation is needed.

Temperature: The measurement of temperature with bead thermistors is fraught with difficulty. As mentioned above, unwanted heating is possible from several sources. Wagner (ref. 44) evaluated the thermal influences on a hypothetical descending bead with mounting corresponding to the Deltasonde instrument. The temperature acquired by the bead was then compared with a "standard" temperature-height curve in order to provide estimates of the excess of observed temperature over ambient. The excess, referred to by Wagner as "mean total error" thus provides a basis by which to "correct" observed rocket temperature profiles to obtain profiles more nearly representative of the actual state of the atmosphere. His mean total error, corresponding to descent from 80 km in a standard atmosphere, was 33.5 °C at 65 km, decreasing to 5 °C at 50 km. Variation about this mean total error, by 3.5° at 50 km and 9° at 65 km, was possible when the reference conditions were altered (descent altitude and fall rate, model atmosphere used, etc.). Though useful for improving the observed temperatures, the Wagner corrections could not be applied with absolute precision, if only because the model atmospheres used for comparison do not reflect the total atmospheric variability.

There followed intensive investigation on the part of several authors who concentrated on error analysis for improved sensor mounts (Morrissey and Carten, ref. 45). Comparative results were collected together by Ballard (ref. 46). Though improved sensor mounts were indispensable, the greatest error source was judged to be the aerodynamic heating, which depends on the sensor fall rate. The fall rate, in turn, depends on the ejection altitude and on the ambient density (e.g., a greater fall rate at a given altitude would be expected in high latitudes in winter, when the atmospheric density at mesospheric altitudes is greatly reduced). The aerodynamic heating can be shown to vary up to about 30% from one firing to another. Ballard therefore logically

concluded that a standard correction applicable to all firings is not feasible. The practicality of individual corrections has been examined preliminarily by Henry (ref. 47).

In view of the inherent uncertainty in standard corrections, the decision whether or not to apply them must rest with the individual user. Values determined by several investigators to be generally applicable for a fall rate of 125 mps at 60 km, but for different sensor arrangements, range from 2° to 5°C at 50 km, and 5° to 20° at 60 km. Ballard is of the opinion that temperatures can be obtained to an accuracy of $\pm$ 2% below 60 km. (Uncorrected data can probably be obtained with this accuracy below about 50 km.) Time constant and fall rate considerations preclude the routine use of rocket network data for analysis of small-scale variability. It is quite possible, however, that extremely careful reduction of data from serial observations would permit the reliable analysis of certain small-scale features.

The above discussion applies primarily to American practices. For the wire temperature element used at West Geirinish, Scotland, Almond (ref. 30) indicates radiation and aerodynamic heating corrections of 3.5°C and 2.1°C at 50 km, 6.5°C and 7.9°C at 60 km, respectively, for specified conditions of fall and angle of exposure. The Soviets use multiple resistance thermometers and claim a rms error of 2°C at 40 km, 8°C at 50 km, and 12°C at 70 km (Quiroz, ref. 18).

Radiosonde-rocketsonde temperature differences: Evidence is available of some disagreement between rocketsonde and radiosonde temperatures in the region of overlap (about 20-35 km), the difference generally increasing with height. Thiele and Beyers (ref. 48) found only a 1- to 2-degree mean difference at 20-32 km, in two short series of observations in 1965. The difference is considered by these authors to be explainable by excessive infrared cooling of the radiosonde rod thermistor. The standard deviation of the temperature differences ranges from 1 to 3°C in the layer analyzed, and they believe that the larger departures from the mean difference are due to real time and space variability, since radiosonde and rocket do not measure at precisely the same point in time and space. Earlier, Finger, Woolf and Anderson (ref. 49) had made a comparison based on one year of data which agrees approximately with the results of Thiele and Beyers at about 32 km, but then shows increasing difference and dispersion at higher altitudes. Both analyses indicate that in the mean the rocketsonde temperatures are higher than the radiosonde temperatures, but there are enough counter-examples (radiosonde temperatures higher) to make simplication misleading. This problem will require further probing.

Special Meteorological Rocket Soundings

Aside from the conventional soundings described above, whose ceiling is near 60 km, there are two other leading methods for measuring the neutral middle atmosphere--the rocket grenade and falling sphere techniques. Details of these methods have been presented in numerous publications (e.g., Craig, ref. 4; Smith et al., ref. 50; Jones and Peterson, ref. 51).

In the grenade method, temperatures and winds are calculated from the propagation of sound from grenades exploded serially after ejection from a medium-size rocket. Pressures and densities are obtained hydrostatically by upward integration. The falling-sphere method involves measurement of the atmospheric drag calculated either from radar determinations of the deceleration rates for an inflated sphere (e.g., the ROBIN falling sphere), or from telemetered accelerometer data in the case of a rigid sphere. For this method, the density is found from the drag equation, under the assumption of zero atmospheric vertical motion; and it has been a common practice to obtain hydrostatically-derived temperatures as well. For the temperature calculations, downward integrations are performed with the aid of a fictitious initial temperature, with the result that real temperatures are not obtained until some 10-15 km below the starting level. Winds are commonly obtained over the height range in which the fall rate of the sphere is reduced sufficiently to make it wind-sensitive.

The number of soundings made by these methods is an order of magnitude smaller than by the conventional thermistor and parachute methods (Figure 1b). This is largely due to the relatively high cost of the soundings and/or relative complexity of data reduction. A special case is the ROBIN falling-sphere technique, which involves the use of a small rocket such as the ARCAS and which has been "routinized" to the point that the observational results are now accorded the same treatment in MRN data publications as the thermistor-chute data. The number of grenade soundings through 1967 exceeds 200 (Table 7), the leading experimenters being the U.S. NASA (W. Nordberg, W. Smith et al.), a United Kingdom research group (see publications by G. V. Groves), and a Japanese group. A substantial number of these were obtained during the IQSY (1964-65), a period of intensified activity. The leading falling-sphere experimenters have been L. Jones and J. Peterson, of the University of Michigan; P. Pearson, of the Australian Weapons Research Establishment; and at the U.S. Air Force Cambridge Research Laboratories, G. Faucher, A. Faire, and K. Champion. The detailed results and error analysis for early ROBIN falling-sphere observations are due to N. Engler, University of Dayton, under AFCRL sponsorship. A useful account of early measurements (to 1960) by grenade, sphere, and other methods applicable to the middle mesosphere has been given by Quiroz (ref. 52). Comprehensive

TABLE 7. Number of grenade and sphere soundings (ROBIN spheres excluded) to 1967.

| | | | GRENADE | | | SPHERE | | | ACTIVITY |
|---|---|---|---|---|---|---|---|---|---|
| | | | Before 1964 | 1964-1965 | 1966-1967 | Before 1964 | 1964-1965 | 1966-1967 | |
| Ascension I. | 08S | 14W | | 4 | 0 | | | | NASA |
| Barking Sands | 22N | 160W | | | | | | 9 | Sandia Corp. |
| Carnarvon | 25S | 113E | | | | | 4 | 0 | Australian Weap. Res. Est. |
| Eglin AFB | 30N | 87W | | 4 | 2 | 1 | 5 | 3 | USAF |
| Ft. Churchill | 59N | 94W | 15 | 18 | 10 | 3 | 4 | 0 | NASA/Univ. of Mich./ USAF |
| Guam | 14N | 145E | 9 | 0 | 0 | | | | NASA |
| Kronogard | 66N | 20E | 7 | 3 | 0 | | | | US/Sweden |
| Kwajalein | 09N | 168E | | | | 7 | 6 | 0 | Univ. Mich. |
| Michikawa | 40N | 140E | 10 | 0 | 0 | | | | Japan |
| Natal | 06S | 35W | | | 17 | | | | Brazil/US |
| Pt. Barrow | 71N | 157W | | 11 | 21 | | | | NASA |
| Sonmiani | 25N | 67E | | 1 | 3 | | | | Pakistan/UK/US |
| Wallops I. | 38N | 75W | 23 | 27 | 17 | 6 | 5 | 3 | NASA/Univ. Michigan |
| White Sands | 32N | 105W | | | | 7 | 1 | 9 | USAF/Univ. Michigan |
| Woomera | 32S | 137E | 19 | 6 | 0 | 1 | 32 | 0 | Austr. Weap. Res. Est./ UK Res. Gp. |

Notes:
1. Not included in this table are several locations where a single sounding was obtained, such as Kiruna, Sweden; Salto di Quirra, Italy; LAPAN Space Center, Indonesia; Kagoshima, Japan; and several ship locations.

2. On several dates, combined experiments have been conducted. For example, the grenade soundings at Eglin AFB were combined with vapor trail measurements; in four of the Woomera grenade soundings chaff was also released for measurement of the wind; at Kronogard soundings involved particle sampling in noctilucent cloud.

efforts to collect all density data obtained by these methods to 1965 have been made by Quiroz (ref. 53) and Minzner and Jacobson (ref. 54). The reason for emphasizing the role of grenade and sphere results is that, although the quantity of data obtained is significantly less than the data from the "routine" soundings, and despite the generally decreasing accuracy of observation at the higher altitudes, these data constitute the main body of information on which our detailed knowledge of the mesospheric neutral structure is based. To evaluate this knowledge, a few statements regarding measurement accuracies are needed.

The grenade soundings provide measurements generally to 90 km. The temperatures are effectively averages for layers 2-3 km thick, sometimes greater, depending on the height spacing of grenade explosions. The accuracy of measurement, which has been examined and re-examined by the NASA experimenters, depends among other factors on the location and array of ground microphones in relation to the position of the grenade explosions. Smith et al. (ref. 50) have recently indicated standard errors in the temperature as follows:

> 1-2°C at 40 km, increasing to 4°C at 85 km,
>    for Wallops I. (after mid-1965) and
> Fort Churchill
>
> 5-8°C for Wallops I. before mid-1965
>
> 2°C at 40 km, increasing to 6°C at 85 km,
>    for Pt. Barrow.

The change at Wallops Island is due to an improvement in the microphone array in 1965. Since the temperatures are layer averages, the error may be larger at discrete altitudes.

As for the measurements with spheres, various techniques have been followed, varying with the sphere characteristics (inflatable or rigid, equipped with an accelerometer or not) and ground equipment. Radar-tracked inflatable spheres with either a metallized surface (e.g., Australian soundings) or internal corner reflector (U.S. ROBIN soundings) are relatively inexpensive, but of course can be used only at sites with precision radars. By far the largest number of measurements has been obtained with ROBIN balloon spheres, beginning in 1960. Densities from ROBIN soundings are obtained generally between 40 and 70 km, and winds to lower altitudes. Between 1960 and 1966 several hundred such observations have been made, principally in low latitudes. Because of improper balloon behavior and therefore gross uncertainty in the coefficient of drag, densities have been derived in only about one-half of the soundings (Lenhard and Kantor, ref. 55; Engler, ref. 37). ROBIN soundings

obtained _operationally_, as by the Air Force at Ascension Island in 1963-64, have been reported in the data publications of the MRN.

Jones and Peterson (ref. 51) point out that w.'th the most advanced radars measurements of density are possible to 11C or 120 km. Important series to 100 km or above have been obtained at Kwajalein (Peterson et al., ref. 56); Woomera (Pearson, ref. 57, and various W.R.E. reports), White Sands, N.M. (Champion and Faire, ref. 58), and other locations (Table 7).

Spheres with internal accelerometer, which are more elaborate and expensive than the passive-tracked spheres, have been used less commonly. The most sensitive sphere system combines an inflatable envelope with internal accelerometers measuring all components of acceleration (Faucher et al., ref. 59). With this system a density profile to 128 km was obtained at Eglin AFB in July 1965. These authors ultimately envision soundings up to 150 km.

The main error in sphere density measurements is usually due to (1) inaccuracy in measuring the accelerations, and (2) uncertainty in the drag coefficients, particularly in the transonic and supersonic regimes. Representative error data are given in Table 8.

## PRESENT KNOWLEDGE BASED ON METEOROLOGICAL ROCKET DATA

### Climatological Findings

It can easily be shown that in spite of the observational errors discussed in the preceding section, the meteorological rocket results have been capable of efficiently delineating the broad atmospheric structure and circulation above radiosonde levels. As was seen, the rocket thermistor data are subject to an error of several degrees in the vicinity of 50 km, and are _possibly_ in error by a few degrees near 30 km, where _rocketsonde-radiosonde_ differences are still awaiting explanation. Corresponding density errors below 50 km are expected to amount to 2-3% of the density. These errors are, however, small in comparison with the overall ranges of temperature and density observed. Quiroz, Lambert, and Dutton (ref. 29), in one of the _earliest comprehensive derivations of climatological results from MRN_ observations, indicate that the temperature variability increases to a maximum at 40-45 km (Table 9), followed by a decrease to the stratopause. The density variability, on the other hand, increases nearly monotonically with height to at least 52 km. For either parameter, both the indicated ranges and standard deviations exceed the _error magnitudes by several factors_. It is in the analysis of small-scale variability, such as the diurnal variation, or in a

TABLE 8. Representative Error Data for Falling Sphere Measurements

| | Density | Wind |
|---|---|---|
| ROBIN (1-meter) | 3-3.5% (40-70 km) for FPS-16 radar, rigid sphere and optimum curve fit. Accuracy deteriorates for less than optimum conditions. | 1 mps (30-50 km), incr. to 3 mps (60-70 km), for optimum conditions. 2.5 mps to 5 mps for non-rigid sphere. |
| Accelerometer sphere (0.66-meter, Univ. of Michigan) | 5% (30-105 km)[a], 10% (105-120 km), with "best radar." | 3 mps (30-70 km) |
| Inflatable metallized sphere (2-meter, W.R.E., Australia) | Subsonic region: 6%(70 km) decr. to 2% (40 km) if zero vertical motion assumed; 6% (70 km) decr. to 4%(56 km) incr. to 8% (40 km) for W=2 mps. Supersonic region: measurement accuracy for accelerations[b] decreases to 10% at 97 km (with error in $C_D \geq 5\%$). | |
| Inflatable-accelerometer sphere | Measurement error for accelerations, 2% (88 km) incr. to 10% (128 km)[b]. $C_D$ error near 5%. | |

SOURCES: Ref. 37, 51, 57, 59.

a
 At Mach 1, in vicinity of 70 km, density error probably exceeds value shown.
b
 By drag equation, density error is proportional to acceleration error.

regime of greatly diminished seasonal variability, as in the tropics, that contamination by observational errors may become a problem.

