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FOUR-D GLOBAL REFERENCE ATMOSPHERE TECHNICAL DESCRIPTION

Part I

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15. SUPPLEMENTARY NOTES

This document was prepared based on the engineering design problems which have been identified or anticipated for the Space Shuttle program.

16. ABSTRACT

An empirical atmospheric model has been developed which generates values for pressure, density, temperature, and winds from surface levels to orbital altitudes. The output parameters consist of components for: (1) latitude, longitude, and altitude dependent monthly and annual means, (2) quasi-biennial oscillations, and (3) random perturbations to simulate partially the variability due to synoptic, diurnal, planetary wave, and gravity wave variations. Quasi-biennial and random variation perturbations are computed from parameters determined from various empirical studies and are added to the monthly mean values. This model has been developed as a computer program called PROFILE which can be used to generate altitude profiles of atmospheric parameters along any simulated trajectory through the atmosphere. The PROFILE program was developed for design applications in the Space Shuttle program. Other applications of the model are discussed, such as for global circulation and diffusion studies, and for generating profiles for comparison with other atmospheric measurement techniques, (e.g. satellite measured temperature profiles).

The results are given in two parts, viz: TMX-64871 , Four-D Global Reference Atmosphere, Technical Description, Part I and TMX-64872 , Four-D Global Reference Atmosphere Model Users Manual and Programmers Manual, Part II.

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PREFACE

This preface covers a two-part publication. NASA TMX-64871 , Four-D Global Reference Atmosphere, Technical Description and NASA TMX-64872 , Four-D Global Reference Atmosphere Model, Users Manual and Programmers Manual, Part II, both with publication date of September 1974.

The motivation for the development of a global reference atmospheric model is from recognized needs for engineering design, mission planning, performance analysis, and possibly operational usage for the Space Shuttle program.

The concept of a global reference atmospheric model has its origin as an extension of the Range Reference Atmospheric Model which is a model of the gas properties over a particular geographic location. Particular range reference atmospheric models are the Patrick Reference Atmosphere (Annual) which is valid for Cape Kennedy, Florida, Vandenberg AFB Reference Atmosphere (Annual) and Edward AFB Reference Atmosphere (Annual). To represent the dispersions in the gas properties, pressure, temperature, and density there are also the Hot and Cold Reference Atmospheres for these three sites. Range Reference Atmospheres have been developed for a number of U. S. National Missile Test Ranges under the auspices of the Range Commanders Council/ Meteorology Group (formerly the Inter-Range Instrumentation Group/Meteorological Working Group, IRIG/MWG).

The first development toward the present global reference atmosphere was a Four-Dimensional World-Wide Model valid for 0 - 25 km altitude. The four dimensions come from the three coordinates, latitude, longitude, and altitude, plus time, where time is with respect to monthly reference periods. The parameters modelled are gas properties and moisture. The monthly means and daily variation of these parameters are obtained for any latitude, longitude, altitude, and monthly reference period by a computer interpolation program. This four-dimensional world-wide model was developed for the design and performance analysis of earth viewing instrumentation used on earth orbiting satellites.

Man-made earth orbiting satellites created a need for and a means to develop atmospheric models at orbital altitudes. Models for these altitudes have a much different form than those at lower altitudes because of the strong solar influence which contributes to variation and the contrasting differences in the basic measurements. Orbital altitude models express the gas properties as continuous variables with respect to time. The variables are given by a few simple, but complex equations, as a function of time with parameters for solar activity. The data for orbital models are derived from continuous sensors (satellites) which make many earth revolutions, over short periods up to many years covering all earth reference coordinates, whereas the data available for modelling at lower altitudes are derived from point measurements in time which are constrained to fixed earth coordinates of latitude and longitude, e.g., rawinsonde and meteorological rocketsonde measurements. Although difficult as it is to establish, a continuous atmospheric model from the earth's surface to and including orbital altitudes is required for a mission of the Space Shuttle. Layered models with respect to altitude and at discrete latitudes are not satisfactory for a Space Shuttle flight performance analysis. The Four-Dimensional Global Reference Atmosphere presented in this report is a first attempt to offer a means to represent the gas properties in a continuous manner over all altitudes for all earth coordinates (latitude and longitude) from the earth's surface up to orbital altitudes or from orbital altitudes down to the earth's surface.

The Four-D Global Reference Atmosphere Model (GRA) is in the form of a computer program which has several options for output data. The computer card input depends on the desired output option. The principal input parameters are height, latitude, longitude, solar activity parameters (geomagnetic index, F10.7 and 81 day mean 10.7 cm flux), date (month, day, and year or annual reference period) and Greenwich time. The computer used is the Univac 1108 with a core requirement of slightly under 32K words. All magnetic tapes are seven track. One program tape and one data tape are required for all altitudes above 30 km and from one to four data tapes for altitudes below 30 km altitude. Standard card punch is required if one of the optional card outputs is selected. The computer program is completely documented in a separate volume, entitled "Four-D Global Reference Atmosphere Model, Users Manual and Programmers Manual, Part II". Qualified requestors may receive the computer program, which includes the program magnetic tape and the required magnetic data tapes, and the documental manual by addressing their request to Chief, Aerospace Environment Division, ES41, Space Sciences Laboratory, NASA Marshall Space Flight Center, AL 35812.

A feature of the GRA is that representative wind fields may also be derived. This was done to assure consistency in the modelling process and for scientific interest in the general circulation pattern and for potential applications for long-term diffusion processes. With some innovations one can envision further adaptations and applications of the GRA for a general class of ascending and descending aerospace vehicles.

It is envisioned that as more familiarity with this Global Reference Atmosphere is gained, improvements and adaptations of various computer program options will be developed for specific problems. However, any near future revisions will not change the basic program.

The Four-D Global Reference Atmosphere Model should be used in its entirety where appropriate to include the monthly means and standard deviations of dispersions of the gas properties and the Monte Carlo generated profiles along the trajectory. For some analyses it may be sufficient to use only the means plus and minus 2.3263 standard deviations of the variables to obtain satisfactory engineering design or operational solutions. The means ± 2.3263 standard deviations give the 1st and 99th percentile values of the variables which is the 98th interpercentile range of the variables. In other cases, such as maximum point aerodynamic heating, or for some particular feature of the guidance and control system a number of Monte Carlo generated atmospheric profiles may be required to obtain design and performance limits.

O. E. Smith and W. W. Vaughan
September 1974

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1. INTRODUCTION AND SUMMARY

At the International Conference on Aerospace and Aeronautical Meteorology (ICAAM) it was recommended by Smith et al. (1972) that range reference atmospheres for the launch site be used for the boost flight plase of the Space Shuttle, that the U.S. Standard Atmosphere 1962 be used for nominal trjaectory and aerodynamic heating for the Shuttle Orbiter re-entry, and that the density perturbation model (Smith et al., 1971) be used to account for re-entry phase variations. Smith et al. also pointed out that as shuttle design studies progressed, improved techniques in the implementation of perturbation models were expected. They established as a goal the development of a so called 4-D model to give pressure, temperature, and density variables and their structure as a function of the three spatial coordinates latitude, longitude, altitude and the time domain (seasonal and perhaps time of day) over the altitude range from sea level to 185 km. This report describes an empirical atmospheric model, developed by Georgia Tech, which is a first attempt to meet these goals.

The Georgia Tech computer model, called PROFILE, is an amalgamation of two previously existing empirical atmospheric models for the low (< 25 km) and high (> 90 km) atmosphere, with a newly developed latitude-longitude dependent model for the middle atmosphere. The high atmospheric region above 115 km is simulated entirely by the Jacchia (1970) model. The Jacchia program sections are in separate subroutines so that later Jacchia models (Jacchia, 1971) or other thermospheric-exospheric models could easily be adapted and substituted into the PROFILE program if required for special applications. The atmospheric region between 25 km and 115 km is simulated by a newly developed latitude-longitude dependent empirical model modification of the latitude dependent empirical model developed by Groves (1971), which is described more fully later in this report. Between 90 km and 115 km a smooth transition between the modified Groves values and the Jacchia values is accomplished by a fairing technique. Below 25 km the atmospheric parameters are computed by a 4-D world-wide atmospheric model developed for NASA by Allied Research Associates (Spiegler and Fowler, 1972). Between 25 and 30 km an interpolation scheme is used between the 4-D results and the modified Groves values. Figure 1.1 presents a schematic summary of the PROFILE program atmospheric regions and how they are modeled.

The modifications to Groves model to produce longitude as well as latitude variations in the monthly mean were accomplished in two steps. First upper air summary map data for monthly means at the 10 mb level for 1966 and 1967 (NOAA, 1969b) and the 2 and 0.4 mb levels for 1966, 1967, and 1968 (NOAA, 1969a, 1970, 1971) were read and converted to values for the 30, 40, and 52 km levels. The upper air map values at the 2 and 0.4 mb levels were extended around the entire northern hemisphere by subjective extrapolation. Next the 30, 40, and 52 km latitude-longitude dependent values were extrapolated to 90 km by an extrapolation scheme developed by Graves, et al. (1973). All of the map generated and extrapolated data were converted to percent deviation from the longitudinal mean and these are applied as deviations (called *stationary perturbations*) to the Groves model values, which are taken as the latitude dependent longitudinal means.

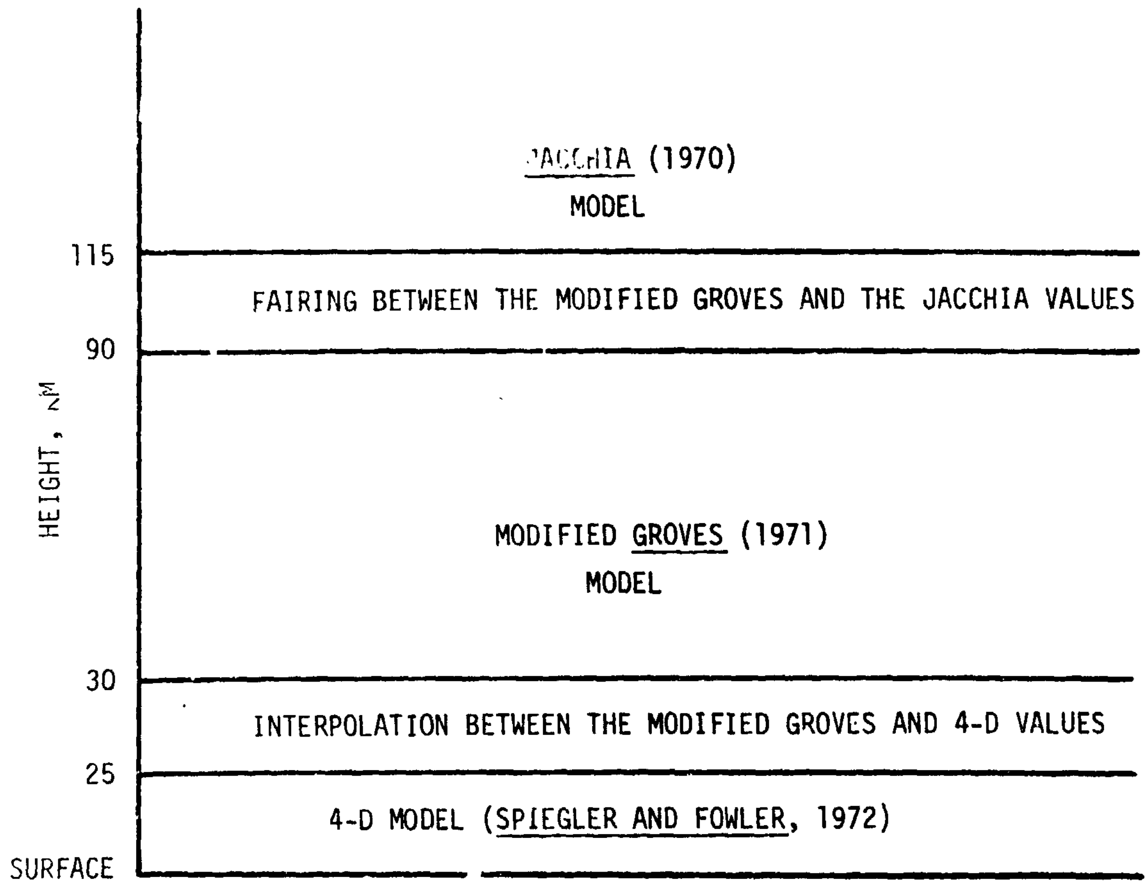


Figure 1.1 Schematic summary of the atmospheric regions in the PROFILE program and the simulation methods used for mean monthly values in each region

The seasonal variations in the middle atmosphere (25-115 km) are assumed to be the same in northern and southern hemispheres with a six months phase lag. That is the southern hemisphere July is the same as the northern hemisphere January. In the 4-D region ($\leq$ 25 km) separate global coverage data values are available for each of the twelve months. A set of annual reference period data are also available for the 4-D and modified Groves regions. If the annual reference period is selected, the Jacchia section sets the exospheric temperature to 1000^{o} K to represent annual mean conditions.