More stable statistics based on larger data samples than those in Table 9 are now available. Means and standard deviations for individual stations are now included monthly in the MRN data publications. The statistics are for the current month and for that month in all the years of observation. Data are given not only for temperature and density, but for the pressure and wind (W-E and S-N components), as well. Later MRN data (Murgatroyd, ref. 60) confirm the variability trends described above. In particular, the MRN data have provided missing detail, to about 60 km, in a basic pattern of variability previously suggested by the less abundant, but higher-reaching, rocket grenade and sphere soundings.

This pattern, outlined in Figures 3, 4 and 5, is characterized by an increasing variation of the density to about 65-70 km (Quiroz, ref. 61); increasing variation of the pressure to about 60 km (Kantor, ref. 62); and decreasing variation of the temperature from the maximum at 40-45 km (Table 9) to a minimum at 60-65 km. These features are hydrostatically and dynamically consistent, as indicated in the following elaboration. Certain simplifications will be made in the interest of not burdening the discussion. In particular, it is necessary to take into account that the observed seasonal variability of temperature, pressure and density diminishes equatorward, so that a single annual curve lying intermediate between the extremes in Figure 3 might be used to represent conditions over the equator. In winter the pressure and density of the stratosphere and mesosphere generally increase from high to low latitudes. The temperature increases equatorward below about 65 and decreases above 65 km. In summer the latitudinal gradients of pressure and density are reversed and weaker and the field of temperature is less well defined. Salient dynamic and hydrostatic features, implicit in Figures 3-5, are as follows:

(1) In accordance with the geostrophic wind equation, the horizontal wind reaches a maximum just above 60 km, where the horizontal pressure variation is maximum. (The maximum wind level may vary slightly with latitude, as indicated in Figure 5.)

(2) In accordance with the latitudinal temperature distribution, the zonal wind in the stratosphere and mesosphere is generally westerly in winter, easterly in summer. At 60-65 km, the latitudinal gradient of temperature vanishes, implying through the thermal wind equation zero vertical shear of the geostrophic wind. Above about 60 km the strength of the westerlies, in the mean, is expected to decrease in response to the reversed latitudinal temperature gradient. The level of zero shear (maximum wind) is in some respects similar to the jet stream level of the upper troposphere.

TABLE 9.  Range between 1 and 99 percentile values of temperature (°C) and density (percent of mean), based on combined data for 8 stations (11°-64°N),1960-62 (from ref. 29); with means and standard deviations.

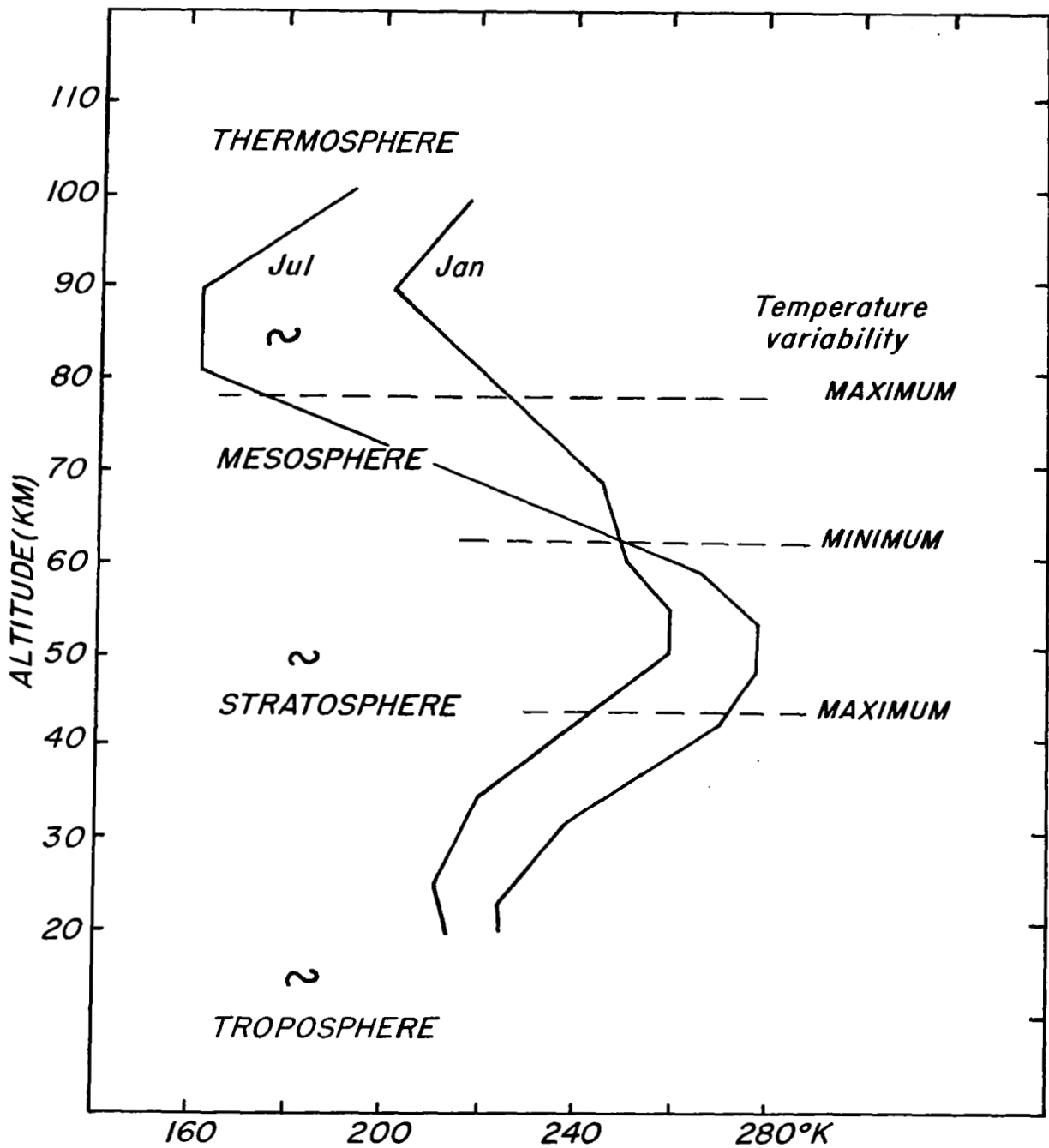| HEIGHT | | TEMPERATURE | | | DENSITY | | | No. of |
|---|---|---|---|---|---|---|---|---|
| kft | km | Range | Mean | Std. Dev. | Range | Mean $g\ m^{-3}$ | Std. Dev. /Mean | Obs. |
| 100 | 30.5 | 35°C | 230°K | 7°C | 29% | 17.2 | 5.5% | 190 |
| 110 | 33.5 | 45 | 237 | 9 | 36 | 10.8 | 5.9 | 228 |
| 120 | 36.6 | 60 | 246 | 11 | 35 | 6.81 | 6.5 | 219 |
| 130 | 39.6 | 70 | 255 | 14 | 41 | 4.35 | 7.6 | 205 |
| 140 | 42.7 | 75 | 265 | 14 | 48 | 2.83 | 8.4 | 171 |
| 150 | 45.7 | 51 | 272 | 13 | 54 | 1.88 | 9.6 | 140 |
| 160 | 48.8 | 50 | 276 | 12 | 55 | 1.27 | 10.6 | 111 |
| 170 | 51.8 | 51 | 280 | 10 | 61 | 0.86 | 12.1 | 77 |

Figure 3. Average temperature for 60°N, according to U.S. Standard Atmosphere Supplements, 1966 (ref. 63). Upper mesosphere is warmer in winter and typically contains several inversion layers.
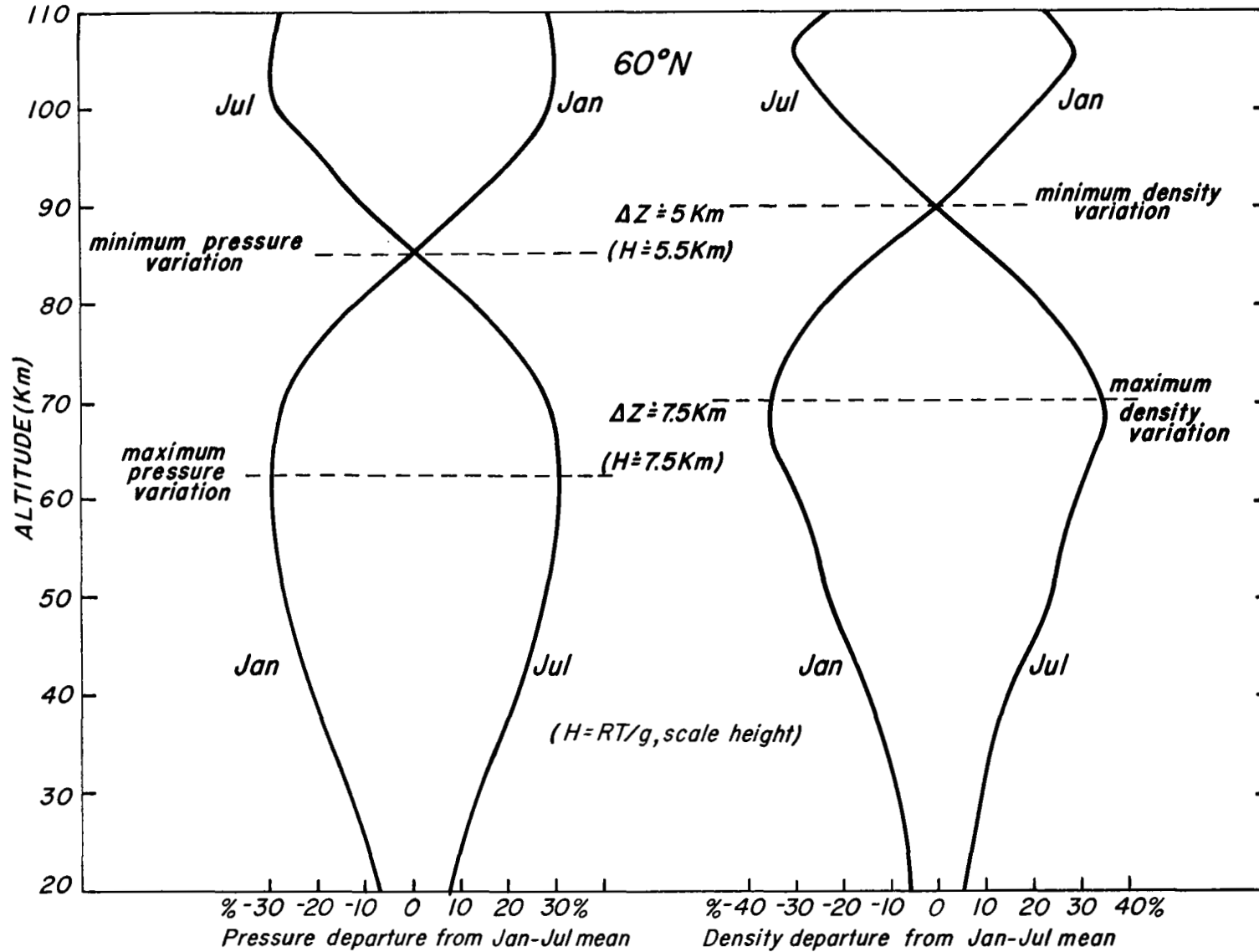
Figure 4. Curves of pressure and density departure from mean, 60°N, based on data in Standard Atmosphere Supplements, 1966 (ref. 63). Level of minimum (maximum) density variation occurs about one scale-height above level of minimum (maximum) pressure variation. Temperature relation is discussed in text.
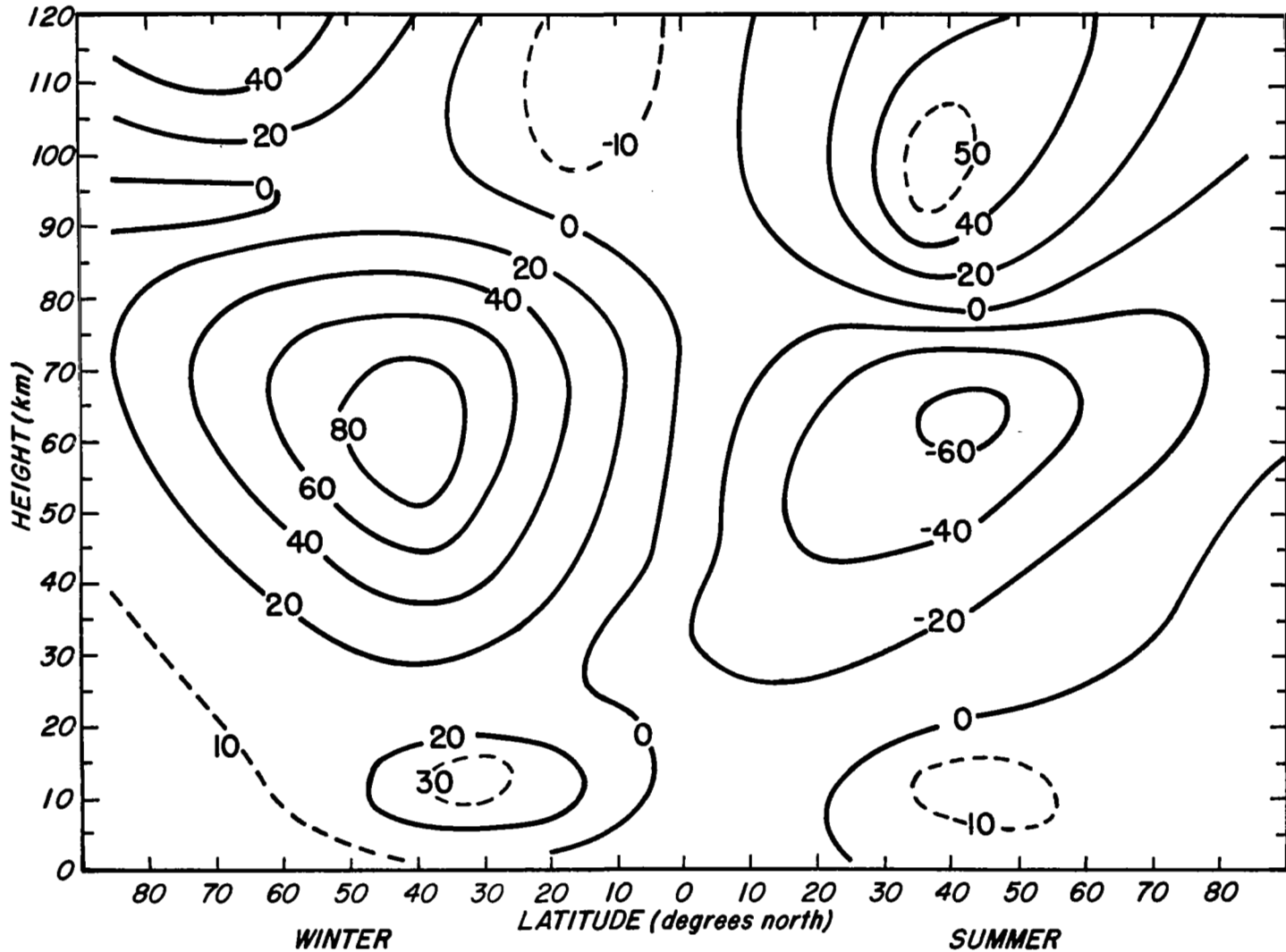
Figure 5. Mean zonal wind (m sec$^{-1}$), positive from west (from Newell, ref. 64). Figure is schematic in some respects and is intended primarily to illustrate the basic summer-winter alternation in the middle atmosphere. Not reflected are biennial and semiannual cycles and, at the higher altitudes, the great variability revealed by, e.g., gun-probe measurements (Murphy and Bull, ref. 24; Kochanski, ref. 65).

(3) The observed height structure of maxima and minima in the variation of density, pressure and temperature can be shown, qualitatively at least, to be valid hydrostatically. It is evident from the integrated hydrostatic equation,

$$p = p_0 \left(\frac{T}{T_0}\right)^{-g/R\gamma} \qquad \gamma = +\partial T/\partial z \qquad (1)$$

$$g, \text{ acceleration of gravity}$$

or

$$\rho = \rho_0 \left(\frac{T_0}{T}\right)\left(\frac{T}{T_0}\right)^{-g/R\gamma} \qquad (1a)$$

that variations in the temperature structure must be reflected in variations in the pressure and density at altitude. The importance of the height separation can be seen from an equation developed by Quiroz and Miller (ref. 66), relating density changes at altitude to pressure and temperature changes at a base altitude, separated by $\Delta z$ :

$$\frac{1}{\rho}\frac{\partial \rho}{\partial t} = \frac{1}{p_0}\frac{\partial p_0}{\partial t} + \frac{1}{H}\left(\Delta z - H_0\right)\frac{1}{T_0}\frac{\partial T_0}{\partial t} \qquad (2)$$

Eq. (2) indicates that for a height separation of one scale height ($H_0 = RT_0/g$), density variations at altitude are entirely "specified" by the pressure variations at the base altitude, since for this height separation the temperature coefficient vanishes. For height separations near one scale height, the temperature coefficient is very small. For a reasonably uniform temperature structure, a maximum in the pressure variability at some altitude therefore implies a maximum in the density variability one scale height above, and similarly for minima. Thus, in spite of non-uniform temperature structures, one sees in Figure 4 maximum pressure variation at about 60 km paired with maximum density variation near 67.5 km, and minimum pressure variation at about 85 km paired with minimum density variation a few kilometers higher.

The three thermodynamic variables, p, $\rho$, T are of course interdependent. The pressure variation itself at 60 km is dependent on the temperature variation at lower altitudes. The following relationship for <u>pressure</u> changes at altitude,

$$\frac{1}{p}\frac{\partial p}{\partial t} = \frac{1}{p_0}\frac{\partial p_0}{\partial t} + \left(\frac{\Delta z}{H}\right)\frac{1}{T_0}\frac{\partial T_0}{\partial t} \qquad (3)$$

indicates that temperature variations have increased weighting with increasing values of the coefficient $\Delta Z/H$, that is, as the height separation $\Delta Z$ increases. Qualitatively, therefore, it is expected that the large pressure variation at 60 km would be strongly associated with the large temperature variation at 40-45 km.

30

(4) By similar reasoning, the level of minimum seasonal density variation near 90 km and the reversed seasonal variation in the lower thermosphere can be shown to be related, respectively, to the seasonal temperature reversal above 65 km. These features are significant especially in relation to the development of models of the thermospheric structure (e.g., Mahoney, ref. 67; Harris and Priester, ref. 68), which depend on the choice of boundary conditions near the base of the thermosphere.


Synoptic Findings


Figure 3 grossly oversimplifies the actual temperature structure found in the atmosphere. In summer there is a fairly smooth lapse rate in the mesosphere, culminating in very low mesopause temperatures; but in winter the observed temperature profiles in high latitudes indicate very great variability, as is illustrated dramatically by rocket grenade results for Pt. Barrow in Figure 6.

Within the same season, variations at the heights of interest may be due to (1) synoptic changes (quasi-periodic or non-periodic), (2) tidal effects (period 24 hours or less), (3) internal gravity waves (period less than about 2 hours), or (4) non-systematic (turbulent) eddies. It is possible that all four types of perturbations are represented in Figure 6 (two of the soundings are in daylight). The separation of effects is of extraordinary difficulty. The ensuing remarks will concentrate on recent efforts in synoptic analysis at rocket levels (up to the lower mesosphere), and on the possibilities for synoptic analysis at the higher altitudes of Figure 6. Periodic small-scale oscillations will be considered later in this report.

By the end of the past decade and with the impetus of improved observational coverage by radiosondes in the IGY (1957-58), daily synoptic map analyses were being made to as high as 10 mb ( ~31 km).[4]

In the early 1960's attempts were made to draw synoptic maps above radiosonde levels. The early efforts involved the use of rocket wind observations to specify streamlines up to 60 km (Keegan, ref. 70). Soon thereafter

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[4]
Various groups have engaged in high-level analysis. Especially notable are the published map series produced by the Free University, Berlin; and by the Upper Air Branch (formerly Stratospheric Analysis Project), NMC, ESSA. The NMC charts have been analyzed objectively by computer since 1964 (Finger, Woolf, and Anderson, ref. 69).
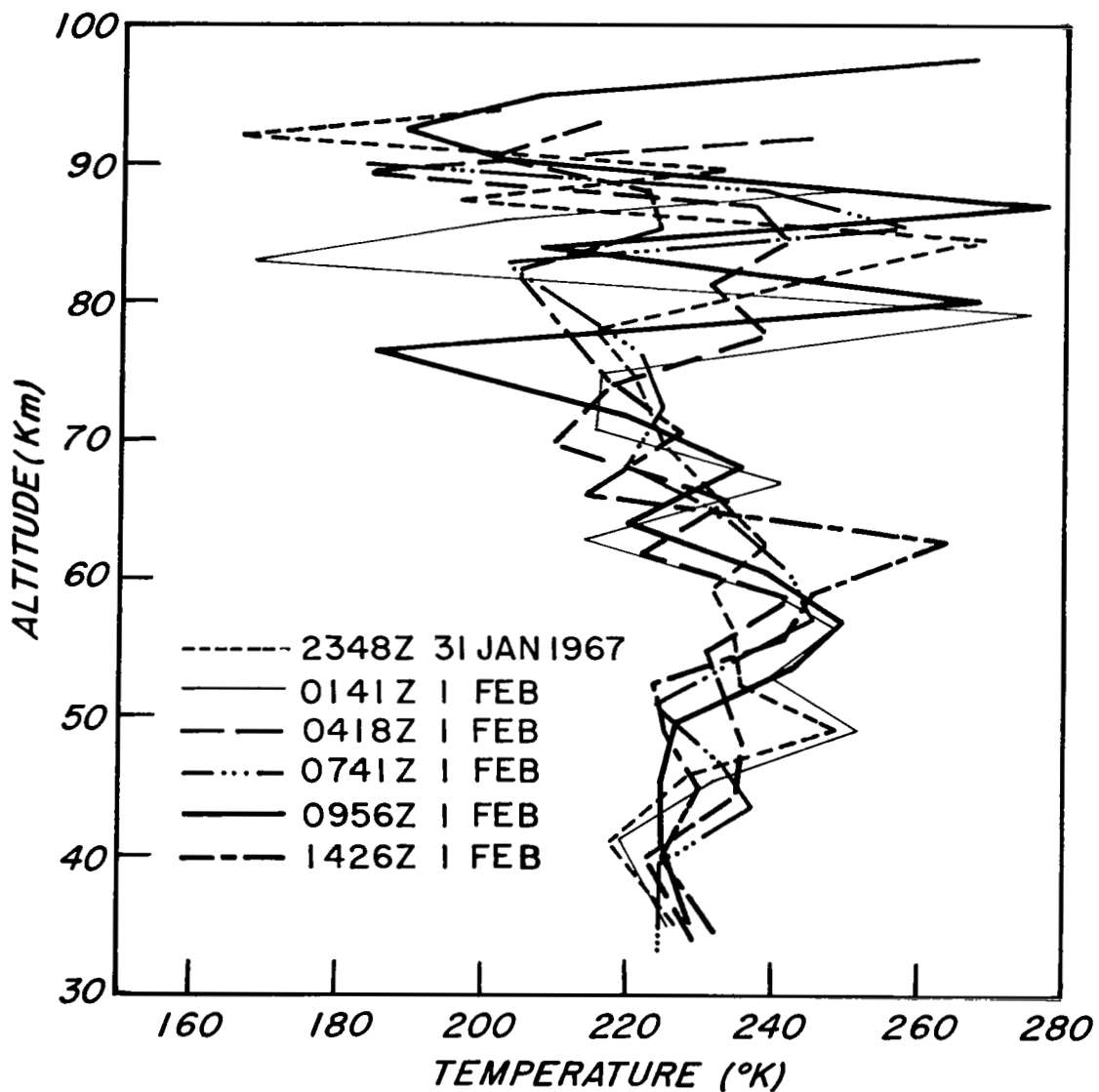
Figure 6. Rocket grenade temperature profiles for Pt. Barrow, Alaska, winter 1966 (from Smith et al,, ref. 50). Although these soundings were taken during a 24-hr. period, they typify the great variability in winter previously noted at Churchill and Wallops I.

a procedure was devised for using rocket wind and temperature data for constructing constant-pressure charts at 2 and 0.4 mb (approximately 42 and 55 km) (Finger et al., ref. 71). With improvements in rocketsonde sensor mounts and improvements in the observational coverage by both radiosondes and rockets, it became possible to produce a continuous series of weekly charts at 5, 2, and 0.4 mb (Finger et al., ref. 2). Charts for the IQSY, 1964-65, have been published (U. S. Weather Bureau, ref. 72), and analysis after 1965 continues.

The rocketsonde analyses have shown that a strong seasonal circulation occurs in the stratosphere at least up to the highest level analyzed, 0.4 mb (55 km). The summertime circulation pattern consists of an extremely persistent anticyclone centered very near the Pole, with an easterly circulation dominating most of the hemisphere (Figure 7a). In winter, the circulation is much more complex. The basic feature is a cold polar cyclone and mean hemispheric westerlies, with the westerlies generally increasing with height to the region of maximum pressure gradient near 60 km. However, the symmetry of this system is often deformed by a persistent warm anticyclone centered in the Aleutian-Kamchatka region of the North Pacific (Figure 7b). Large-scale systems such as this anticyclone can be easily traced to at least the stratopause, although in some cases they exhibit considerable vertical slope within the layer from 20 to 55 km. A limited number of synoptic charts up to 70 km (Warnecke and Nordberg, ref. 73) indicate that the large-scale systems persist even beyond that altitude. Figure 7c depicts a disturbed situation in which the anticyclone has moved over the polar region. This modification was related to the passage of a warm pool of air, evident mainly at 100 to 30 mb, from the North Pacific across Canada and onto Europe.

Rocket observations taken in the Southern Hemisphere indicate that the seasonal variations are similar to those in the Northern Hemisphere. Especially interesting observational series are those taken in the Antarctic in 1962-63, which indicated a stratospheric warming in mid-winter (Quiroz, ref. 74; Julian, ref. 75); and those taken during the NASA Mobile Launch Expedition aboard the USNS Croatan in 1965. Croatan rocketsonde data obtained between the 70th and 80th meridians from the equator to 60°S have been studied in relation to comparable data (from map analyses) for the Northern Hemisphere (Finger and Woolf, ref. 76). The upper stratospheric circulation for the early autumn season of both hemispheres was found to behave in a similar manner, although the circulation of the Southern Hemisphere was more intense. This finding is consistent with the concept of a more intense stratospheric polar cyclone in the Southern Hemisphere, advanced by Wexler (ref. 77).

In equatorial latitudes a complex circulation regime occurs, marked by a semi-annual alternation of easterlies (January, July) with westerlies (April, October) in the upper stratosphere (Reed, ref. 78; Quiroz and Miller,
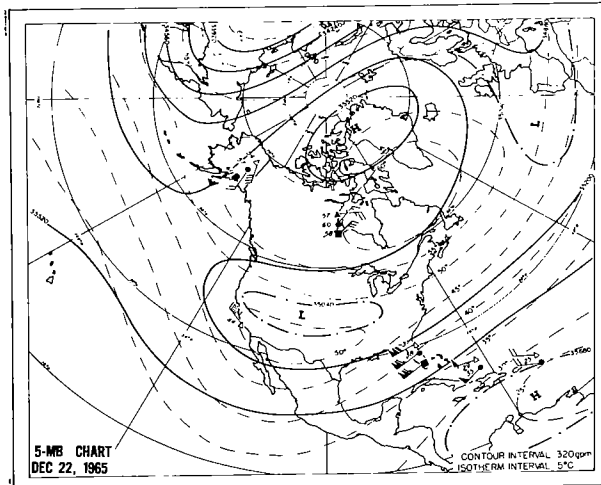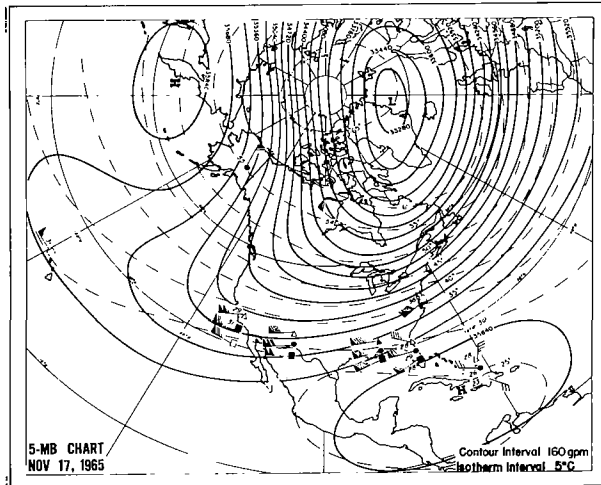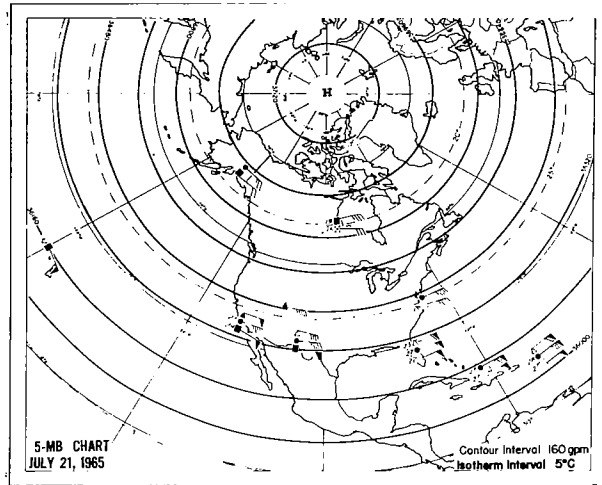
Figure 7. (a) Typical synoptic situation at 5 mb in summer (top), and (b) in winter (middle); and (c) disturbed situation in winter (bottom).