The monthly mean geostrophic winds are computed from horizontal pressure gradients, estimated by finite differences. Wind shear in the monthly mean wind is estimated from horizontal temperature gradients, similarly determined. These parameters serve as a consistency check on the pressure temperature fields of the empirical model.

In addition to the monthly mean values of pressure density and temperature, two types of perturbations are evaluated: quasi-biennial (QBO) and random. The QBO oscillations in pressure, density, temperature, and winds, empirically determined to be represented by an 870 day period sinusoidal variation, have amplitudes and phases which vary with height and latitude. The QBO amplitudes are primarily significant at low altitudes ($\simeq$ 20 - 40 km) at equatorial latitudes and at higher altitudes (50-60 km) at high latitudes.

The random perturbations have height and latitude variable standard deviations developed from perturbation data of Youngblood (1972), Groves (1971), and Justus and Woodrum (1972, 1973). An analytical technique is used to ensure proper horizontal and vertical correlations of the random perturbations. The horizontal and vertical correlation scales are taken to increase linearly with height between empirical values determined by Buell (1971, 1972) near the 500 mb surface to values estimated from chemical release and other studies by Justus and Woodrum (1972, 1973) near the 100 km level.

The PROFILE program was developed for application in the design and analysis of space shuttle re-entry heating, dynamics, stability, and control, external tank re-entry and dispersion analysis, etc. In addition to trajectory analysis studies there are a wide range of other applications for the PROFILE computer model. (1) It can serve as a reference atmosphere whenever one is needed to represent more detailed conditions than those accounted for in the 1966 U.S. Standard Atmosphere Supplements (COESA, 1966) or by the Groves (1971) model. (2) The PROFILE program can provide first approximation profiles in atmospheric measurement techniques which rely on an iterative solution of winds or temperature profiles (such as infrasonic measurements.) (3) The PROFILE program can provide temperature or other parameter profiles for comparative purposes for results from other atmospheric measurement techniques, such as satellite infrared scanner measurements of temperature profiles. (4) The latitude-longitude-height dependant mean horizontal winds could provide transport winds for global circulation or diffusion analyses. (A method to estimate the latitude-longitude-height dependent mean monthly vertical wind from slopes of isentropic sur-surfaces is now being investigated for possible addition into a modified PROFILE program for global diffusion analysis.)

The lack of many required atmospheric data (especially in the eastern and southern hemispheres in the 25-120 km height range) causes several obvious limitations to the PROFILE program as it is presently constructed. However, the program has been designed so that revised observational data could be employed with a minimum of alterations. The Groves data, the stationary perturbations, the random perturbation magnitudes, and the QBO amplitudes and phases are all read from a data tape which could be updated as any of these data sets are revised. The PROFILE program also has options to read the random perturbation data and/or the QBO data from an alternate input file (such as a card file), if revised data values are to be input but the tape is not yet updated. Two likely areas for update of these input data are more extensive reading of the upper air maps to produce revised stationary perturbation values, and substitution of newer random perturbation magnitudes, such as given by Cole (1972).

2. THE JACCHIA SECTION (ABOVE 90 KM)

The Jacchia (1970) model for the thermosphere and exosphere was originally implemented to compute atmospheric density at satellite altitudes. The Jacchia model accounts for temperature and density variations due to solar and geomagnetic activity, diurnal and semi-annual variations, and seasonal and latitudinal variations. The Jacchia model assumes a uniformly mixed composition from sea level to 105 km, with diffusive equilibrium among the constituents (nitrogen, oxygen, argon, helium, and hydrogen) above 105 km. Fixed boundary values for temperature and density are assumed at 90 km.

A computer implementation of the Jacchia model (called J70) was provided to Georgia Tech by R. L. King of Northrop Services, Inc. Alterations, discussed below, were then made to account for seasonal variations (not implemented on the J70 program) and to allow atmospheric pressure to be computed (not part of the original Jacchia model).

The major addition to the Jacchia model was probably the inclusion of the seasonal-latitudinal variations of the density, temperature, molecular weight, and pressure.

Jacchia (1970) describes the seasonal-latitudinal variations of density for altitudes above 90 km and gives an analytic expression of these variations as:

$$\Delta \operatorname{Log} \rho = 0.02(z - 90)\,(\phi/|\phi|)\,\exp[-\,0.045(z - 90)]\,\sin^2\phi\,\sin[360(d + 100)/y] \qquad (2.1)$$

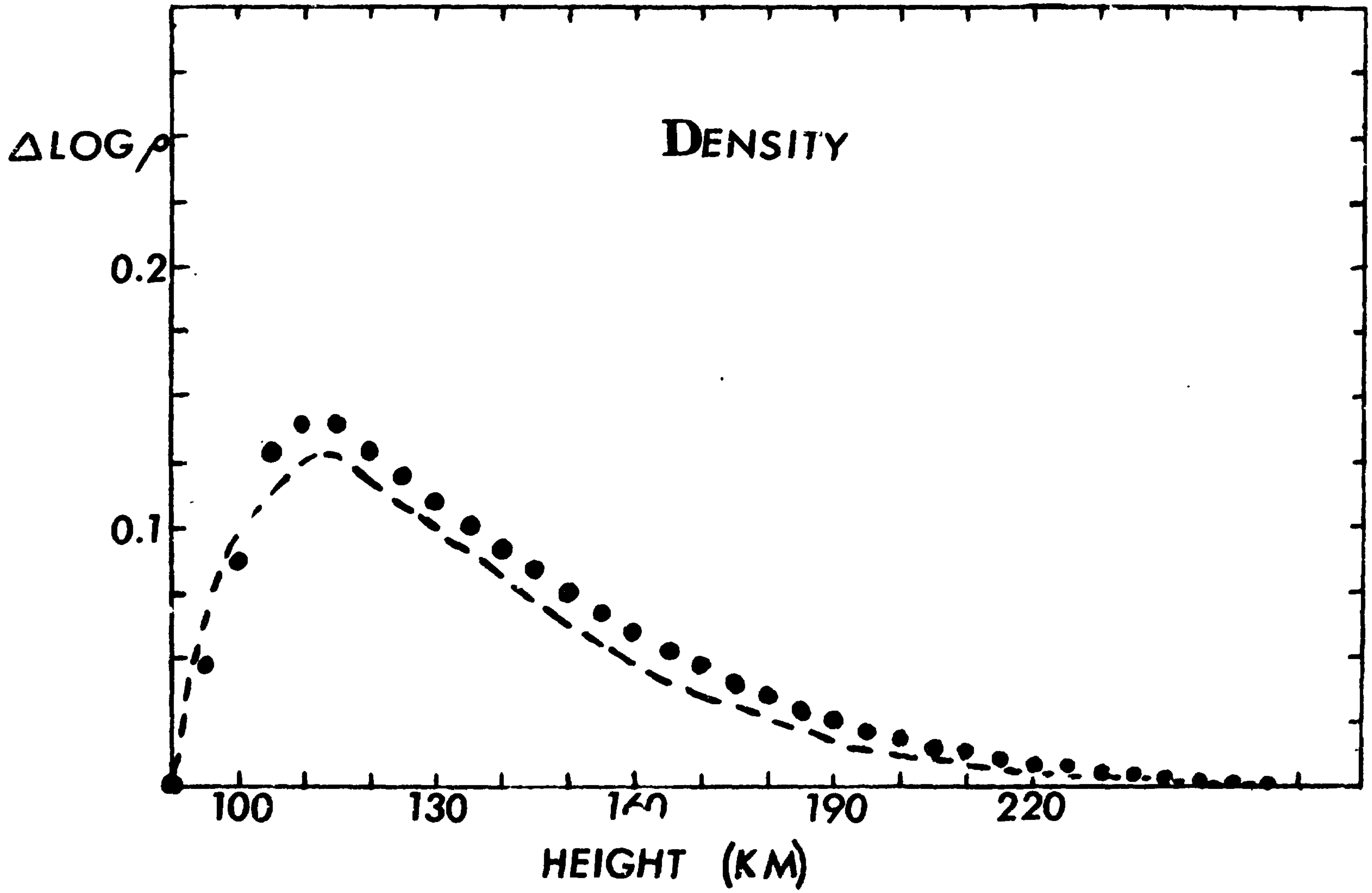


Figure 2.1 Amplitude of the seasonal variation of the log of the density versus height. The points are data from CIRA, 1965 and U.S. Standard Atmosphere Supplements, 1966. The dashed line represents the evaluation of equation 2.1 for a latitude of 60°.

where ϕ is the geographic latitude, z is the height, y is the duration of the tropical year in days (365 or 366), and d is the number of days elapsed since January 1. Seasonal-latitudinal variations of density can also be obtained from CIRA, (1965) for heights 90 to 120 km and seasonal variations can be obtained from the U.S. Standard Atmosphere Supplements, (COESA, 1966) for heights 120 km and above. Values calculated from equation (2.1) seem to compare best with the values from CIRA, (1965) and the U.S. Standard Atmosphere Supplements, 1966, for a latitude of 60^{0}. Thus it is assumed that the seasonal variations from the U.S. Standard Atmosphere Supplements, 1966, are for a latitude of 60^{0}. A comparison of equation (2.1) with the 1966 Standard Atmosphere Supplements and the CIRA (1965) atmosphere results is shown in Figure 2.1.

Seasonal variations of the temperature were also obtained from CIRA (1965) and the U.S. Standard Atmosphere Supplements (1966). Temperature variations from the Standard Atmosphere were found for both the exospheric temperatures of 600^{0} and 2100^{0}. These two variations were essentially the same but the averages of the two variations were taken. An analytic expression of the seasonal-latitudinal variations of the temperature was obtained by first fitting an analytic equation to the above variations. Then, it was assumed that this equation was true for a latitude of 60^{0} and the latitude variations were assumed to be the same as that of the density. Thus, the following analytic equation for the seasonal-latitudinal variations of the temperature was obtained.

$$\frac{\Delta T}{T}(100) = \begin{cases} [-2.292(z - 110) + 0.02154(z - 110)^2 - 4.177 \times 10^{-5}(z - 110)^3] \\ \exp[-0.290655(|z - 110|)^{1/2}(\phi/|\phi|) \sin^2\phi \sin[360(d + 100)/y] \\ \qquad\qquad\qquad\qquad 90 \le z \le 260 \\ 0.0 \qquad\qquad\qquad\qquad z \ge 260 \end{cases} \qquad (2.2)$$

where the variables are defined the same as for equation (2.1). Figure 2.2 shows the agreement between equation (2.2) evaluated for latitude of 60^0 and the values from CIRA, 1965 and the U.S. Standard Atmosphere Supplements, 1966.

Seasonal variations of the molecular weight were also obtained from CIRA, 1965 and the U.S. Standard Atmosphere Supplements, 1966. Variations from the standard atmosphere were obtained for exospheric temperatures of 600^0 and 2100^0 and averaged. No latitude variation of the molecular weight was assumed. An analytic equation was then fitted to the variations as given below.

$$\Delta M = \begin{cases} 0.006(z - 90) \sin[360(d + 100)/y] & 90 \le z \le 120 \\ [0.0108(z - 90) - 1.1285 \times 10^{-4}(z - 90)^2] & \\ \exp[-0.02424(z - 90)] \sin[360(d + 100)/y] & 120 \le z \le 230 \\ 0.0 & z \ge 230 \end{cases} \qquad (2.3)$$

where the variables are defined the same as for equation (2.1). Figure 2.3 shows the agreement between equation (2.3) and the data values.

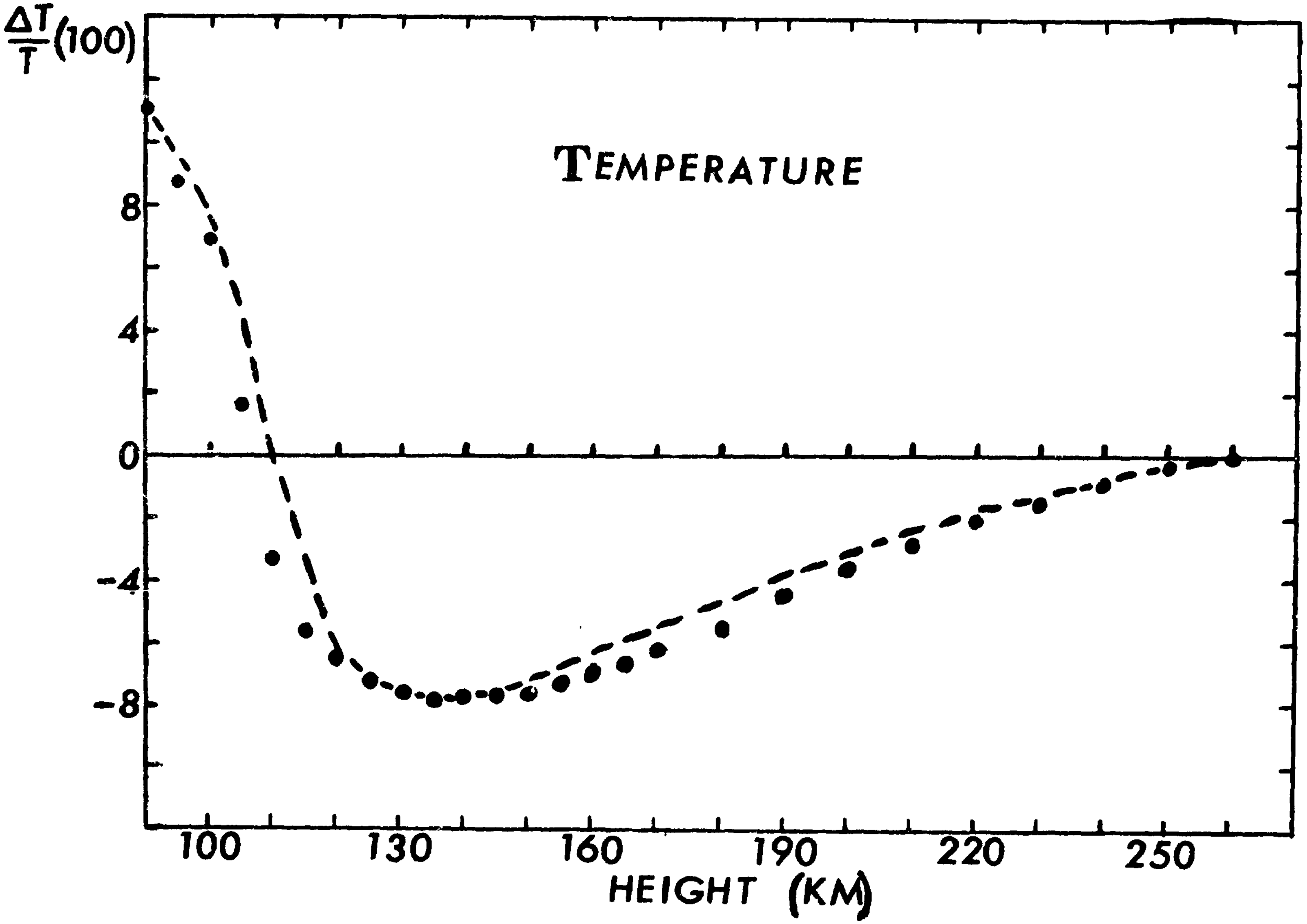


Figure 2.2 Amplitude of the seasonal variation of the relative temperature versus height. The points are data from CIRA, 1965 and U.S. Standard Atmosphere Supplements, 1966. The dashed line represents the evaluation of equation 2.2 for a latitude of 60^o.

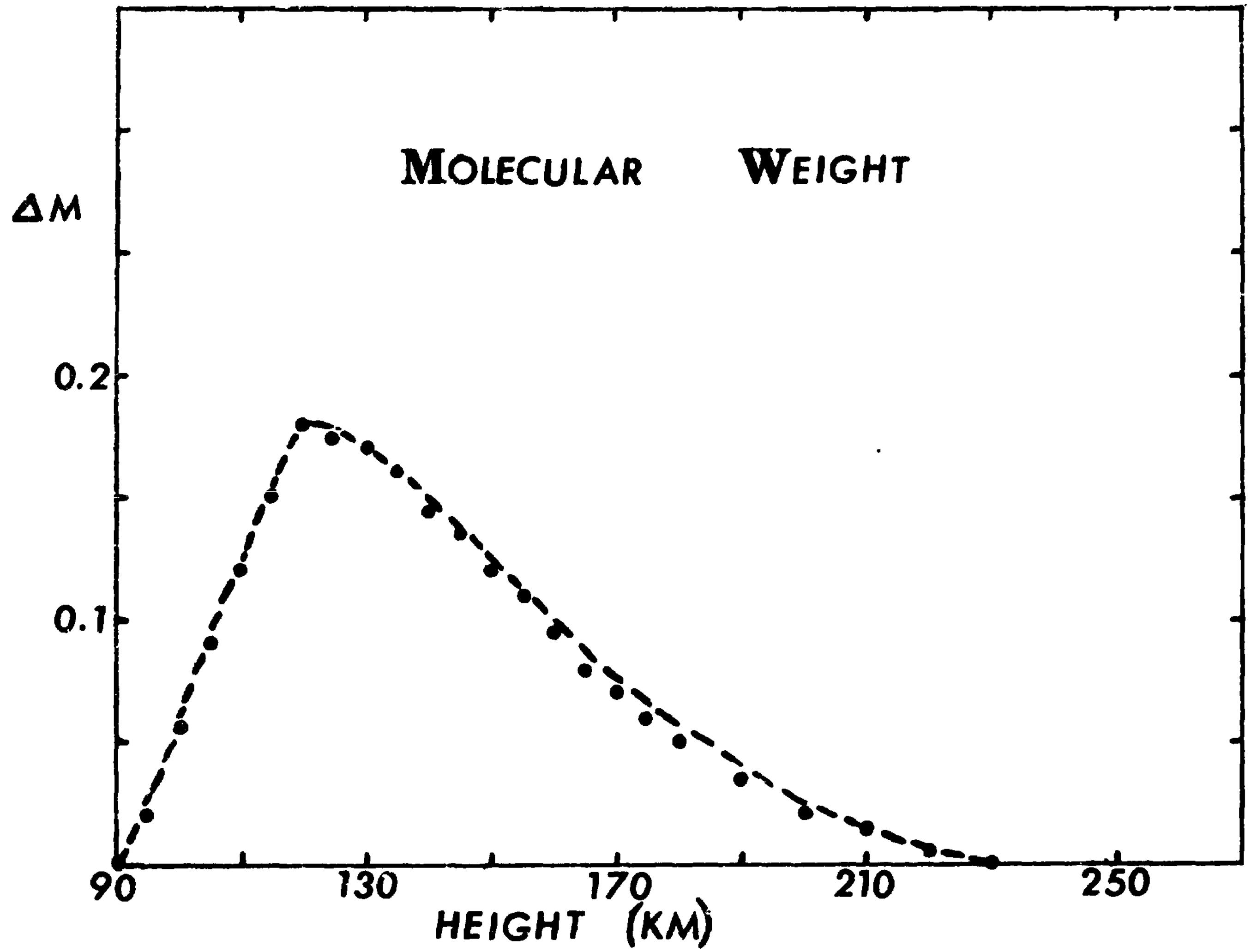


Figure 2.3 Amplitude of the seasonal variation of the molecular weight versus height. The points are data from CIRA, 1965 and U.S. Standard Atmosphere Supplements, 1966. The dashed line represents the evaluation of equation 2.3

The seasonal variations in the molecular weight were needed so that the pressure could be calculated from the ideal gas law:

$$P = \frac{\rho RT}{M} \tag{2.4}$$

where P is the pressure, ρ, T, and M are the density, temperature, and molecular weight respectively including a mean value plus the seasonal-latitudinal variations, and R is the universal gas constant. Thus, the value of pressure includes a mean plus the seasonal-latitudinal variations.

3. THE 4-D SECTION (BELOW 25 KM)

The 4-D atmospheric model, developed by Allied Research Associates (Spiegler, and Fowler, 1972) was designed to extract from data tapes and interpolate on latitude and longitude, mean monthly and daily variance profiles of pressure, density, temperature, at 1 km intervals from the surface to a height of 25 km for any location on the globe. The data tapes contain empirically determined atmospheric parameter profiles at a large array of locations. The northern hemisphere grid array is equivalent to the NMC grid network. Grids spaced at 5 degree intervals of latitude and longitude are used in the equatorial and southern hemisphere regions.

The only technical change made in the 4-D program was to use a modified latitude-longitude interpolation method, discussed in Appendix A. However, there were several modifications in programming details of the 4-D model, which are discussed in the users manual and programmers manual sections of this report.

The method of application of the 4-D model in the PROFILE program is as follows: At the first time that atmospheric parameters at a location below 30 km are required, a set of atmospheric profiles of monthly mean and daily variances of pressure, density, and temperature are generated at a 16 point grid of locations spaced at 5 degree latitude and longitude intervals (a slightly different grid is used near the poles). This grid of profiles, covering $15^{0} \times 15^{0}$ of latitude-longitude is then stored in the computer and all further atmospheric parameter values in the 0-25 km range are found by interpolation between locations within this grid. Only one call on the 4-D program to generate a profile grid is made during any particular trajectory or profile evaluation. If the trajectory goes outside this grid while the height remains below 25 km, the program attempts an estimate of the atmospheric parameters by an extrapolation technique in the case of the polar grid or uses the values of the nearest grid point in the case of the $15^o \times 15^o$ non-polar latitude grid.

The location of the grid points to be evaluated is determined dynamically based on the position and direction of travel along the trajectory when the 4-D grid is first required. Figures 3.1 and 3.2 shows the locations of the two types of 4-D grid, non-polar latitudes and polar latitudes, and the method of orienting the grids with respect to the trajectory orientation.

The 4-D data tapes normally contain data for the surface to 25 km in 1 km steps. At locations where the surface is at more than 1 km above sea level the surface value will be followed by one or more zero records, and the first non-zero record above the surface value will be at the lowest integer km higher than the surface. For example, if the surface is at 700 m then there will be data at surface, 1 km, 2 km, etc., but if the surface is at 1.3 km the data will contain the surface, one zero record, 2 km, 3 km etc. In order to make proper use of the surface data, in the cases where zeros appear at some heights, and even in the case where valid one km data is present, the altitude of the surface must be determined. The latitude and longitude interpolation is first done at the surface to determine interpolated surface temperature T_0, pressure p_0, and density ρ_0. Next the latitude-longitude interpolation is done at the lowest height h_s where all four of the necessary interpolation grid points have valid (i.e. non-zero) data. This interpolation at height h_s gives latitude-longitude interpolated values