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ref. 79); and a puzzling and much-discussed alternation of easterlies with westerlies, in the lower and middle stratosphere, with period of about 26 months (Reed, ref. 80). The equatorial cycles have been studied with data for individual rocket stations; improvements in the tropical observing network will make it possible to extend rocket-level maps across the equator and perhaps to gain significant new information concerning the detailed structure of these cycles.

Possibly the most important distinction between winter and summer, throughout the upper stratosphere and lower mesosphere, is the much greater synoptic variability in winter, as evidenced by traces of the height and temperature of various pressure surfaces in 1964-65, over Fort Churchill, Canada (Figure 8). Although many of the wintertime oscillations at one level have their counterpart at other levels, situations may occur with disparate trends. For such cases, single-station analysis suggests the transition from one form of pressure system to another above the station. The synoptic maps often reveal, however, that the dominant effect is one of pressure systems sloping with height, retaining their identity to high levels.

The synoptic maps are particularly well suited for the study of stratospheric warmings in winter. Warmings of major proportions, such as occurred in January of 1957, 1958, 1963, and in late December 1967, have far-reaching effects on the fields of density, pressure, and flow. Rocketsonde data, used either in synoptic analyses or in time and space cross-sections, are becoming a particularly valuable tool for the study of such warmings. The first use of synoptically analyzed data was in connection with the major warming of January 1963 (Finger and Teweles, ref. 82). The analysis leaves no doubt that a deep layer was affected, from the tropopause up to at least the lower mesosphere.[5] The data for this event, together with limited rocket data available for other warming periods, suggest that the maximum amplitude of warming occurs near 45 km. The event of late December 1967 is now being studied with the benefit of a larger sample of data than has heretofore been available, and the results of this study it is believed will be of considerable interest.

Warmings of lesser amplitude have occurred more often. One such case can be perceived in late February 1964 in Figure 8. Maximum amplitude of the temperature wave appears to occur at the 5- to 2-mb levels, while maximum amplitude of the pressure wave is indicated at some higher altitude (the height of the 0.4-mb pressure surface rises from approximately 52 km

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[5]
    Jones et al. (ref. 83) presented falling-sphere data indicating a density increase at Ft. Churchill by nearly a factor of 2, in connection with the warming of January 1958, at altitudes at least up to 80 km.
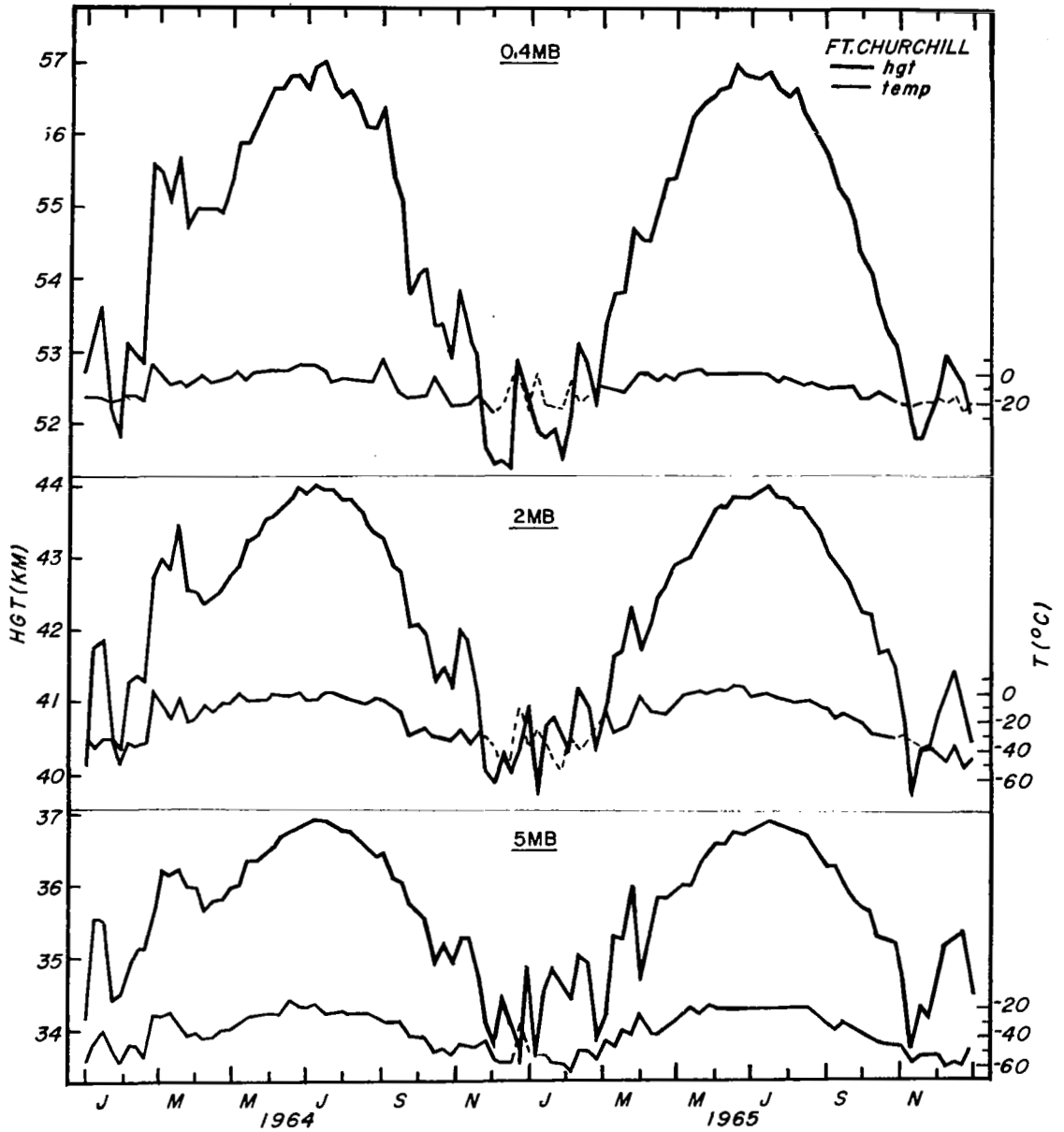
Figure 8.  Time-sections of height and temperature of indicated pressure surfaces over Churchill (59°N) (adapted from Johnson and Gelman, ref. 81).

to nearly 56 km). This warming was of the single-source variety, having developed entirely from the relatively warm anticyclone of the Aleutian region, in distinction to the classical mid-winter type of warming. (The latter is typified by a splitting of the polar vortex, with anticyclones from the North Atlantic and Aleutian-Siberian area rapidly intensifying and merging over the polar area.). The evolving structure of this single-source case in 1964 is well delineated in the rocket-level synoptic charts. These maps show the anticyclone sloping poleward with height. At 5 mb a temperature increase by 50 °C occurred over west Greenland from February 19 to March 4. By late March, the anticyclone was situated over the pole at all levels analyzed, down to 10 mb, with an easterly circulation having replaced the normal westerly circulation of winter as far south as the Mexican border.

Stratospheric warmings, whose physical origin remains unclear, are of interest for a number of reasons. Perhaps the most important one is the possibility of a relationship with the lower-level circulation. For example, Julian and Labitzke (ref. 84) suggest that blocking at tropospheric levels was connected with the onset of the 1963 mid-winter warming.

Ionospheric physicists are particularly interested in the phenomenon because of a possible relationship with large increases in the electron concentration of the D- and E-regions (e.g., Belrose, ref. 85). Their investigations to date have been generally hampered by the lack of comparable ground-based radio measurements and upper air meteorological data. The body of data being developed from the high-level synoptic maps should aid greatly in the pursuit of meaningful relationships.

An important parameter with regard to the electron density changes is the neutral density, upon which the electron production depends. Maps of the neutral density at constant height (30, 40 km) have been derived from the rocket-level constant-pressure analyses mentioned above (Quiroz, ref. 86). These show remarkably large geographical variations of the density in winter. Figure 9, for example, indicates a density 40% below standard over Greenland on January 6, 1965, increasing to 15% above standard over Kamchatka, at 40 km. A case of stratospheric warming would be particularly interesting, since on the basis of observational evidence and in accordance with the physical reasoning of the preceding section, a large density increase would be expected in the mesosphere (in the D-region) in association with a large temperature increase in the upper stratosphere.

Synoptic maps at mesospheric levels would thus be of considerable value. Their construction would not only require improved observational coverage above the ceiling of current MRN data but would also involve certain problems not encountered at the lower levels. An example of these problems is the isolation of diurnal variations, whose amplitude is expected to increase with
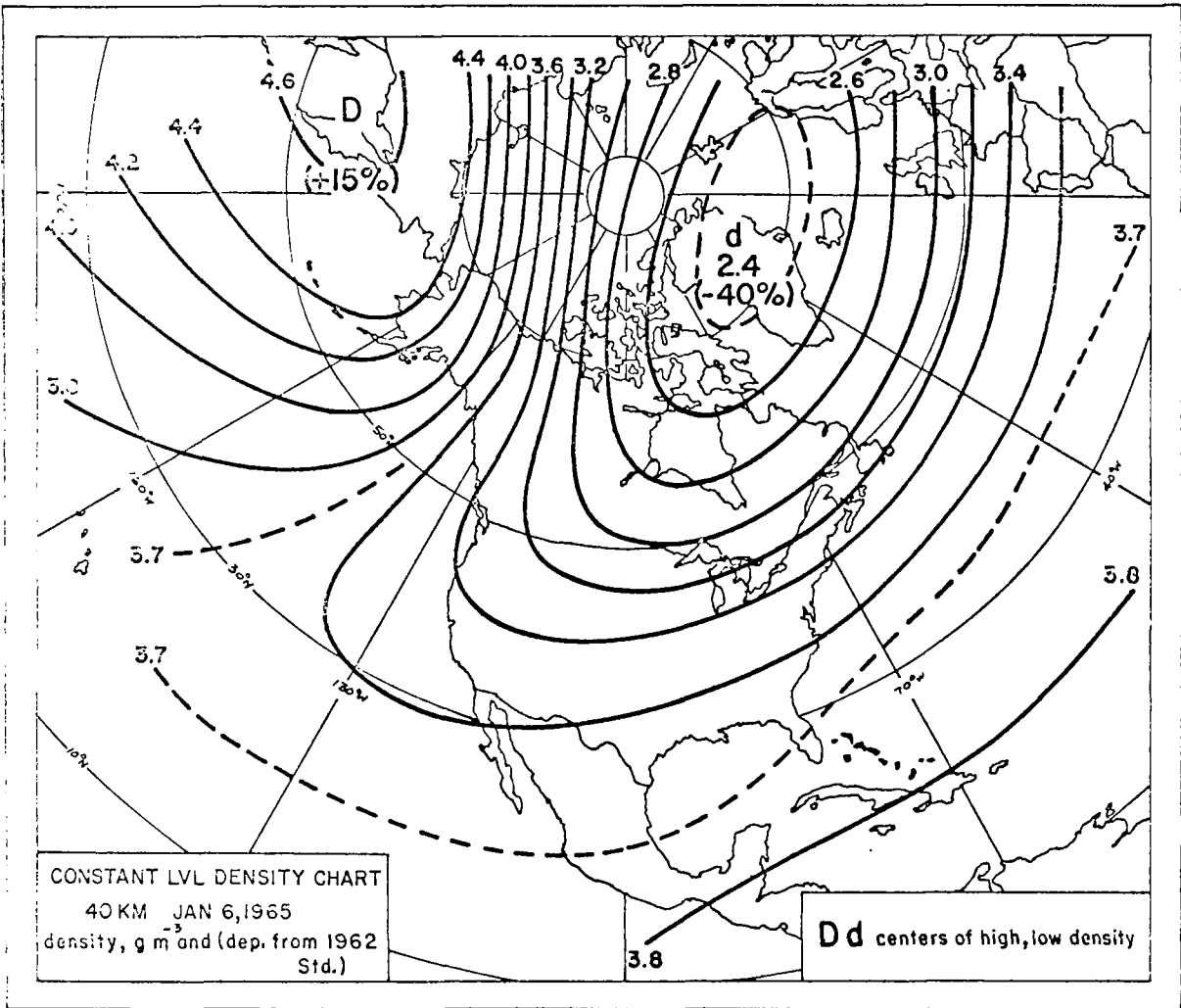
Figure 9. Constant-height density map, 40 km, Jan. 6, 1965 (from Quiroz, ref. 86).

CONSTANT LVL DENSITY CHART
40 KM    JAN 6, 1965
density, g m$^{-3}$ and (dep. from 1962 Std.)

D d centers of high, low density

D (+15%)

d 2.4 (-40%)

Contour values: 4.6, 4.4, 4.2, 4.4, 4.0, 3.6, 3.2, 2.8, 2.6, 3.0, 3.4, 3.7, 3.8, 3.7, 3.7

height (though not monotonically) (Lindzen, ref. 87).

Kellogg (ref. 88) has pointed out that a high-resolution observing network would be required above 70 km in order to separate out the various scales of motion and structure. The conventional synoptic network approach is valid, he believes, up to 70 km. Such a network he regards as essential to conduct studies of the role of the large-scale baroclinic eddies in transporting energy and momentun.

## Knowledge of Diurnal Variations

Earlier it was indicated that although the observational results from meteorological rockets have served well to delineate the gross atmospheric features, error in the observations has made it difficult to determine the small-scale variations in time and space. Thus numerous, specially-designed experiments have had to be conducted in an effort to determine, e.g., the diurnal variation of temperature and wind. Groves (ref. 89) has given a comprehensive account of both theoretical solutions and observational evidence for the magnitude and phase of diurnal and semi-diurnal variations, as a function of height. Table 10 (patterned after a similar table by Groves) lists rocket experiments designed to reveal information on diurnal variations. From theory and at least on the basis of meteor observations (these have provided information most plentifully at about 90-100 km), the amplitude of diurnal variations is expected to increase significantly with height. Near 95 km the meteor data indicate diurnal wind variations involving tens of m sec$^{-1}$ and density variations whose range may exceed 30% of the mean density. At radiosonde levels (below 30 km) the free-air diurnal variations of temperature, density, and wind have been estimated at less than 2°C, 2%, 2 m sec$^{-1}$, respectively. Thus there is understandable concern for measuring these variations at intermediate rocket levels. According to the theoretical work of Lindzen (ref. 87), phase and magnitude are strongly latitude-dependent. Thus both the complex structure of diurnal variations, together with the need for isolating observational error, may explain why only partial success has been obtained in past observational studies.

A critical factor is the time period over which measurements are taken. Over a sufficiently long period (at least a few days) synoptic trends can be subtracted out; over even longer periods, synoptic variations can be averaged out and lunar gravitational influence, if significant, can be minimized. The cost of rocket series sustained over many days and involving frequent launchings per day is, however, prohibitive. Thus experimenters have sometimes chosen brief time periods or periods near the equinoxes with the object of minimizing synoptic influences. However, irregular variations are still encountered, possibly due to observational error and/or associated with

TABLE 10.  Multiple Rocket Launches for Diurnal Sampling Below 100 Km[a]

| Date | Launch Site | Altitude Range, Km | Sounding Technique | Successful Launchings | Reference |
|---|---|---|---|---|---|
| 1961 May 9-10 | Eglin AFB, Fla. | 35-65 | ROBIN sphere | 23 in 23 hours | Lenhard, ref. 90 |
| 1963 Oct 15-16 | Woomera | 30-80 | grenade | 4 in 10 hours | Groves, ref. 91 |
| 1964 Feb 7-8 | White Sands | 30-60 | parachute, thermistor | 12 in 24 hours | Beyers and Miers, ref. 92, 99 |
| Nov 21-22 | White Sands | 30-60 | parachute, thermistor | 12 in 24 hours | Miers, ref. 93 |
| 1965 Apr 29-30 | Woomera | 30-85 | grenade | 5 in 7 hours | Groves, ref. 94 |
| May 10-11 | Carnarvon | 40-95 | sphere | 8 in 21 hours | Rofe et al., ref. 95 |
| Jun 30- Jul 2 | White Sands | 40-60 | parachute, thermistor | 16 in 51 hours | Beyers et al., ref. 96; Thiele, ref. 97 |
| Sept 8-9 | Wallops I. | 30-50 | parachute, thermistor | 16 in 39 hours | Finger and Woolf, ref. 49 |
| Oct 9-11 | White Sands | 30-60 | parachute, thermistor | 12 in 24 hours | Thiele, ref. 97 |
| 1966 Apr 11-13 | Ascension I. | 30-60 | parachute, thermistor | 24 in 48 hours | Beyers and Miers, ref.98 |
| 1967 Jan 31- Feb 1 | Pt. Barrow | 35-95 | grenade | 6 in 15 hours | Smith et al., ref. 50 |
| Dec 13-15 | C. Kennedy, Fla. | 30-60 | parachute, thermistor (long lead-wire) | 25 in 3 days | unpublished |

[a]
This table brings up to date a similar table compiled by Groves, ref. 89.

gravity waves with periods of hours or minutes.

Despite all these difficulties a roughly coherent picture is emerging. In Figures 10-12 the results of various research efforts have been pieced together to represent the indicated amplitude of the diurnal variation of temperature and wind (meridional component). Similar analyses are given by Groves for the semidiurnal component (generally smaller) and for zonal winds, and also for the corresponding phases.

The major problem revealed in these figures is believed to be the apparent discrepancy between observational estimates of the temperature variation and theoretical calculations such as those of Lindzen. To illustrate, much of the observational data for 45 km indicate a diurnal amplitude in the neighborhood of 5 °C (range 10 °C), in contrast to a theoretical value of less than 2 °C. The possibility that the rocket observations are strongly influenced by radiational error has been considered, but general agreement on the magnitude of radiation effects has not been reached. The estimates of Wagner and others, reviewed by Ballard and mentioned earlier in this report, are not sufficiently large to explain the difference between the observed and theoretical amplitudes. The results from the more recent series of rocket observations at White Sands (October 1965) and Ascension Island (April 1966) (Beyers and Miers, ref. 98), indicate slightly reduced amplitudes above 50 km, in comparison with the earlier findings at White Sands. Above 50 km, these newer results appear to approach the values of Lindzen, but at 40-50 km large differences persist. The solution to this important problem must therefore await further investigation.

Observational evidence for the magnitude and phase of the diurnal variation of pressure and density is sparse at 30 to 90 km. The meteor results suggest rather large amplitudes for the density variation in the vicinity of 95 km, although the low accuracy of determination leaves the results open to further interpretation. Jones and Peterson (ref. 51) have deduced a somewhat smaller amplitude at 80 to 100 km, on the basis of only four pairs of day-night sphere soundings. The structure indicated by these soundings is highly variable, and more sampling is clearly needed. A consistent model for the pressure, density, and temperature variations is needed, but real progress will require resolution of the above-mentioned disparity between the observed and theoretical temperature variations.
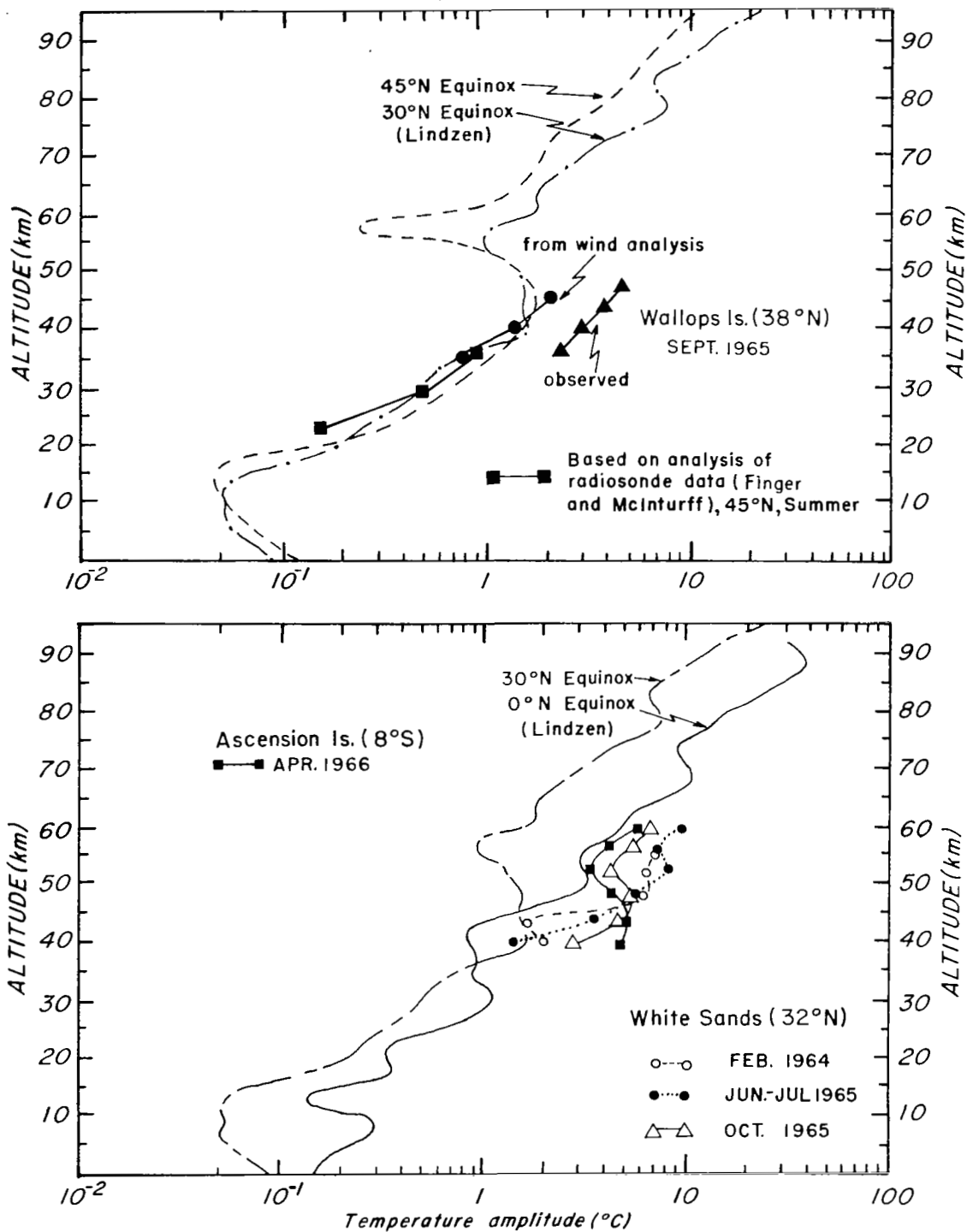
Figure 10. Amplitude of diurnal temperature variation. Theoretical results according to Lindzen, ref. 87. Observational results from Finger and Woolf, ref. 49, and Finger and McInturff, ref. 100 (upper diagram); and from Beyers and Miers, ref. 98, etc. (lower diagram).
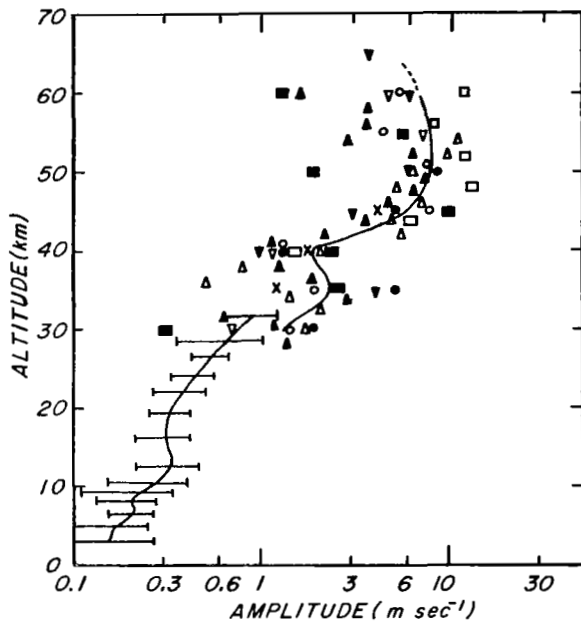
42

Figure 11.  Observational evidence from rockets and balloons for diurnal variation of meridional (N-S) wind (from Groves, ref. 89).

| CODE FOR FIGURE | REFERENCE |
|---|---|
| △ White Sands, summer (grouped data) | Reed et al., ref. 19 |
| ▽ 11 stations near 30°lat., summer | Groves, ref. 94 |
| □ White Sands, 30 Jun-2 Jul 65 | Beyers et al., ref. 96. |
| ○ Eglin, 9-10 May 61 | Miers, ref. 93; Lenhard, ref. 90 |
| ▼ Carnarvon, 10-11 May 65 | Rofe et al., ref. 95 |
| ■ White Sands, 7-8 Feb 64 | Miers, ref. 93 |
| ● White Sands, 21-22 Nov. 64 | Miers, ref. 93 |
| ▲ Ascension I., annual | Reed et al., ref. 19 |
| ⊢⊣ 8 stations (balloon data), averages with std. deviations | Harris et al., ref. 101 |
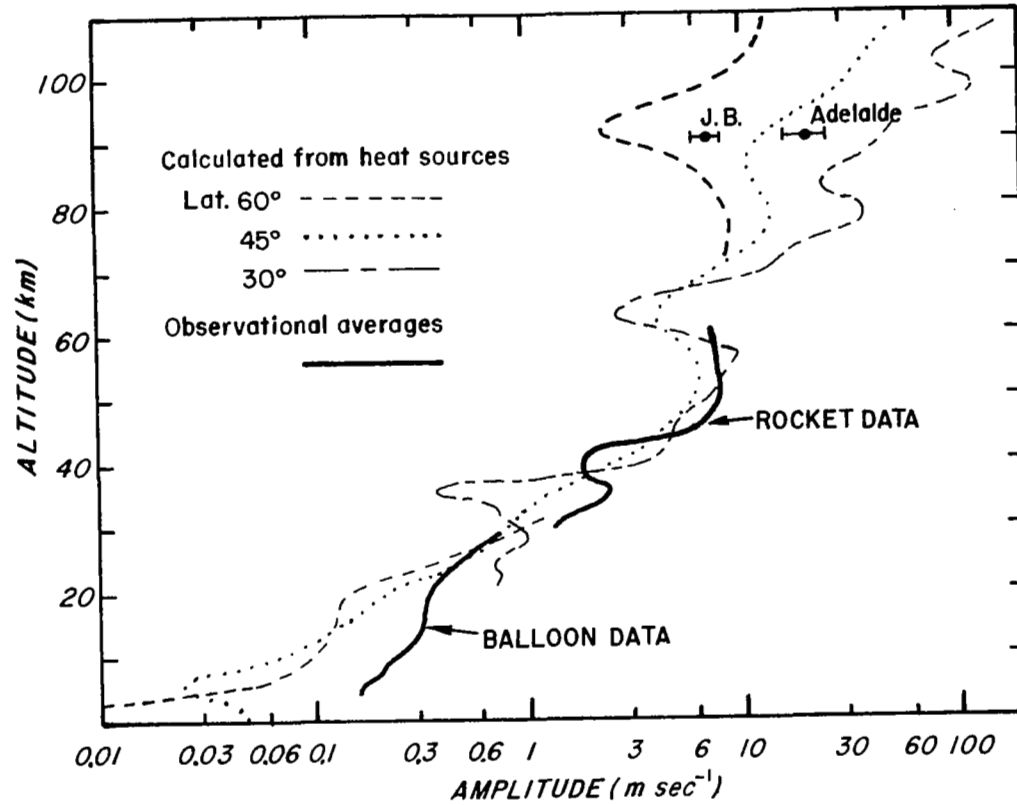
Figure 12. Observational evidence of diurnal variation of meridional (N-S) wind compared with theoretical curves of Lindzen (ref. 87). From Groves, ref. 89. Solid curves were fitted by Groves to observational data in preceding figure. Estimates from meteor observations at Jodrell Bank (53°N) and Adelaide (35°S) are entered near 90 km.