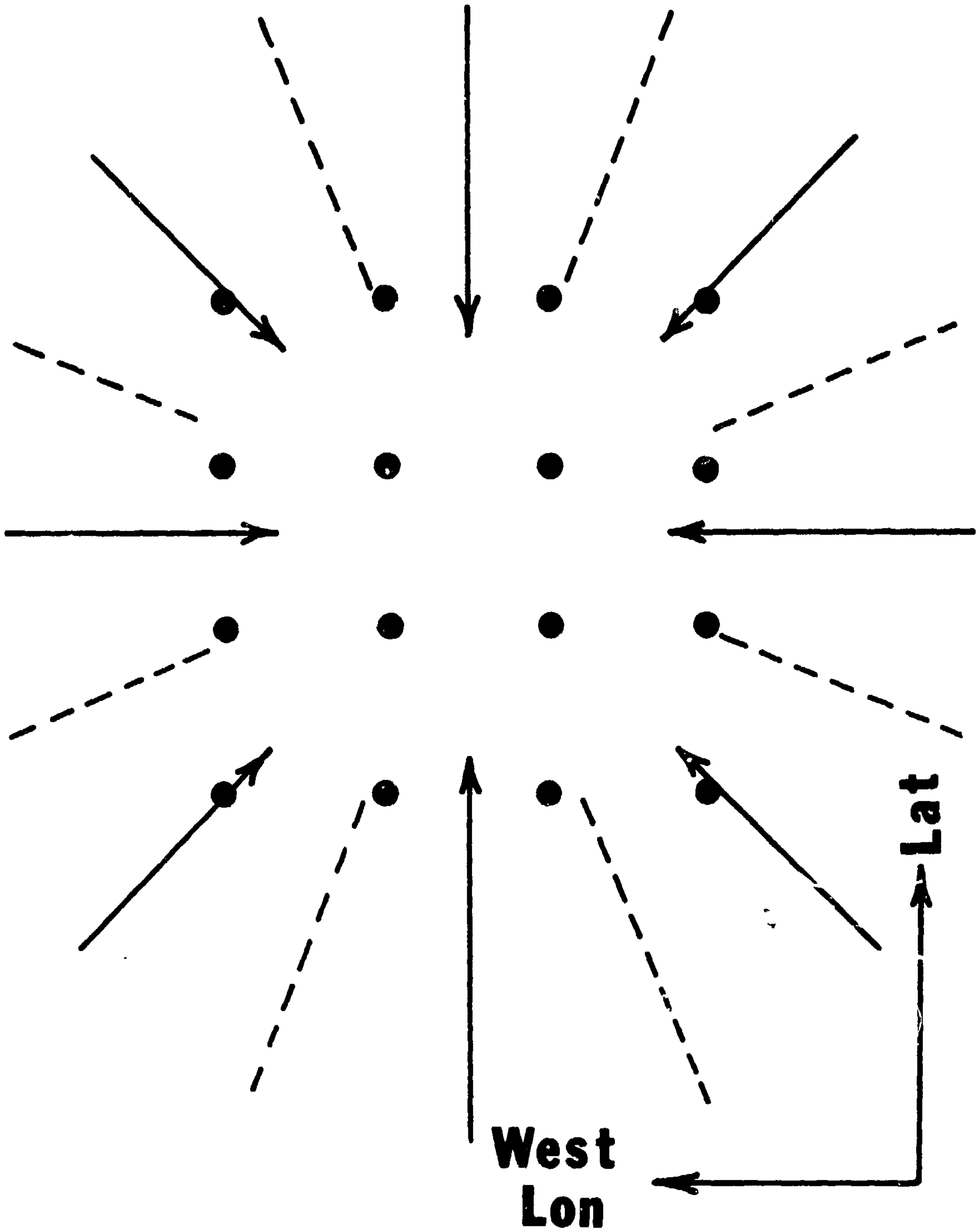


Figure 3.1 Location of the $15^{o} \times 15^{o}$ non-polar 4-D grid locations with respect to position and direction of travel. Arrows represent different possible directions of travel. Orientations of the grid are illustrated for the different positions, represented by the tips of the arrows, when the 4-D grid is first required.

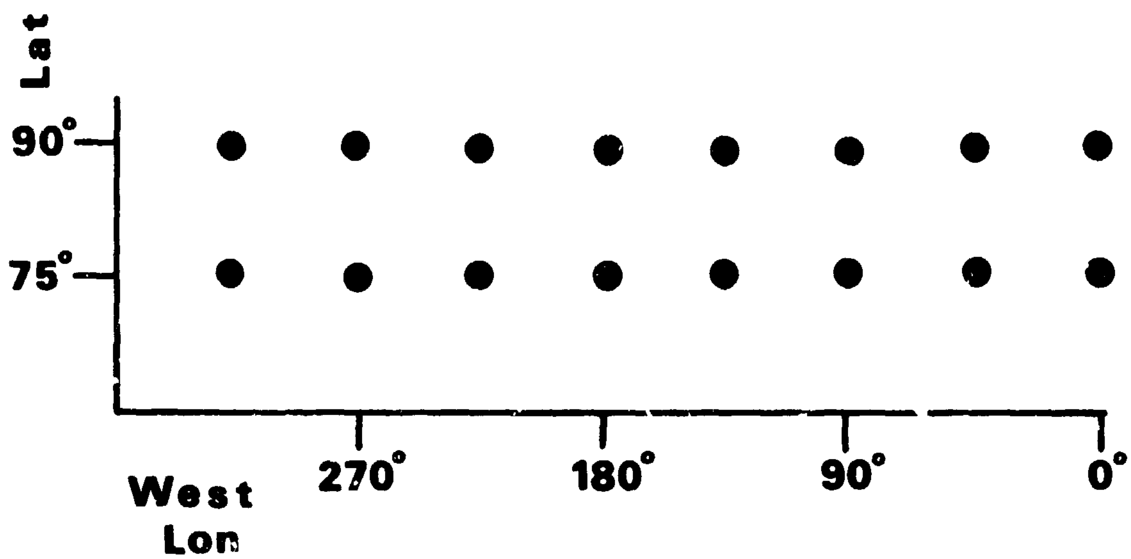


Figure 3.2 Polar 4-D grid used when the latitude is greater than 75^0 and the trajectory is headed northward (north trajectory component greater than 0). A similar grid is used near the south pole when the latitude is less than -75^0 and the trajectory is headed southward.

of pressure p_s, density ρ_s, and temperature T_s. The temperature is assumed to vary linearly between the surface (at still unknown height z_0 above sea level) and height h_s

$$T = T_0 + (T_s - T_0)(z - z_0)/(z_s - z_0) \tag{3.1}$$

Then, from the hydrostatic equation it can be shown that the pressure must vary as

$$p_s/p_0 = (T_0/T_s)^{g(z_s - z_0)/R(T_s - T_0)} \tag{3.2}$$

if $T_s \neq T_0$ and

$$p_s/p_0 = \exp\left[- g(z_s - z_0)/R\,T_0\right] \tag{3.3}$$

if $T_s = T_0$, where g is the acceleration of gravity and R is the gas constant for air. By taking the logarithm of either (3.2) or (3.3) and solving for the unknown height z_0, then one obtains

$$z_0 = z_s + R\,T_z \ln(p_s/p_0)/g \tag{3.4}$$

where the factor T_z is given by

$$T_z = T_0 \qquad \text{if } T_0 = T_s \tag{3.5}$$

$$T_z = (T_0 - T_s)/\ln(T_0/T_s) \quad \text{if } T_0 \neq T_s \tag{3.6}$$

Especially in the southern hemisphere, the 4-D data records sometimes do not go all the way to 25 km. When this occurs, interpolation between the highest valid data and the Groves (plus stationary perturbation) values at 30 km is used to fill in the missing data. If the highest valid height is below 20 km the interpolation is between the highest valid height and the Groves values at 25 km. All zero variances are filled in by using the same relative variance (e.g. σ^2_p/p^2) as for the highest valid height.

4. THE MODIFIED GROVES SECTION (25-90 KM)

The starting point for the middle atmosphere (25-110 km) is the latitude dependent model of Groves (197.). This empirical model combines many observations from a wide range of longitudes. Observational results over approximately six years were used to compute longitudinal averages, which are presented versus latitude and month. Latitude coverage of the Groves model is from the equator to 70° or in some cases 80°. Southern hemisphere data were utilized in developing the Groves model as northern hemisphere data with a 6-month change of date. Tabulations of the Groves model are at intervals of 5 km in height, 10° in latitude (northern hemisphere), and one month in time (southern hemisphere displaced six months).

Extension of Groves Data to 90°

The first problem to be overcome in using the Groves model for entire global coverage is that there are no Groves values at 90° (and in many cases none at 80°) latitude. In order to overcome this difficulty an interpolation scheme was used which was based on an assumed parabolic variation across the poles. If Groves values of an atmospheric parameter y are known up to 80° latitude, then the 90° latitude Groves value is computed from

$$y_{90} = (4y_{80} - y_{70})/3 \tag{4.1}$$

If Groves values of the atmospheric paramater y are known only up to 70° latitude, then the 80° and 90° latitude Groves values are computed from

$$y_{90} = (9\, y_{70} - 4\, y_{60})/5 \quad (4.2)$$

$$y_{80} = (8\, y_{70} - 3\, y_{60})/5 \quad (4.3)$$

Figure 4.1 illustrates the interpolation scheme as applied to Groves June temperature at 110 km.

Chart Data for Longitude Variations

The Groves model data has only height and latitude variation for each month. If longitude variation is desired, the Groves model data must be modified to incorporate this additional variation. Unfortunately the Groves region (25-110 km) is data-sparse, and most of the available data have already been used by Groves in the development of his model. A scheme, described more fully below, for using 10, 2, and 0.4 mb map data and extrapolating up to 90 km, was devised for purposes of evaluating longitude dependent relative deviations from the Groves data. These deviations, called *stationary perturbations* were evaluated at longitudes 10°, 40°, 70°, ... 340° for latitudes 10°, 30°, 50°, 70°, and 90°.

Because of time limitations, only the 1966 and 1967 10 mb monthly mean values (NOAA, 1969b) were read and averaged. The 2 mb and 0.4 mb weekly mean maps for 1966, 1967, and 1968 (NOAA, 1969a, 1970, 1971) were read for the first week of each month, and averaged over the three years. For the 10 mb maps complete northern hemisphere coverage was available. However, for the 2 mb and 0.4 mb maps, data had to be subjectively extrapolated over approximately half of the hemisphere. A typical extrapolated 0.4 mb chart is illustrated in Figure 4.2

Interpolation of Chart Data to Constant Height Levels

After the upper air chart data were averaged, the next step was to

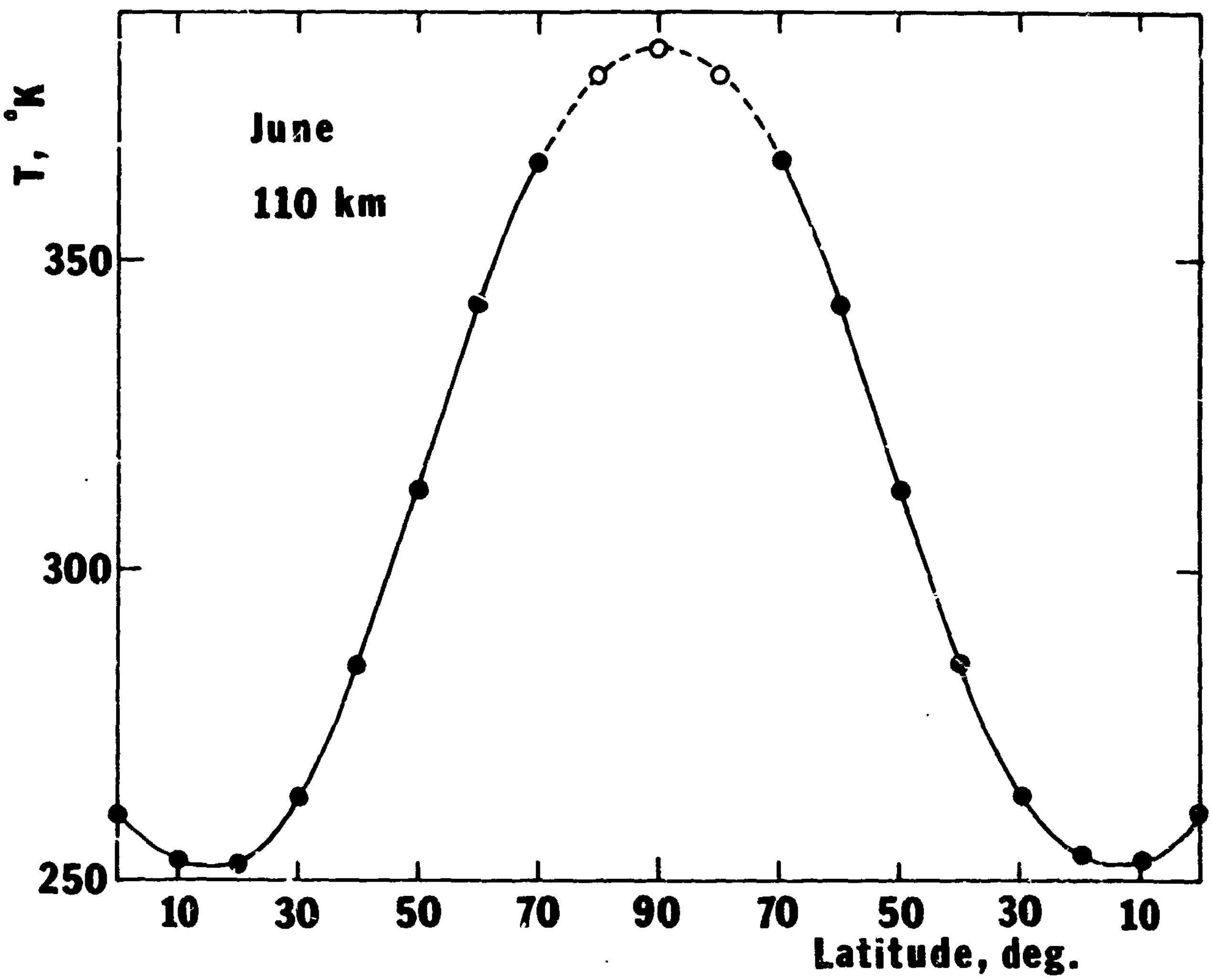


Figure 4.1 Groves interpolation to 80° and 90°. Solid dots are original Groves values. Open circles are interpolated values at 80° and 90°. Left side of graph represents Groves values vs. latitude at an arbitrary longitude x. Right side represents Groves values vs. latitude at longitude x + 180°. Dashed curve represents parabolic interpolation across the pole, as given by equations (4.2) and (4.3).