## Small-Scale Variation

In recent years there has been a surge of interest in small-scale wave-like features indicated in the rocket data profiles. These features are of at least three-fold importance: (a) the perturbations may provide an effective mechanism for energy transfer in the middle atmosphere and to the thermosphere; (b) at sufficiently high altitudes they are expected to provide a major component of the overall atmospheric variability; and (c) analysis of the data profiles can be done with greater confidence only when all scales of motion and their effects are considered.

Hines (ref. 102) and others have shown that the middle atmosphere is capable of sustaining a family of waves of the acoustic-gravity type. Consequently, most analyses and discussions of the small-scale features have been within the "wave" concept. To date, however, the wave theories have neither been proved nor disproved by observation.

One reason for this failure to authenticate the theories concerns the inadequacy of the available observations. Data on three parameters are required: the horizontal wavelength, vertical wavelength, and temporal frequency. While the vertical wavelength can be investigated in a single sounding, a study of the three variables requires a complicated and expensive experiment with adequate resolution in time and space. A second reason, and perhaps the more serious is that, to date, there is no consensus of opinion on the best way to treat the data statistically to arrive at the desired result (e.g., Lettau, ref. 103; Webb, ref. 104; Mahoney and Boer, ref. 105; Miller et al., ref. 43; Greenhow and Neufeld, ref. 106). Clearly, objective methods are needed to resolve the wavelength spectrum.

In this new field of investigation, questions have been appearing faster than they can be answered; yet there is hope that the various results being obtained will ultimately fall into a meaningful, even though complex, pattern.

## SOME ATMOSPHERIC PROBLEMS AT 60-120 KM

In the preceding section we have alluded to some of the problems above 60 km which remain essentially unsolved. In some cases theory has been advanced farther than observations and in other cases the opposite is true. In general, there is no doubt that adequate observational samples are needed to corroborate certain theories or better define their range of applicability in the atmosphere. From the standpoint of observation, both the experimental and synoptic approaches are needed. The former is geared to test a hypothesis or model and may involve rocket soundings at close intervals in time and space.

The latter typically involves a relatively coarse observational grid over a large area. Both require many observations, which calls for the design of an economical and accurate technique of measurement.

The importance of problems above 60 km lies not only in the need for improved knowledge of the structure and circulation of the middle atmosphere itself, but also derives from the possibilities for interaction (1) with other height domains of the atmosphere, and (2) with vehicles traversing the middle and the upper atmosphere.

With regard to the latter, a realistic survey of atmospheric effects on aerospace vehicles would show that the majority of the known problems involve the atmosphere below 60 km. Measurements to 100 km and above are generally desirable, but it remains to be shown that there are real engineering requirements for data above 60 km. These exist, though they do not appear to be numerous. An example of a real requirement is the need for realistic density distributions along the trajectory of reentry vehicles, for use in evaluating the aerodynamic heating. (Other reentry trajectory problems occur at lower altitudes.) For certain vehicles the neighborhood of the mesopause ($\sim$80 km) is critical, as here large vertical density gradients are expected in association with low temperature and temperature inversion. For lifting reentry vehicles with an oscillating quasi-horizontal trajectory through the lower mesosphere, horizontal gradients of the density are important (Quiroz, ref. 86). A problem requiring knowledge of the density structure below 200 km is satellite orbital decay and impact prediction. The remaining lifetime of a satellite in the last days and hours of its history has been shown to be a function of the density of the lower thermosphere (Gazley, Rowell, and Schilling, ref. 107); and Schilling (ref. 108) has re-emphasized that the density structure must be known with high accuracy in order to obtain successful predications. A related problem, of concern especially to the Air Force, is the prediction of the orbital position of certain satellites, for which recourse is made to existing thermospheric models. These models for the most part have been based on a fixed boundary condition at 120 km. This assumption is unrealistic, since significant variability is expected on the basis of past observations reaching 120 km, and on the basis of the temperature profiles observed in the upper mesosphere, which if interpreted hydrostatically, would suggest appreciable variability of the pressure and density in the lower thermosphere. The effects on vehicles of wind shear and turbulence and of particle concentrations occurring, for example, in noctilucent clouds, are not yet known (for the heights under consideration). Arguments concerning these effects are reviewed by Sissenwine (ref. 3).

Problems of a purely meteorological nature are numerous. Those discussed below are but a few from the total complex of problems emerging from consideration of the compositional changes and neutral-ion interactions of the lower thermosphere. A more comprehensive account is available in the

Proceedings of the AMS Symposium on Meteorological Investigations Above 70 Km (Quiroz, ed., ref. 109).


## The Temperature Gradient Reversal near 65 km


The reversal of the horizontal temperature gradient at about 60-65 km is one of the principal problems of the meteorology of the middle atmosphere. The mesosphere above 65 km is warm in winter near the pole in the presence of radiative cooling, while in summer with constant sunlight the upper mesosphere is cold. A number of theories seeking to explain this paradox have been presented. As emphasized by Newell (ref. 64), "atmospheric motions and temperature changes produced by adiabatic compression and expansion must be introduced to provide a proper explanation of the temper-ature patterns." The role of the meridional circulation, with sinking over the polar regions in winter and rising motion in summer, appears vital. Large-scale subsidence, together with chemical heating from the recombination of atomic oxygen dissociated at higher altitudes, was proposed by Kellogg (ref. 110) to account for the warm winter pole. Both Newell (ref. 111) and Leovy (ref. 112) have suggested a counter-gradient heat flux; Newell indicates this could be achieved as a result of dynamically-driven large-scale eddies and Leovy has demonstrated that the expected temperature pattern could arise from radiatively-driven mean meridional motions. The relative contribution of the large-scale eddies cannot be ascertained with confidence, Leovy suggests, until a "good distribution of [rocket] observations with time of day" is available. This is particularly true above 60 km, where observational coverage in a "network" sense has not been achieved.


## Vertical Motion Determination


A closely allied problem is the determination of the height profile of vertical motion. If the vertical motion could be determined accurately by observation, it is believed much of the theoretical work on the middle atmo-sphere could be accelerated, including the explanation of the seasonal temp-erature patterns. Further specific examples of the importance of the vertical motion are:

(1) In the absence of photo-chemical equilibrium, vertical (and meridional) motion is invoked to explain the observed <u>ozone concentration.</u> Quantitative evaluation is needed of the subsidence process, by which a high ozone concentration is believed to be imparted to the lower stratosphere at high latitudes in winter, culminating in a springtime maximum.

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(2) Likewise, a numerical measure is needed of subsidence into the upper mesosphere, which in winter might lead to chemical heating by the recombination of atomic oxygen.

(3) The sustenance of noctilucent cloud particles within a few kilometers of the mesopause has been postulated to depend on the occurrence of sufficient upward motion (Charlson, ref. 113).

(4) The derivation of density data from the atmospheric drag on falling spheres may be affected by the prevailing vertical motion, commonly assumed to be zero. Kern and Rapp (ref. 114) have carried out an analysis indicating that neglect of the vertical motions exceeding a few cm sec$^{-1}$ may result in significant errors in the density.

Vertical motion is difficult to measure anywhere in the atmosphere. Indirect estimates based on the adiabatic vertical motion equation have yielded values in the lower and middle stratosphere of generally less than 2 cm sec$^{-1}$ (Miller, ref. 115; Kays and Craig, ref. 116). At much higher altitudes surprisingly large values have been deduced from observation of rocket grenade gas clouds (Groves, ref. 117), about 10 m sec$^{-1}$; and from clouds of chemicals ejected from rockets at 100-110 km, -5 to +15 m sec$^{-1}$. It is possible that these large motions are highly localized, in analogy with updrafts in thunderstorms, which may reach 10 m sec$^{-1}$ or more. If on the other hand these values are indeed representative of the large-scale field of vertical motion, then among other things the acceleration term, dw/dt, in the vertical equation of motion may have unsuspected importance. In other words, some reservation should accompany the assumption of hydrostatic equilibrium until better knowledge of mesospheric vertical motions is available.

## Inter-Level Relationships

Equation (2), on the basis of assumed hydrostatic equilibrium, predicts that large temperature changes at some altitude should result in large density changes at a higher altitude separated by substantially more than a scale-height. Quiroz and Miller (ref. 66) found from rocket observations that the correlation between the density and the temperature actually was highest for separations of about 2.5 scale-heights. Thus it is of interest to evaluate mesospheric structural changes relatable to temperature changes in the stratosphere. Vivid evidence of stratospheric influence on the mesosphere is available in the case of major stratospheric warmings. The density structure of the lower thermosphere, similarly, can be studied in relation to the temperature variability of the mesosphere.

Inter-level comparisons are statistically possible provided adequate data samples are available, and clearly the observational coverage above 60-70 km is still unsatisfactory in many respects, emphasizing the need for an economical, easily repeatable measuring technique. The status of availability of data on the neutral density in the highly important region, 90-120 km, in particular, will be discussed as a separate problem below.

Increased understanding of inter-level relationships is possible from further study of the hydrostatic assumption. The relationship given in Equation (2) was derived assuming a constant lapse rate. This is an unrealistic condition for the analysis of very deep layers with marked lapse rate changes such as occur at the stratopause and mesopause and in the high-latitude mesosphere in winter. Thus a generalization of Equation (2) is needed to aid in the analysis of layers with complex thermal structures.

Density Distribution in the Lower Thermosphere (90-120 km)

A persisting problem is the delineation of the density structure of the lower thermosphere, which as mentioned earlier is relevant to the generation of thermospheric models and also is of vital importance in satellite reentry prediction. Two things may be said at once: (1) the available density soundings are still few; and (2) the accuracy of measurement is low. Despite these limitations, a model of the density structure in this region has been constructed (U.S. Standard Atmosphere Supplements, 1966) which neatly stratifies winter (high density) and summer (low density) conditions. This basic pattern is also indicated in our Figure 4 and is in hydrostatic agreement with the reversal of the temperature gradient lower down at about 65 km. Two qualifications are appropriate: (1) the actual density soundings available above 90 km do not consistently follow this pattern: some wintertime soundings show rather low density, with differences from the average winter values which greatly exceed the estimated observational error; and (2) the wintertime temperature structure of the upper mesosphere is itself highly variable, which suggests that the density structure for the lower mesosphere may be more complex than has been assumed. Moreover, stratospheric influence appears to be possible even to these altitudes. Thus there is great need for better observational sampling of this region, preferably in coordination with other measurements down to radiosonde heights. The possibility of large diurnal variations is, of course, a complicating factor which must be taken into account in any analysis of the data.

## Tidal and Small-Scale Oscillations

The state of research on small-scale oscillations has been discussed earlier in this report. There is clearly a need for further experimental and theoretical work. The optimum spacing in time and distance of soundings required to observe the oscillations has been the topic of much discussion, particularly during 1967-68. A valuable survey of opinion has been made by Lindzen (ref. 118).

The importance of these oscillations is not limited to the description of the phenomena. At high altitudes, tidal variations are a large part of the overall atmospheric variations and must therefore be taken into account in a variety of practical problems. Internal gravity waves are an example of small-scale oscillations, although their vertical and horizontal wavelengths may be as much as several km and several hundred km, respectively, in the mesosphere and lower thermosphere. As Lindzen points out, tides and gravity waves are often physically similar systems, but their differing periods permit, or may require, a different observational approach. Observation of the gravity waves is especially difficult because in general one may expect to find gravity waves of different periods and wavelengths coexisting.

Whether or not ideal experiments can be designed for the definitive measurement of tidal and gravity waves, it is clear that economical measuring techniques are needed, since many measurements are required. There is some hope that gun-probe measurements of the wind will prove of value. A system for observing ionized meteor trails has been developed in France (Spizzichino, ref. 119) which can continuously monitor the horizontal wind between 80 and 110 km with a $\pm 1$ km height resolution and a 5-15 minute time resolution. Barnes (ref. 120), who has reviewed radar observing capabilities for meteor observatories in various world locations, is less optimistic, citing at best a height resolution of $\pm$ 2 km. He is of the opinion that radar meteor trail observations will be useful for synoptic and tidal studies, but only partially useful for observing gravity waves. In any case, the meteor population is such that good observations of the wind are expected only at 80-120 km. The determination of atmospheric density from meteor radar trails is less reliable, but this matter continues to be pursued.

These remarks thus re-emphasize the need for reliable rocket soundings above routinely achieved altitudes. Whether an economical and reliable technique can be found that gives the desired measurements remains to be seen.

# SUMMARY AND JUSTIFICATION OF OBSERVATION AND ANALYSIS PROGRAM FOR 60-120 KM

A meteorological rocket sounding has been defined herein as one carried out by an easily repeatable technique, providing measurements of neutral atmospheric properties, primarily the temperature, pressure, density, and motion. Only the total mass density has been considered in this report, although high-altitude data are clearly needed for at least two important constituents, ozone and water vapor.

Meteorological rocket soundings have further been distinguished as "routine" or "special," according to relative cost and ease of data reduction. Routine soundings at present involve a basic expenditure per sounding ranging from a few hundred dollars to about $2,500. By the end of 1966, close to 30 rocket stations had launched rockets repetitively, resulting in nearly 8,000 routine observations. The bulk of the data, however, were obtained at less than a dozen stations. Less than half of the observations included temperature, nearly all gave wind data. Pressure and density were derived by hydrostatic integration for most of the temperature soundings. The pressure was measured directly and routinely in Soviet meteorological rocket soundings; in the United States pressure gages with small rockets have been used only experimentally. With regard to requirements for synoptic analysis, it is pertinent that only 21% of the total soundings were obtained north of 40°N.