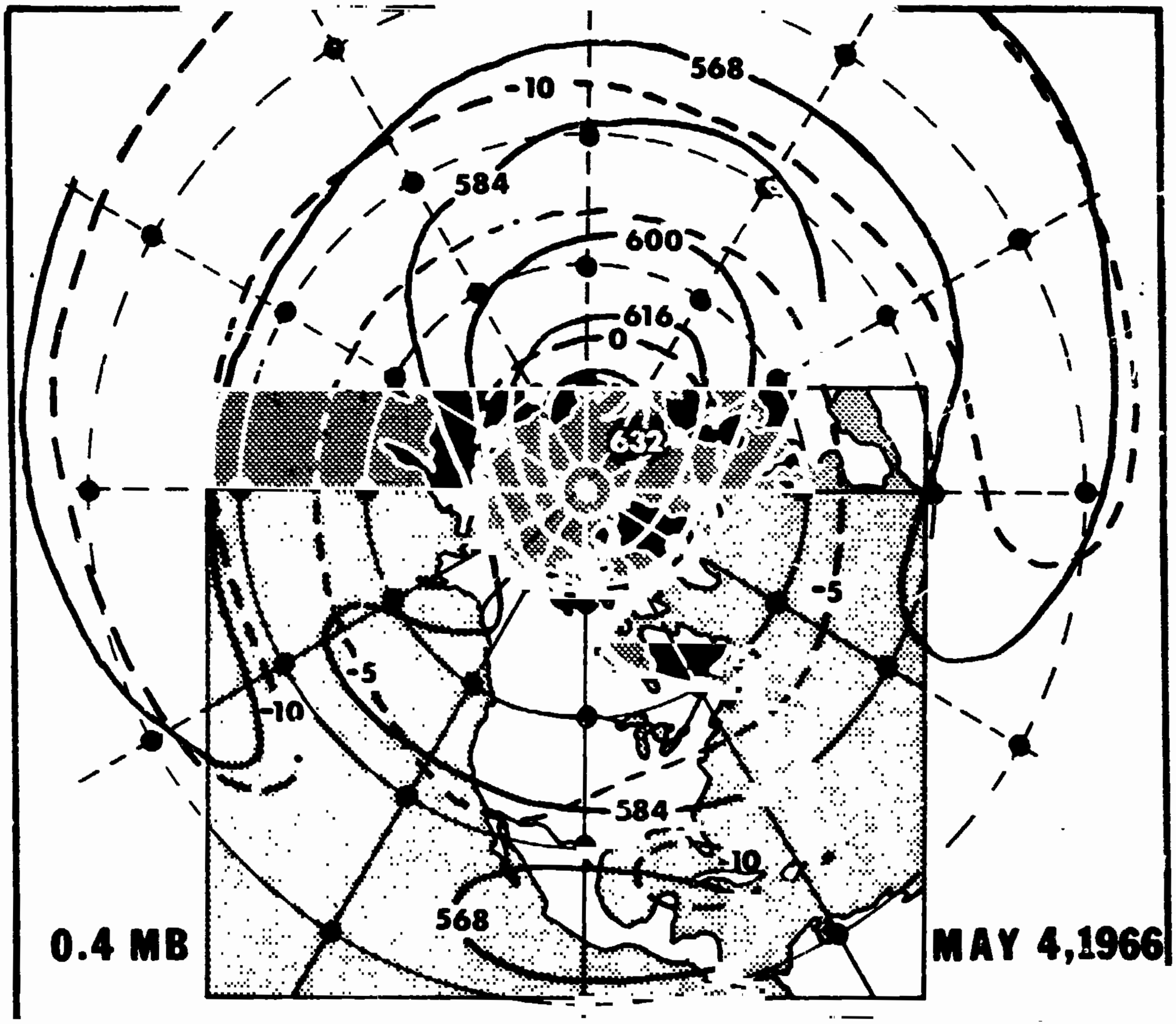


Figure 4.2 The subjectively extrapolated 0.4 mb chart for May 4, 1966. Height contours are in decameters above 50 km. Contour interval is 16 decameters. The isotherm interval is 5^{0} C. The shaded rectangular area shows the original chart. Dots show locations of points which were read to generate latitude-longitude variable stationary perturbations about the Groves model as a longitudinal mean.

convert the readings to constant heights of 30, 40, and 52 km. This was done by assuming that the temperature followed a constant lapse rate between each chart level and the nearest interpolation altitude. The method of selection of the lapse rates is illustrated in Figure 4.3. The 10 mb to 30 km lapse rate is set equal to the Groves 25 to 30 km lapse rate if the 10 mb surface is below 30 km and to the Groves 30 to 35 km lapse rate if the 10 mb surface is above 30 km, similarly with the 40 km level. The 0.4 mb to 52 km lapse rate is always taken to be the Groves 50 to 55 km lapse rate, regardless of whether the 0.4 mb surface is above or below 52 km. The chart values of height of a given pressure surface were converted to pressure values at the corresponding constant height level (i.e. 30, 40, or 52 km) by the relation

$$p_1 = p_0 (T_0/T_1)^{g/R\gamma} \qquad (4.4)$$

where subscript zero represents conditions on the constant pressure surface, subscript 1 represents conditions on the constant level surface, γ is the temperature gradient between the two levels, g is the acceleration of gravity and R is the gas constant for air. T_1 in equation (4.4) is determined by

$$T_1 = T_0 + \gamma\Delta z \qquad (4.5)$$

where Δz is the height difference between the two surfaces ($\Delta z > 0$ if the constant level surface is above the constant pressure surface). If γ is zero, then equation (4.4) becomes

$$p_1 = p_0 \exp[- g \Delta z/RT_0] \qquad (4.6)$$

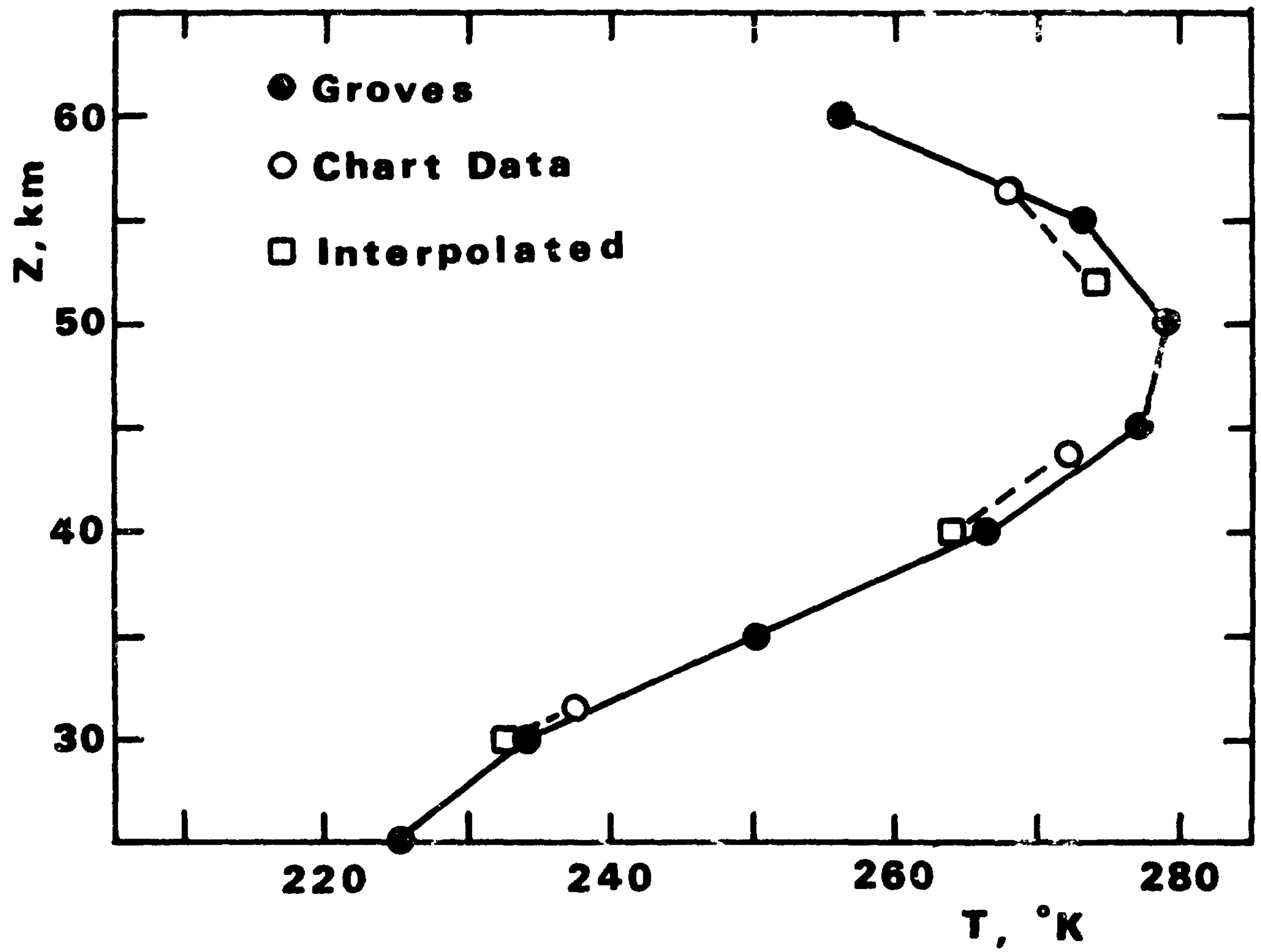


Figure 4.3 Method of interpolating the 10, 2, and 0.4 mb average chart data temperature values to constant levels of 30, 40, and 52 km.

Proper account was taken for the fact that the chart levels were in geopotential height and the desired constant level surfaces of 30, 40, and 52 km are geometric height surfaces. After interpolated pressures and temperatures have been evaluated, densities are computed from the perfect gas law.

Extrapolation of the 52 Km Level Values to 90 Km

In order to introduce longitude variability at heights above 52 km, the extrapolation technique of Graves, et al. (1973) is used to project the 52 km interpolated chart data up to 90 km. The 5 extrapolation height levels are 60, 68, 76, 84, and 90 km. The extrapolation between known (or previously computed) values at level n to level n + 1 proceeds according to the following steps:

Step 1 - Compute new density ρ_{n+1} from previous pressure and temperature by the relation

$$\rho_{n+1} = a_n + b_n p_n + c_n T_n \tag{4.7}$$

where the coefficients are from Table 1 of Graves et al. (1973)

Step 2 - Compute the new pressure p_{n+1} by a numerical integration over 1 km height intervals Δz by the relation

$$p_{n+1} = p_n - \sum_{z_n}^{z_{n+1}} \rho(z)\, g(z, \phi)\, \Delta z \tag{4.8}$$

where g is the height and latitude dependent acceleration of gravity.

Step 3 - Apply corrections to the new pressure and density. Revised pressure integration correction parameters at the latitudes required here are shown in Figures

4.4 through 4.6. These curves were evaluated by interpolating the integration correction curves given in Figures 4-6 of Graves, et al. (1973), using an interpolation scheme similar to that used to extrapolate the Groves data to polar latitudes (see Figure 4.1). Density correction curves were developed similarly from those given in Figure 7 of Graves et al. (1973).

Step 4 - The new temperature is computed from the perfect gas law, using the already evaluated new pressure and density. The gas constant is assumed not to vary with height up to 90 km.

The Stationary Perturbations

After the chart data have been interpolated to 30, 40, and 52 km and extrapolated to 60, 68, 76, 84, and 90 km, the stationary perturbations (relative deviations to be added to the Groves values) are calculated. At each altitude and latitude the stationary perturbation s_y for a parameter y (which can represent pressure, density, or temperature) is computed by the relation

$$s_y = (y - \langle y \rangle)/\langle y \rangle \qquad (4.9)$$

where $\langle y \rangle$ represents the longitude averaged value of y (i.e. averaged around a circle of fixed latitude). Note that the definition of s_y makes it be identically zero at the pole. The stationary perturbation s_y for parameter y is added to the Groves value G_y to produce the longitude variable modified Groves value G'_y, according to the relation

$$G'_y = G_y(1 + s_y) \qquad (4.10)$$

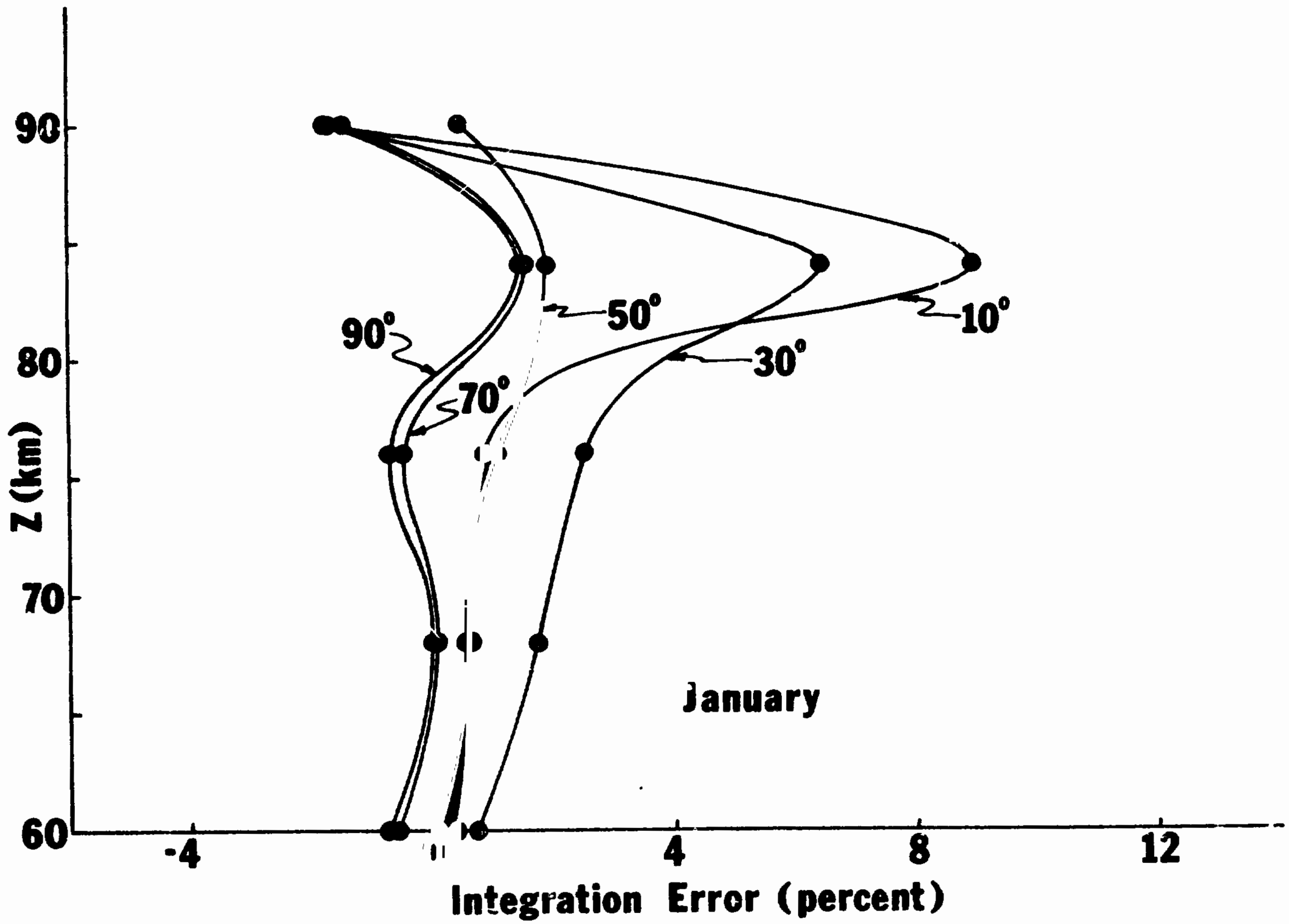


Figure 4.4 Integration correction to be applied to the pressure computed by equation (4.8) for the month of January.

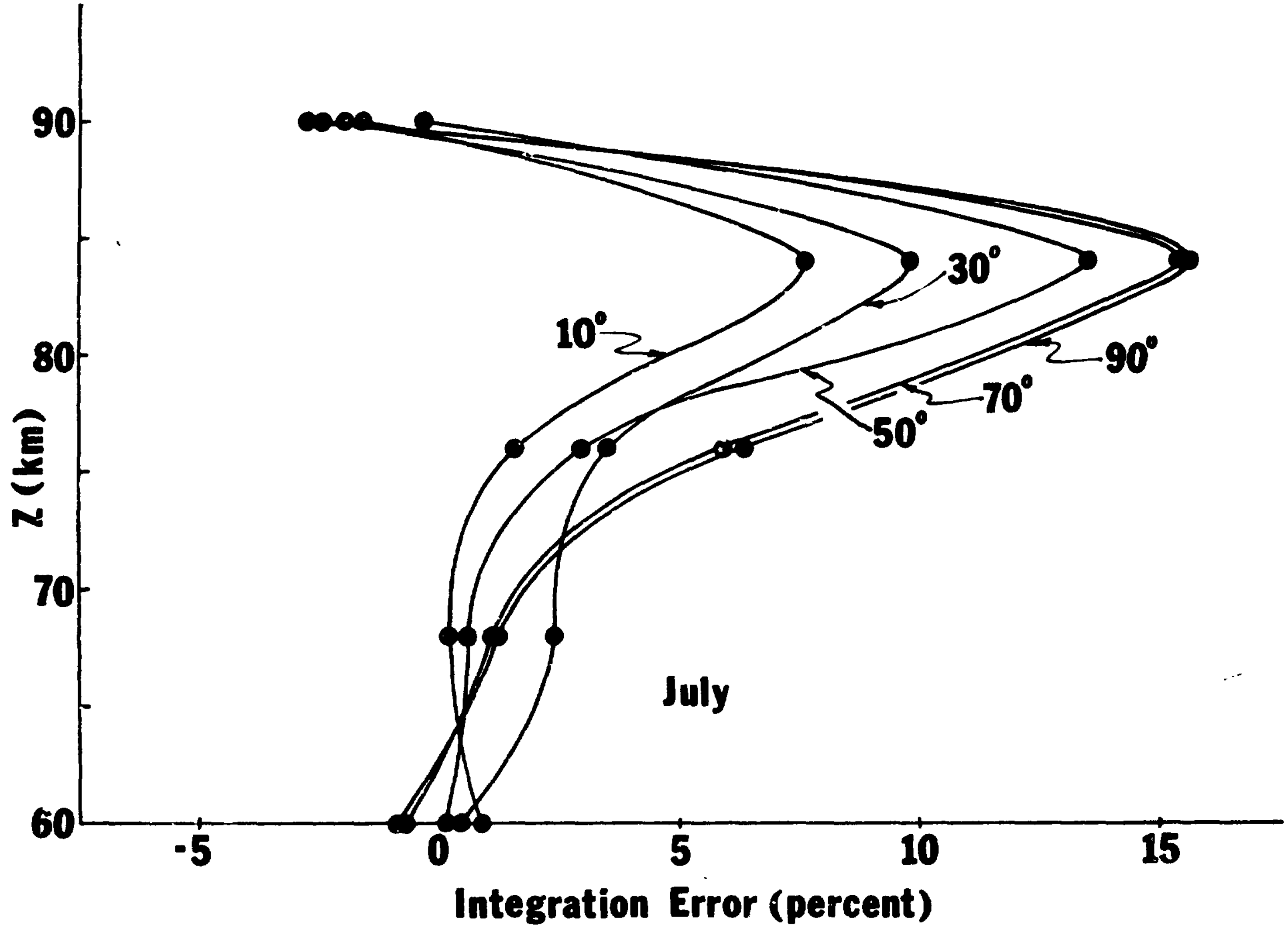


Figure 4.5 As in Figure 4.4 for the month of July.

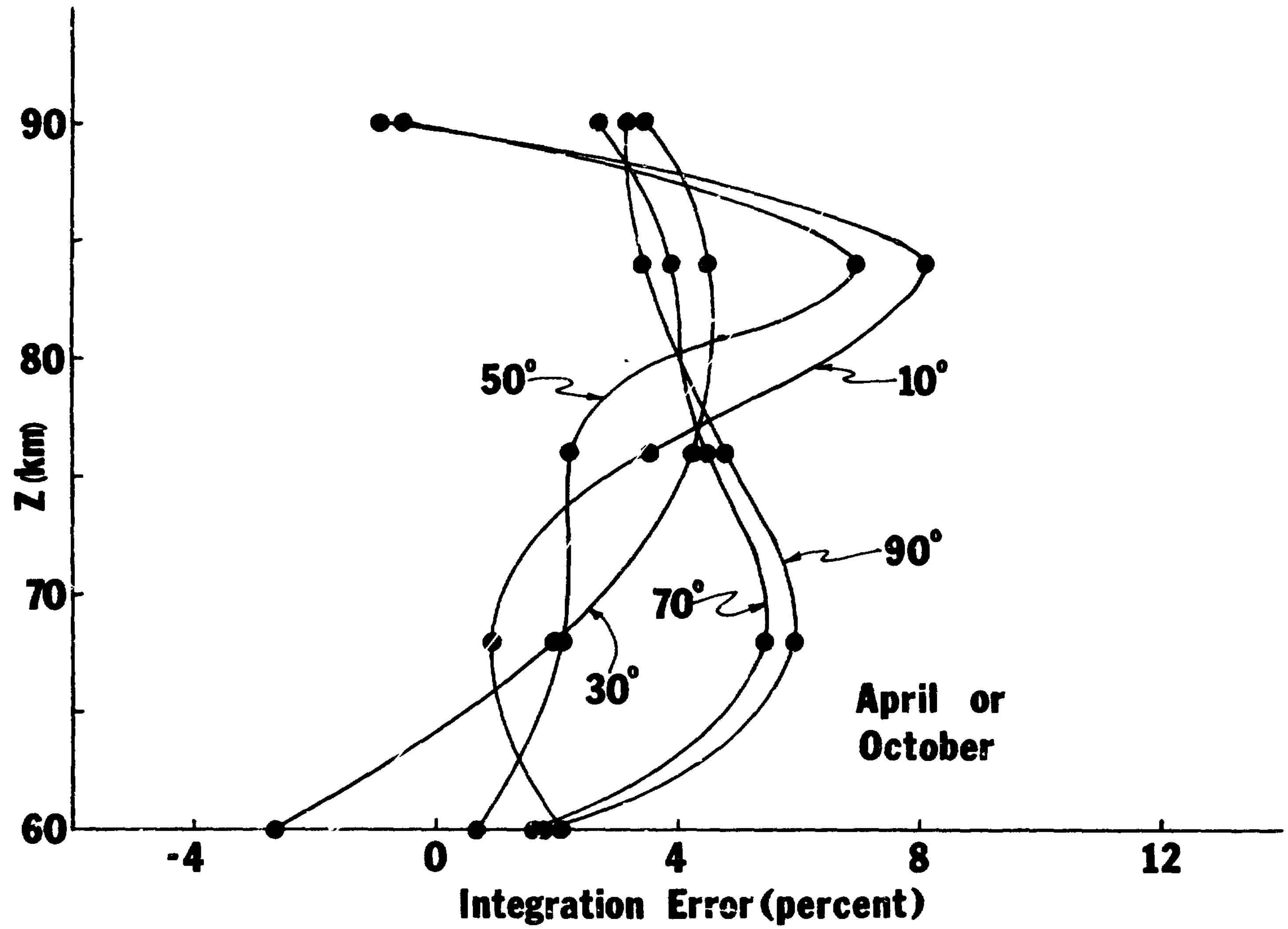


Figure 4.6 As in Figure 4.4 for the months of April or October.