The maximum altitude of reliable data in the routine soundings is typically within 10 km of 60 km. Accuracies cannot be stated simply, since they depend on so many factors, discussed in the text. Wind errors typically fall in the range 3-10 mps. Fine-scale reduction of precision-radar data may result in greater accuracy. Thermistor measurements of the temperature have been judged to be accurate within a few degrees up to 50-55 km. The greatest error source is believed to be aerodynamic heating of a descending sensor, which is strongly variable from one firing to another. A standard correction applicable to all firings therefore does not appear attainable at present.

Although the number of "special" soundings obtained (grenade, sphere, etc.) is an order of magnitude less, and the observational error sometimes greater, these soundings nevertheless constitute the main body of observational data on which our recent knowledge of the mesospheric neutral structure is based. (In combination with meteor trail observations and chemical trail experiments, they make up the main part of the observational basis for knowledge of the neutral mesosphere and lower thermosphere.) Their relatively high cost, however, makes them prohibitive for routine meteorological use and an economical and reliable sensing technique is needed for measurements to the vicinity of 100-120 km.

The broad results obtained from both routine and special soundings were indicated as hydrostatically and dynamically consistent. Much of the large-scale variability and certainly the small-scale features have yet to be explained satisfactorily, even with the knowledge gained from theoretical and observational studies of the past few years. Stratospheric warmings in winter, whose origin has not yet been established, and diurnal variations at high altitudes are expected to constitute a large part of the variability. Further progress in describing the warmings four-dimensionally (x, y, p, t) has been made with the aid of periodic synoptic analyses to levels in the lower mesosphere, made possible through improvements in the observational coverage by rockets.

A strong need exists for systematic observation and analysis at 60-120 km, above routinely achieved altitudes. Practical justification for a systematic program hinges on requirements for reentry analysis and on the relevance of this region to the thermospheric structure, which has clearly demonstrable effects on orbiting satellites. Another practical consideration is the influence of stratospheric and mesospheric activity on ionospheric radiowave absorption, a subject currently under investigation.

Justification on purely meteorological grounds is based on urgent requirements for solutions to several atmospheric problems. These include:

(1) Explanation of the temperature gradient reversal near 65 km; in particular, explanation of the process leading to a warm polar region in winter above 65 km.

(2) Description of the complete vertical structure of "stratospheric" warmings.

(3) Determination of magnitude and phase of tidal oscillations.

(4) Resolution of the small-scale wave structure.

(5) Improvement of the knowledge of the atmospheric density distribution near the base of the thermosphere.

(6) Determination of the extent of interaction between the middle atmosphere and the troposphere and thermosphere.

# GENERAL REMARKS ON OBSERVATIONAL REQUIREMENTS

Elaborate schedules of observations can be planned to satisfy a variety of needs. Such planning, however, should not detract from the pressing task of finding a suitable observational technique or techniques. Since it does not appear likely that a highly economical and accurate sounding method will be found in the immediate future, the concept of a variable observational schedule should be introduced in the interest of economy. Evidence is available that the atmosphere is synoptically calm in summer to near the mesopause, in contrast to winter. Thus for synoptic requirements relatively infrequent observations are needed in summer.

In general, the observations are needed on three scales: synoptic scale, small-scale (time) and small-scale (space). These would involve, respectively, (1) routine soundings at an adequate number of stations equitably distributed in latitude and longitude, (2) special series of soundings closely spaced in time to gain a better knowledge of tidal (e.g., diurnal) oscillations, and (3) special series of soundings closely spaced geographically to gain better knowledge of small-scale wave structure in the atmosphere. Remarks on these requirements follow.

## Synoptic Requirements

On the basis of the experience of the Upper Air Branch, National Meteorological Center, it appears that a grid separation of about 1500 km between observing sites would provide a minimum acceptable coverage for synoptic analysis at rocket altitudes. Present high-latitude reporting sites (Greely, Churchill, Thule, West Geirinish) are separated by more than 2300 km. The strategic placement of 2-3 additional sites in high latitudes and the regular receipt of rocket reports from the key Soviet station at Heiss Island would add immeasurably to the value of the rocket network. In low latitudes there are small separations between some pairs of missile sites (Pt. Mugu-White Sands, Wallops I.-Cape Kennedy), of the order of 1200 km, but of course large gaps exist in other areas. Again, the addition of 2-3 strategically placed sites would greatly enhance the synoptic network. The expense of soundings at these additional sites could possibly be offset by intelligent reduction of the frequency of rocket firings at certain sites, to perhaps at 10-day intervals in summer (May 15-September 15) and at 5-day intervals in the rest of the year. Such an austere program, however, would be fully rewarding only if successful soundings were assured from all sites, as the result of a strictly coordinated effort. Such a program would not preclude the taking of other observations during special events such as stratospheric warmings.

It is also pertinent to note increasing interest (Newell and Dickinson, ref. 121) in the concept of a global system for simultaneous measurement of the wind at several meteor observatories. Such a system, with proper implementation, would have the capability of delineating the basic flow in the vicinity of 100 km and might further permit the resolution of planetary-scale motions and tides and gravity waves.

## Requirements for Small-Scale Analysis

Closely-spaced observations taken in special series, at more than one latitude and more than one season, will be valuable per se, i.e., for what they may reveal about sub-synoptic structures. At altitudes above 70 km particularly, the results will be needed to apply diurnal and other corrections to observational data used in synoptic analysis. Attention has been called to the numerous diurnal experiments already conducted, and to the prevailing differences among the observational sets and with theory. The need for a sustained, cooperative experiment cannot be overemphasized.

For determination of the first (diurnal) and second (semidiurnal) harmonics in tidal oscillations, at least five observations per day are needed (Haurwitz, ref. 122). Earlier we stressed the requirement for a sufficiently long period of observation, at least several days. Haurwitz indicates it is impossible to predict the length of time required for satisfactory determinations, suggesting that a given experiment might be continued until the error associated with daily fluctuations is determined to be small in comparison with the amplitudes.

For the observation of gravity waves with periods on the order of 100 minutes, data will be needed with time resolution on the order of 20 minutes (Lindzen, ref. 118); vertical resolution of about one kilometer or less and horizontal resolution on the order of less than 10 to 100 km will be needed. In rocket experiments, a strong capability for closely-spaced measurements can be realized through the planned variation of launching azimuth and elevation angles at a single launch site.

## Parameters and Desired Accuracies

With regard to the parameters to be measured, it is clear that the motion and at least one equation-of-state variable ($T$, $\rho$, $p$) are needed, along with rawinsonde data up to the rocketsonde base level, to complete the profiles of all the required data. If nearly simultaneous rawinsonde data are not obtained, then two of the equation-of-state variables should be measured. In view of the importance of the vertical component of motion, means of determining it should be investigated.

With regard to the desirable accuracy of measurement, it is believed that pressures and densities measured within a 3% error below 50 km and within a 5% error above 50 km will be acceptable for most purposes. The larger value is based on a value of 5% that has been considered tolerable for certain operational requirements, and also on the principle of a nearly constant ratio of error to overall variability (pressure and density have generally greater variability in the mesosphere than in the stratosphere). The percentage error in measured temperatures should be smaller, in view of the possibility of error accumulation in the vertical integration process. For synoptic analysis, temperatures with an error of 5°C (about 2%) are considered tolerable at the altitudes of interest. It is emphasized that for small-scale analysis and for analysis in regions with small seasonal variability (as in low latitudes), greater accuracy may be needed.

Upper Air Branch,
    National Meteorological Center, Weather Bureau,
        Hillcrest Heights, Md., August 15, 1968.

REFERENCES

1. Scherhag, Richard, 1966: High-altitude ascents over Berlin. Amer.
   Meteor. Soc., Bulletin, 47, 982.

2. Finger, F.G., H.M. Woolf, and C.E. Anderson, 1966: Synoptic analysis
   of 5-, 2-, and 0.4-millibar surfaces for the IQSY period. Mon. Wea.
   Rev., 94, 651-661.

3. Sissenwine, Norman, 1968: Aerospace systems requirements for
   environmental data in the altitude range 60 to 200 km. Meteor.
   Monographs, Vol. 9, No. 31, 7-18.

4. Craig, R.A., 1965: The Upper Atmosphere. New York, Academic
   Press. 509 pp.

5. Frank, G.A., A.S. Carten, and R.E. Biedenbender, 1966: Economic
   considerations of rocketsondes. Defense Supply Agency, Alexandria,
   Va.

6. Kays, Marvin and R.O. Olsen, 1967: Rocket temperature and wind
   sensors. Amer. Meteor. Soc., Bulletin, 48, 676-682.

7. Boyer, E.D., 1966: Five-inch HARP tests at Barbados, West Indies,
   January-February 1966. BRL Mem. Report 1771, Aberdeen Proving
   Ground, Md.

8. Space Science Board, 1966: Space Research, Directions for the Future.
   Nat. Ac. Sci., Publ. 1403.

9. Boyer, E.D., 1964: Five-inch HARP tests at Wallops Island, September,
   1963. BRL Mem. Report 1532, Aberdeen Proving Ground, Md.

10. Murphy, C.H., G.V. Bull, and H.D. Edwards, 1966: Ionospheric winds
    measured by gun-launched projectiles. J. Geophys. Res., 71, 4535-
    4544.

11. Murphy, C.H. and G.V. Bull, 1968: Gun-launched probes over Barbados.
    Amer. Meteor. Soc., Bulletin, 49, 640-644.

12. Webb, W.L., W.E. Hubert, R.L. Miller, and J.F. Spurling, 1961:
    The first Meteorological Rocket Network. Amer. Meteor. Soc., Bulletin,
    42, 482-494.

13. Webb, W.L., et al., 1962: Inter-Range Instrumentation Group participation in the Meteorological Rocket Network. Amer. Meteor. Soc., Bulletin, 43, 640-649.

14. Webb, W.L. et al., 1966: Meteorological Rocket Network probing of the stratosphere and lower mesosphere. Amer. Meteor. Soc., Bulletin, 47, 788-799.

15. Giraytys, James and H.R. Rippy, 1964: The USAF meteorological rocket sounding network: present and future. Amer. Meteor. Soc., Bulletin, 45, 382-387.

16. Groves, G.V., 1966: World-wide sounding rocket facilities. Spaceflight, 8, 78-85.

17. Bettle, J.F., J.F. Spurling, and F.J. Schmidlin, 1967: The establishment of the Experimental Inter-American Meteorological Rocket Network (EXAMETNET). Presented at AIAA Sounding Rocket Vehicle Technology Conference, Williamsburg, Va.

18. Quiroz, R.S., 1967: Meteorological rocket observations and research in the Soviet Union. Amer. Meteor. Soc., Bulletin, 48, 697-699, 702-703.

19. Reed, R.J., D.J. McKenzie, and J.C. Vyverberg, 1966: Diurnal tidal motions between 30 and 60 kilometers in summer. J. Atmos. Sci., 23, 416-423.

20. Quiroz, R.S. and A.J. Miller, 1967: Note on the semi-annual wind variation in the equatorial stratosphere. Mon. Wea. Rev., 95, 635-641.

21. Belmont, A., R. Peterson, and W. Shen, 1964: Evaluation of meteorological rocket data. NASA CR-138.

22. Webb, W.L., 1968: Meteorological rocket measurements in the mesosphere. Meteor. Monographs., Vol. 9, No. 31, 158-169.

23. Murphy, C.H., 1968: General properties of ionospheric winds. Proc. Third Nat. Conf. on Aerospace Meteor., Amer. Meteor. Soc. (Boston), 488-491.

24. Murphy, C.H. and G.V. Bull, 1968: Ionospheric winds over Yuma, Arizona, measured by gun-launched projectiles. J. Geophys. Res., 73, 3005-3016.

25. Eddy, A., et al., 1965: Determination of winds from meteorological rocketsondes. Report No. 2, Atmos. Sci. Group, Univ. of Texas, Austin, Tex.

26. Kays, Marvin and R.O. Olsen, 1967: Improved technique for deriving wind profiles from rocketsonde parachutes. J. Geophys. Res., 72, 4035-4040.

27. Bollermann, B. and R.L. Walker, 1967: Cajun-Dart 95 kilometer sounding rocket. NASA CR-61175.

28. Thiele, O.W., 1963: Mesospheric density variability based on recent meteorological measurements. J. Appl. Meteor., 2, 649-654.

29. Quiroz, R.S., J.K. Lambert, and J.A. Dutton, 1963: Upper-stratosphere density and temperature variability determined from Meteorological Rocket Network results, 1960-1962. Air Weather Service, Tech. Report No. 175.

30. Almond, R., 1965: Techniques of temperature and wind sounding with the Skua meteorological rocket. Meteor. Mag. (London), 94, 327-331.

31. Farmer, S.F.G., 1965: Results from the Skua meteorological rocket programme. Meteor. Mag. (London), 94, 332-337.

32. Ainsworth, J.E., D.F. Fox, and H.E. LaGow, 1961: Measurement of upper-atmosphere structure by means of the pitot-static tube. NASA TN D-670.

33. Spencer, N.W., R.L. Bogess and D.R. Taeusch, 1964: Seasonal variation of density and temperature over Churchill, Canada, during solar maximum. J. Geophys. Res., 69, 1367-1380.

34. Theon, J. S. and J.J. Horvath, 1968: Some meteorological observations of the Southern Hemisphere stratosphere and mesosphere. J. Geophys. Res., 73, 4475-4480.

35. Thiele, O.W. and N.J. Beyers, 1967a: Upper atmosphere pressure measurements with thermal conducting gages. J. Atmos. Sci., 24, 551-557.

36. Meteorological Working Group, 1965: Meteorological equipment data accuracies. IRIG Document 110-64, Range Commanders Council, White Sands Missile Range, N. Mex.

37. Engler, N.A., 1965: Development of methods to determine winds, density, pressure and temperature from the ROBIN falling balloon. Final Report, Contract AF19(604)-7450, Univ. of Dayton Res. Inst.

38. Smith, L.B., 1960: The measurement of winds between 100,000 and 300,000 feet by use of chaff rockets. J. Meteor., 17, 296-310.

39. Smith, J.W. and W.W. Vaughan, 1961: High-altitude wind observations above Cape Canaveral. Aerospace Engineering, 20, 16-17, 53-54.

40. Rapp, R.R., 1960: The accuracy of winds derived by the radar-tracking of chaff at high altitudes. J. Meteor., 17, 507-514.