The modified Groves values, determined by relation (4.10), are used as the monthly mean values for the altitude range 30 to 90 km. As discussed in Section 1, the monthly means between 25 and 30 km are interpolated between 4-D and modified Groves values, and values between 90 and 115 km are faired between the Groves and Jacchia values. Details of the interpolating and fairing methods are discussed in the next section.

5. INTERPOLATION AND FAIRING

The 4-D data are available on the data tapes at one km height intervals and at $5^{o} \times 5^{o}$ latitude-longitude grids in the southern and equatorial areas and at the NMC grid locations in the northern hemisphere. NMC grid profiles are always converted (by interpolation) to $5^{o} \times 5^{o}$ grids before interpolation to the trajectory locations. Selection of the grid locations according to trajectory direction was discussed in Section 3. The general interpolation requirements for the 4-D section are height interpolation over 1 km and latitude-longitude interpolation over a $5^{o} \times 5^{o}$ square grid.

The Groves data are tabulated at 5 km height intervals and 10^{o} latitude intervals. Interpolation is required between these tabulated locations. The stationary perturbations are evaluated at 20^{o} latitude and 30^{o} longitude intervals and at 30, 40, 52, 60, 68, 76, 84, and 90 km altitudes. Interpolation between these tabulated locations is also required. For values between 25 km and 30 km interpolation between the 4-D data and Groves-plus-stationary-perturbation data are required. The interpolations are always carried out in the PROFILE program by doing the latitude (Groves) or latitude-longitude (4-D) interpolation first, and then doing the height interpolation.

The Jacchia model can be evaluated at any height above 90 km and at any latitude and longitude, so no interpolation is required. However, between 90 and 115 km there is overlap between the Groves data and the Jacchia model, so a fairing procedure is used to effect a smooth transition between the Groves data at 90 km and the Jacchia values at 115 km.

Height Interpolation

The method used to interpolate pressure, density, and temperature over a height interval between heights z_1 and z_2 is to assume linear variation of the temperature and of the logarithm of the density. Thus, interpolation to any height z (such that $z_1 \leq z \leq z_2$) is given by

$$T(z) = T_1 + (T_2 - T_1)(z - z_1)/(z_2 - z_1) \tag{5.1}$$

$$\rho(z) = \rho_1 (\rho_2/\rho_1)^{(z - z_1)/(z_2 - z_1)} \tag{5.2}$$

where subscripts 1 and 2 denote values at heights z_1 and z_2. The pressure can be evaluated from the perfect gas law. However, especially above 90 km, the gas constant can vary with height. So the empirical values of the gas constant is also linearly interpolated by interpolating on the ratio $R = p/\rho T$

$$R(z) = R_1 + (R_2 - R_1)(z - z_1)/(z_2 - z_1) \tag{5.3}$$

Then the pressure at z can be evaluated by

$$p(z) = \rho(z) R(z) T(z) \tag{5.4}$$

Figure 5.1 and 5.2 illustrate the linear interpolation used on a particular 4-D and Groves profile.

Latitude-Longitude Interpolation

The latitude interpolation for the Groves data is done by assuming linear variation between the latitudes ϕ_1 and ϕ_2 (which are at $\Delta\phi = 10^d$ apart). Thus, for any variable y the interpolation to latitude ϕ (such

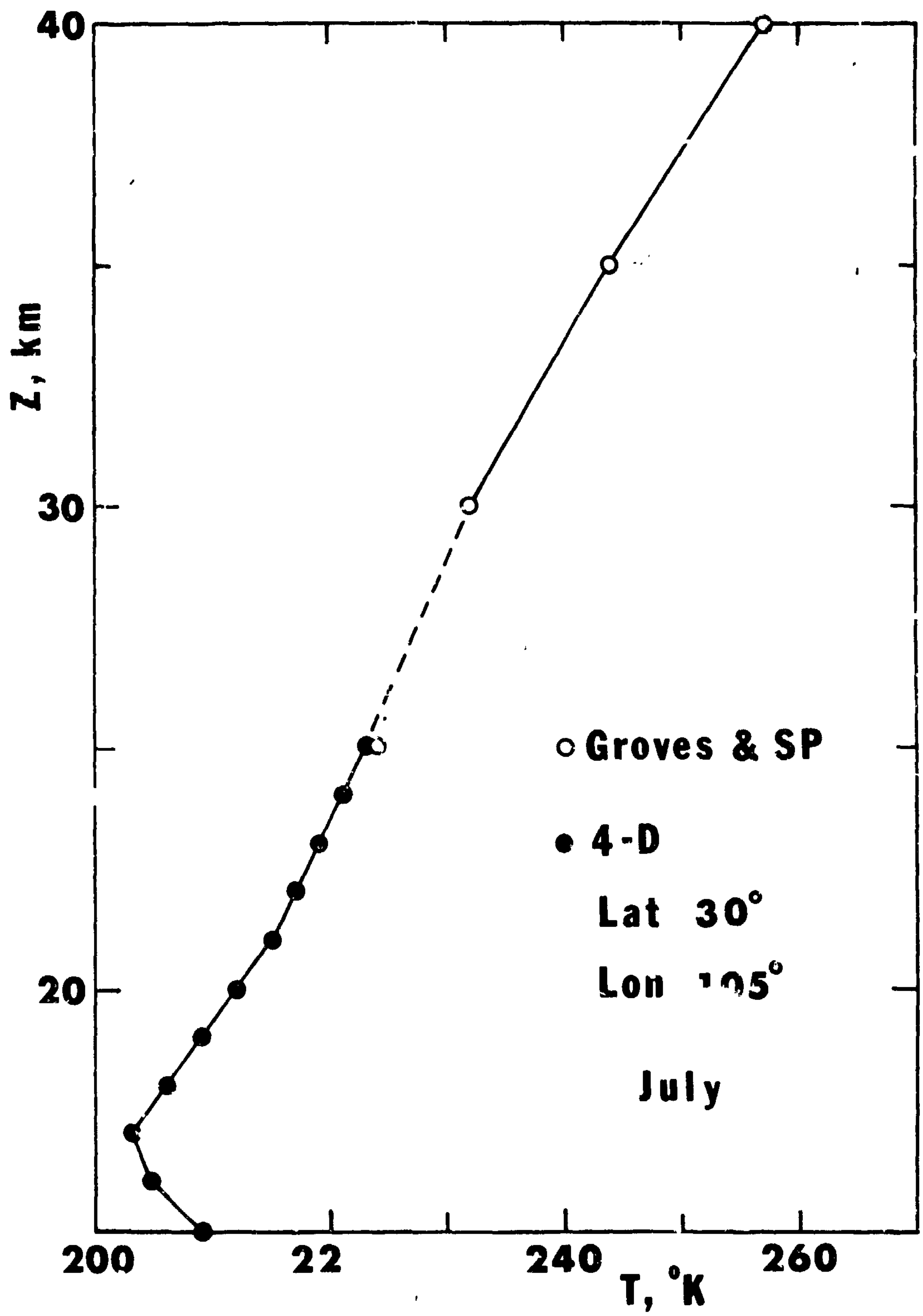


Figure 5.1 The linear interpolation process used for 4-D and Groves temperatures. The dashed line shows the linear interpolation used between 4-D at 25 km and Groves plus stationary perturbations at 30 km.

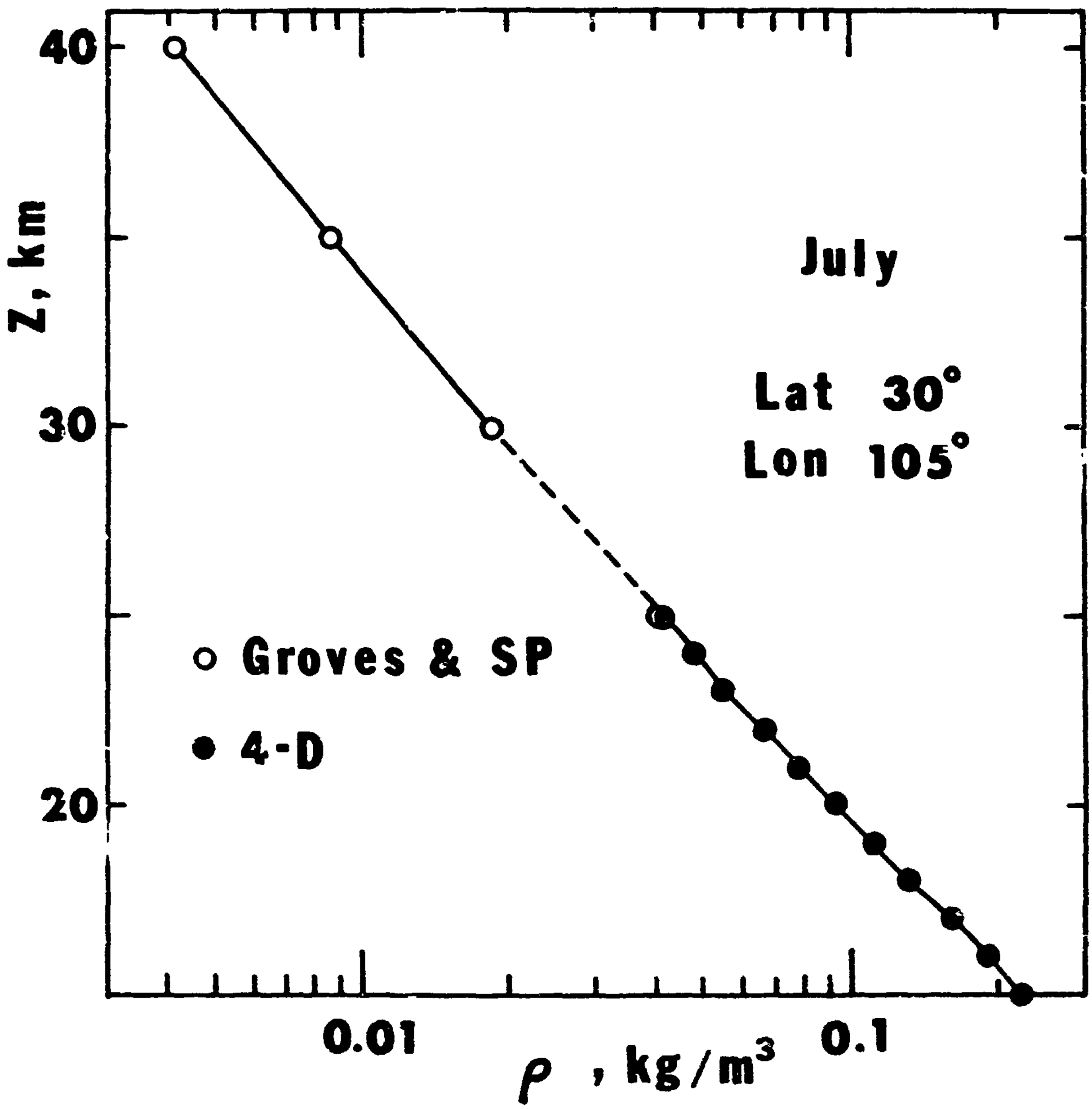


Figure 5.2 As in Figure 5.1 except the linear interpolation is on the logarithm of the density.

that $\phi_1 \leq \phi \leq \phi_2$) is given by

$$y(\phi) = y_1 + (y_2 - y_1)(\phi - \phi_1)/\Delta\phi \qquad (5.5)$$

where subscripts 1 and 2 indicate values at latitudes ϕ_1 and ϕ_2, respectively.

Two dimensional latitude-longitude interpolation between a square or rectangular array of positions, as illustrated in Figure 5.3, at latitudes ϕ_1 and ϕ_2 and west longitudes λ_1 and λ_2, is done by substituting ϕ values for x values and λ values for y values in equation (A-5) in Appendix A. Thus for any latitude ϕ such that $\phi_1 \leq \phi \leq \phi_2$ and any longitude λ such that $\lambda_1 \leq \lambda \leq \lambda_2$, the interpolated value of any parameter F is

$$F(\phi, \lambda) = F_0 + (F_1 - F_0)\delta\phi + (F_2 - F_0)\delta\phi + (F_3 - F_1 - F_2 + F_0)\delta\phi\,\delta\lambda \qquad (5.6)$$

where $\delta\phi$ is $(\phi - \phi_1)/(\phi_2 - \phi_1)$ and $\delta\lambda$ is $(\lambda - \lambda_1)/(\lambda_2 - \lambda_1)$. Latitudes and longitudes of the subscripted F's are illustrated in Figure 5.3.