41. Joint Scientific Advisory Group, 1961: The Meteorological Rocket Network, an analysis of the first year in operation. J. Geophys. Res., 66, 2821-2842.

42. Lally, V.E. and R. Leviton, 1958: Accuracy of wind determination from the track of a falling object. AF Surveys in Geophys., No. 93, AFCRL, Bedford, Mass.

43. Miller, A.J., H.M. Woolf, and F.G. Finger, 1968: Small-scale wind and temperature variations as evidenced by meteorological rocket systems. J. Appl. Meteor., 7, 390-399.

44. Wagner, N.K., 1964: Theoretical accuracy of a meteorological rocket-sonde thermistor. J. Appl. Meteor., 3, 461-469.

45. Morrissey, J.F. and A.S. Carten, 1967: Importance of thermistor mount configuration to meteorological temperature measurements. Amer. Meteor. Soc., Bulletin, 48, 684-689.

46. Ballard, H.N., 1967: A review of seven papers concerning the measurement of temperature in the stratosphere and mesosphere. ECOM Report 5125, White Sands Missile Range, N. Mex., 67 pp.

47. Henry, R.M., 1967: Corrections for meteorological rocket temperature soundings on an individual basis. Paper presented at Amer. Meteor. Soc. Conf. on High-Altitude Meteorology and Space Weather, Houston, March 29-31.

48. Thiele, O.W. and Beyers, N.J., 1967: Comparison of rocketsonde and radiosonde temperatures and an evaluation of computed rocketsonde pressure and density. J. Geophys. Res., 72, 2485-2495.

49. Finger, F.G. and H.M. Woolf, 1967: Diurnal variation of temperature in the upper stratosphere as indicated by a meteorological rocket experiment. J. Atmos. Sci., 24, 230-239.

50. Smith, W.S., L.B. Katchen, and J.S. Theon, 1968: Grenade experiments in a program of synoptic meteorological measurements. Meteor. Monographs, Vol. 9, No. 31, 170-175.

51. Jones, L.M. and J.W. Peterson, 1968: Falling sphere measurements, 30 to 120 km. Meteor. Monographs, Vol. 9, No. 31, 176-189.

52. Quiroz, R.S., 1961: Air density profiles for the atmosphere between 30 and 80 kilometers. Air Weather Service, Tech. Report No. 150.

53. Quiroz, R.S., 1966: Upper-atmosphere densities--radiosonde to satellite altitudes. Air Weather Service, Aerospace Sciences Review, No. 1, 23-26.

54. Minzner, R.A. and Jacobson, S.M., 1966: Density - altitude data from 150 rocket flights and 26 searchlight probings, 1947 through 1964. Tech. Report No. 66-4N, GCA Corporation, Bedford, Mass.

55. Lenhard, R. and A.J. Kantor, 1965: A catalogue of ARCAS-ROBIN soundings. Env. Res. Paper No. 113, AFCRL, Bedford, Mass.

56. Peterson, J.W. et al., 1965: Falling sphere measurements over Kwajalein J. Geophys. Res., 70, 4477-4491.

57. Pearson, P.H.O., 1966: Seasonal variations of density, temperature, and pressure between 40 and 90 km, Woomera, South Australia, March, 1964-March 1965. J. Atmos. Terr. Physics, 28, 1057-1064.

58. Champion, K.S.W. and A.C. Faire, 1964: Falling sphere measurements of atmospheric density, temperature, and pressure, up to 115 km. Res. Paper No. 34, AFCRL, Bedford, Mass.

59. Faucher, G.A., J.F. Morrissey, and C.N. Stark, 1967: Falling sphere density measurements. J. Geophys. Res., 72, 299-305.

60. Murgatroyd, R.J., 1968: Temperature, density and pressure variations in the stratosphere and mesosphere. Meteor. Monographs, Vol. 9, No. 31, 57-71.

61. Quiroz, R.S., 1961: Seasonal and latitudinal variations of air density in the mesosphere. J. Geophys. Res., 66, 2129-2139.

62. Kantor, A.J., 1966: Horizontal and vertical distributions of atmospheric pressure, 30 to 90 kilometers. Air Force Survey in Geophys., No. 181, AFCRL, Bedford, Mass.

63. U.S. Standard Atmosphere Supplements, 1966. Wash., D.C., G.P.O., 289 pp.

64. Newell, R.E., 1968: The general circulation of the atmosphere above 60 km. Meteor. Monographs, Vol. 9, No. 31, 98-113.

65. Kochanski, A., 1964: Atmospheric motions from sodium cloud drifts. J. Geophys. Res., 69, 3651-3662.

66. Quiroz, R.S. and A.J. Miller, 1968: Height-lag correlations of density with pressure and temperature at rocket altitudes of the stratosphere. J. Atmos. Sci., 25, 104-112.

67. Mahoney, J.R., 1968: A numerical study of the variable structure of the lower thermosphere. Meteor. Monographs, Vol. 91, No. 31, 90-97.

68. Harris, I. and W. Priester, 1968: The structure of the thermosphere and its variations. Meteor. Monographs, Vol. 9, No. 31, 72-81.

69. Finger, F.G., H.M. Woolf, and C.E. Anderson, 1965: A method for objective analysis of stratospheric constant-pressure charts. Mon. Wea. Rev., 93, 619-638.

70. Keegan, T.J., 1962: Synoptic patterns at 100,000 to 200,000 feet. Air Force Survey in Geophysics No. 140, AFCRL, Bedford, Mass., 195-210.

71. Finger, F.G., S. Teweles, and R.B. Mason, 1963: Synoptic analysis based on meteorological rocketsonde data. J. Geophys. Res., 68, 1377-1399.

72. U.S. Weather Bureau, 1967: Weekly synoptic analyses, 5-, 2-, and 0.4 mb surfaces for 1964. Tech. Report WB-2. Also, for 1965, Tech. Report WB-3.

73. Warnecke, G. and W. Nordberg, 1965: Inferences of stratospheric and mesospheric circulation systems from rocket experiments. Space Research V, Amsterdam, North-Holland Publ. Co., 1026-1038.

74. Quiroz, R.S., 1966: Midwinter stratospheric warming in the antarctic revealed by rocket data. J. Appl. Meteor., 5, 126-128.

75. Julian, P.R., 1967: Midwinter stratospheric warmings in the Southern Hemisphere: general remarks and a case study. J. Appl. Meteor., 6, 557-563.

76. Finger, F.G. and H.M. Woolf, 1967: Southern Hemisphere stratospheric circulation as indicated by shipboard meteorological rocket observations. J. Atmos. Sci., 24, 387-395.

77. Wexler, H., 1959: Seasonal and other temperature changes in the Antarctic atmosphere. Quart. J. Roy. Meteor. Soc., 85, 196-208.

78. Reed, R.J., 1966: Zonal wind behavior in the equatorial stratosphere and mesosphere. J. Geophys. Res., 71, 4223-4233.

79. Quiroz, R.S. and A.J. Miller, 1967: Note on the semiannual wind variation in the equatorial stratosphere. Mon. Wea. Rev., 95, 635-641.

80. Reed, R.J., 1965: The present status of the 26-month oscillation. Amer. Meteor. Soc., Bulletin, 46, 375-385.

81. Johnson, K.W. and M.E. Gelman, 1968: Temperature and height variability in the middle and upper stratosphere during 1964-1966 as determined from constant-pressure charts. Mon. Wea. Rev., 96, 371-382.

82. Finger, F.G. and S. Teweles, 1964: The mid-winter 1963 stratospheric warming and circulation change. J. Appl. Meteor., 3, 1-15.

83. Jones, L.M. et al., 1959: Upper-air density and temperature: some variations and an abrupt warming in the mesosphere. J. Geophys. Res., 64, 2331-2340.

84. Julian, P.R. and K.B. Labitzke, 1965: A study of atmospheric energetics during the 1963 stratospheric warming. J. Atmos. Sci., 22, 597-610.

85. Belrose, J.S., 1967: The "Berlin" warming. Nature, 214, 660-664.

86. Quiroz, R.S., 1968: Synoptic density maps of the upper atmosphere. J. Appl. Meteor., 7 (in press).

87. Lindzen, R.S., 1967: Thermally driven diurnal tide in the atmosphere. Quart. J. Roy. Meteor. Soc., 93, 18-42.

88. Kellogg, W.W., 1968: Research on the lower fringe of space. Meteor. Monographs, Vol. 9, No. 31, 2-5.

89. Groves, G.V., 1967: Tidal oscillations and gravity waves. Paper presented at IQSY/COSPAR meeting, London, July 20, 1967; University College, London.

90. Lenhard, R.W., 1963: Variation of hourly winds at 35 to 65 km during one day at Eglin Air Force Base, Florida. J. Geophys. Res., 68, 227-234.

91. Groves, G.V., 1965: Diurnal variation in upper atmosphere wind and temperature structure at Woomera, 15-16 October 1963. Space Research V, 1012-1025.

92. Beyers, N.J. and B.T. Miers, 1965: Diurnal temperature change in the atmosphere between 30 and 60 km in the atmosphere over White Sands Sands Missile Range. J. Atmos. Sci., 22, 262-266.

93. Miers, B.T., 1965: Wind oscillations between 30 and 60 km over White Sands Missile Range, New Mexico. J. Atmos. Sci., 22, 382-387.

94. Groves, G.V., 1967: Variations in upper atmosphere wind, temperature and pressure at Woomera during the night of 29/30 April 1965. Space Research VII, Amsterdam, North-Holland Publ. Co., 977-985.

95. Rofe, B., W.G. Elford, and E.M. Doyle, 1966: Diurnal variations in density, temperature, pressure and wind, between 40 and 90 km, in the sub-tropical latitudes of the Southern Hemisphere. Australia, Weapons Res. Est., Tech. Note PAD 116.

96. Beyers, N.J., B.T. Miers, and R.J. Reed, 1966: Diurnal tidal motions near the stratopause during 48 hours at White Sands Missile Range. J. Atmos. Sci., 23, 325-333.

97. Thiele, O.W., 1966: Observed diurnal oscillations of pressure and density in the upper stratosphere. J. Atmos. Sci., 23, 424-430.

98. Beyers, N.J. and B.T. Miers, 1968: A tidal experiment in the equatorial stratosphere over Ascension Island. J. Atmos. Sci., 25, 155-159.

99. Beyers, N.J. and B.T. Miers, 1965: Wind oscillations between 30 and 60 km over White Sands Missile Range, New Mexico. J. Atmos. Sci., 22, 382-387.

100. Finger, F.G. and R.M. McInturff, 1968: The diurnal temperature range of the middle stratosphere. J. Atmos. Sci., 25 (in press).

101. Harris, M.F., F.G. Finger, and S. Teweles, 1966: Frictional and thermal influences in the solar semidiurnal tide. Mon. Wea. Rev., 94, 427-447.

102. Hines, C.O., 1960: Internal atmospheric gravity waves at ionospheric heights. Canadian J. Physics, 38, 1441-1481.

103. Lettau, B., 1966: An analysis of vertical scale structure and wind shear in the mesosphere from falling sphere data. J. Geophys. Res., 71, 1003-1010.

104. Webb, W.L., 1965: Scale of stratospheric detail structure. Space Research, V, 997-1007.

105. Mahoney, J.R. and G.J. Boer, 1968: Horizontal and vertical scales of winds in the 30- to 60-km region. Proc. Third Nat. Conf. on Aerospace Meteor., Boston, Amer. Meteor. Soc., 457-464.

106. Greenhow, J.S. and E.L. Neufeld, 1961: Winds in the upper atmosphere. Quart. J. Royal Meteor. Soc., 87, 472-489.

107. Gazley, C., L.N. Rowell, and G.F. Schilling, 1965: On the prediction of satellite orbit decay and impact. RAND Corp. Memorandum RM-4619-PR.

108. Schilling, Gerhard, 1968: Density and temperature variations in the intervening layer (90-150 km). Meteor. Monographs, Vol. 9, No. 31, 82-89.

109. Quiroz, R.S., ed., Meteorological investigations of the upper atmosphere. Meteor. Monographs, Vol. 9, No. 31, Boston, Amer. Meteor. Soc., 231 pp.

110.  Kellogg, W.W., 1961: Warming of the polar mesosphere and lower ionosphere in winter. J. Meteor., 18, 373-381.

111.  Newell, R.F., 1963: Preliminary study of quasi-horizontal eddy fluxes from Meteorological Rocket Network data. J. Atmos. Sci., 20, 213-225.

112.  Leovy, Conway, 1964: Radiative equilibrium of the mesosphere. J. Atmos. Sci., 21, 238-248.

113.  Charlson, R.J., 1966: A simple noctilucent cloud model. Tellus, 18, 451-456.

114.  Kern, L.C. and R.R. Rapp, 1963: The effect of vertical air motion on atmospheric density determination from ROBIN flights. RAND Corporation Memorandum RM-3687-PR.

115.  Miller, A.J., 1967: Note on vertical motion in the lower stratosphere. Beitr. Physik Atmos., 40, 29-48.

116.  Kays, Marvin and R. Craig, 1965: On the order of magnitude of large-scale vertical motions in the upper stratosphere. J. Geophys. Res., 70, 4453-4461.

117.  Groves, G.V., 1963: High atmosphere wind studies by Skylark rocket cloud release. Proc. First International Symp. on Rocket and Satellite Meteor. (Washington, April 23-25, 1962); North-Holland Publ. Co., Amsterdam, 60-69.

118.  Lindzen, R.S., 1968: Data necessary for the detection and description of tides and gravity waves in the upper atmosphere. Univ. of Chicago, unpublished paper to be presented to COSPAR Working Group II, 15 pp.

119.  Spizzichino, A., 1967: Mésures de vents ionospheriques au moyen d'un radar météorique. Space Research VII, North-Holland Publ. Co., Amsterdam, Vol. 1, 73-75.

120.  Barnes, A.A., Jr., 1968: Winds and densities from radar meteor trail returns, 80 to 120 km. Meteor. Monographs, Vol. 9, No. 31, 190-195.

121.   Newell, R. E. and R. E. Dickinson, 1967:  On the application of a proposed global system for measuring meteor winds.  Pure and Appl. Geophys., 68, 162-172.

122.   Haurwitz, Bernard, 1964:  Tidal phenomena in the upper atmosphere. World Meteor. Orgn., Tech. Note No. 58, 27 pp.