Groves-Jacchia Fairing

To accomplish smooth transition between the Groves values at 90 km and the Jacchia values at 115 km a fairing technique is used. This fairing makes use of a parameter θ defined by

$$\theta = (\pi/2)(z - 90)/(115 - 90) \qquad (5.7)$$

where z is the height at which the Groves and Jacchia values are to be faired. The fairing is accomplished by use of the relations

$$F = F_G \cos^2(\theta) + F_J \sin^2(\theta) \qquad (5.8)$$

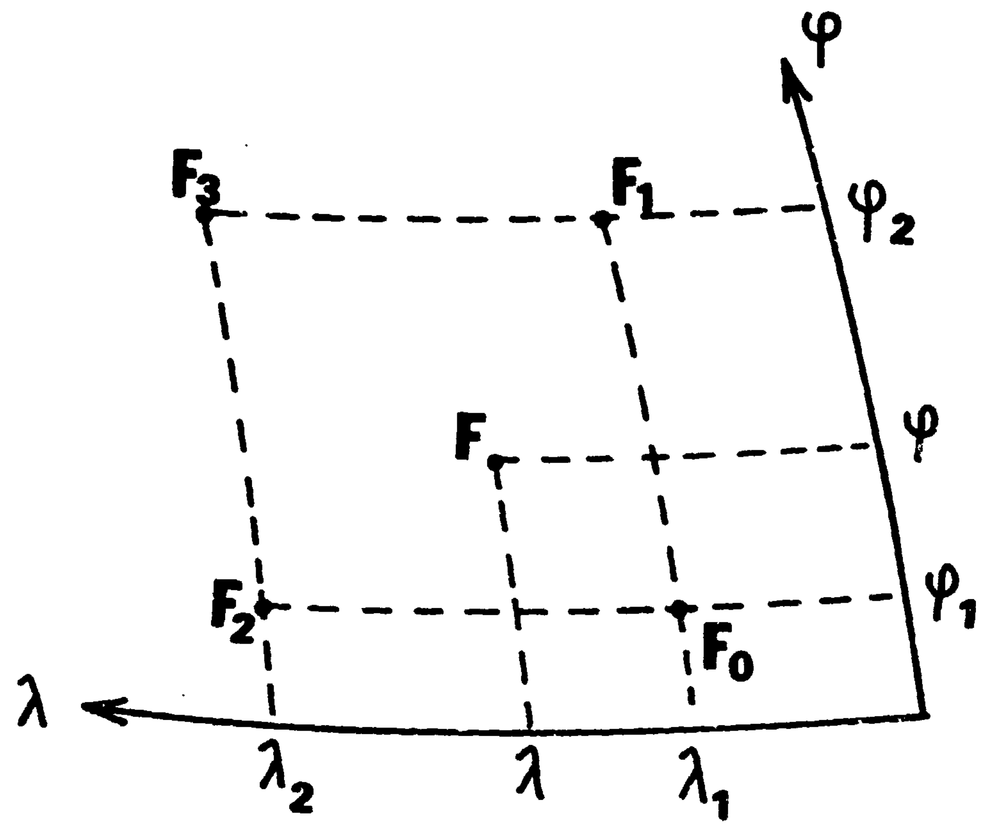


Figure 5.3 Two dimensional interpolation of parameter F as a fuction of latitude ϕ and west longitude λ. The interpolation function is given by equation (5.6)

where F can represent temperature, T, or the logarithms of pressure or density, ln p or ln ρ. From the definition of the parameter θ, F varies from the Groves value F_G at 90 km to the Jacchia value F_J at 115 km in a smooth fashion such that the value of F remains between the value of F_G and F_J between 90 and 115 km. Examples of the application of this fairing technique are illustrated in Figures 5.4 and 5.5. The fairing is done only at the altitudes 95, 100, 105, 110, i.e. heights for which there are Groves values. Linear interpolation is then used to fill in the remaining heights, as discussed in the height interpolation section above.

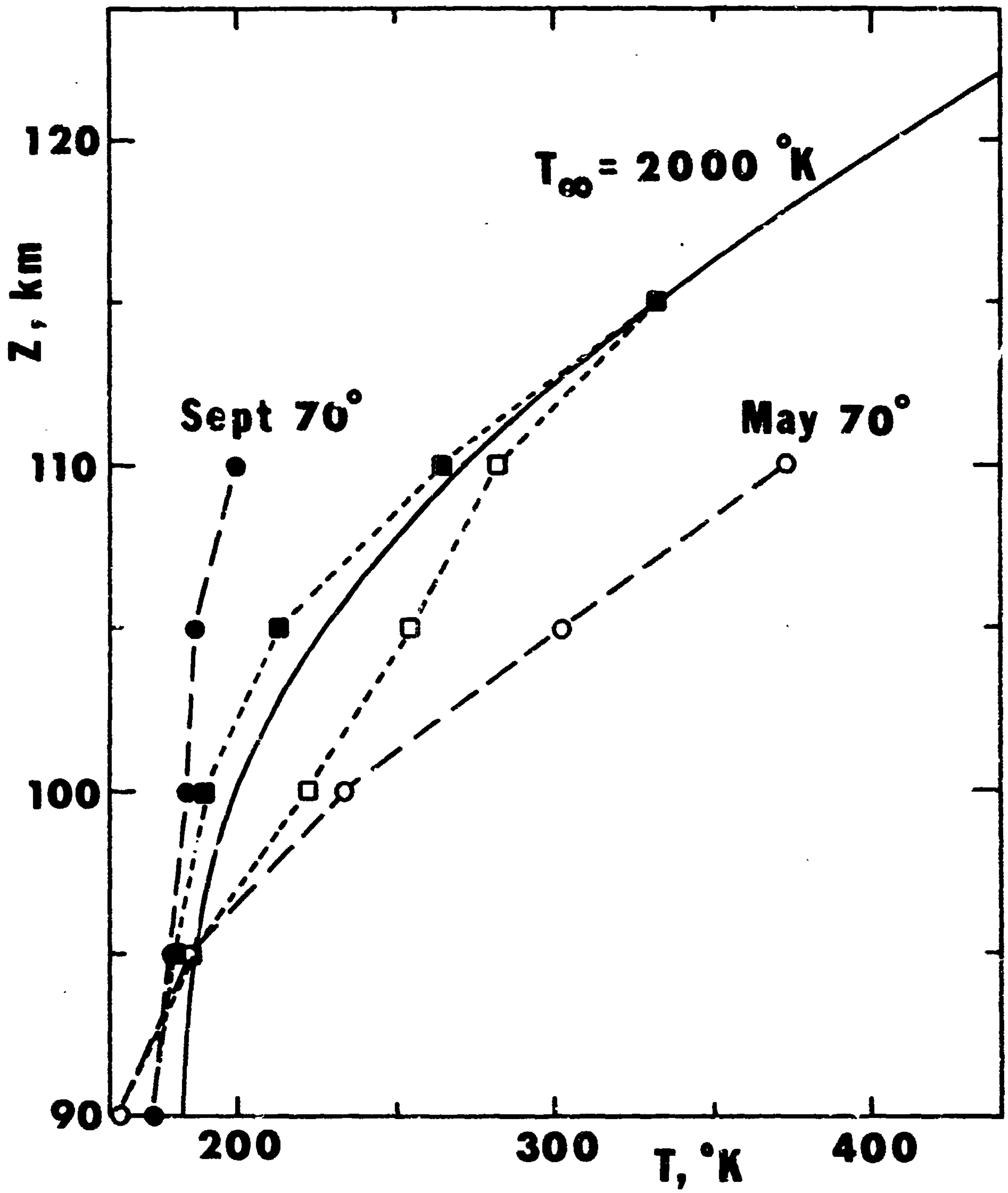


Figure 5.4 Groves - Jacchia fairing for two extreme Groves temperature profiles and the Jacchia temperature for an exospheric temperature T_∞ of 2000 °K.

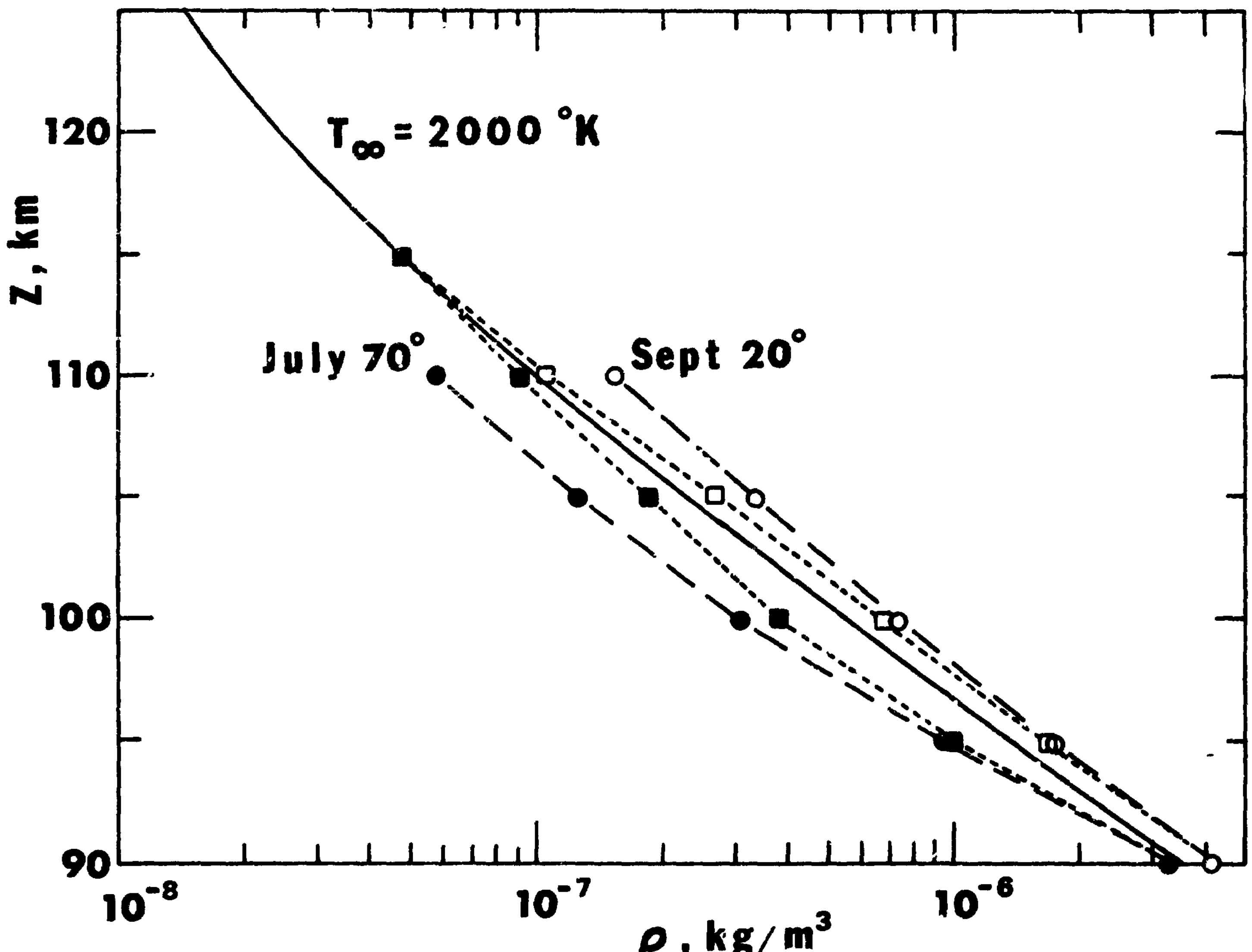


Figure 5.5 Groves - Jacchia fairing for density. Extreme Groves profiles and T_∞ = 2000 °K.

6. THE ANNUAL REFERENCE PERIOD

In addition to the 12 monthly reference periods a set of annual reference period data has also been evaluated for use in the PROFILE program. The annual reference period data for the 4-D and Groves ranges were evaluated as described below. For the Jacchia range the exospheric temperature is automatically set to 1000 °K for the annual reference period.

4-D Annual Reference Period (Below 25 Km)

The 12 4-D monthly tapes have been averaged to produce an annual reference period tape, exactly in the same format as the monthly tapes (and referred to as month 13 for handling purposes in the program). Two aspects, however, make the annual reference tape slightly different from just an average of the information on the 12 monthly tapes: (1) the pressure and density profiles are re-computed from the average temperature profile and the conditions of hydrostatic equilibrium and the perfect gas law, (2) The variation of the monthly means about the annual mean is added to the mean of the monthly variances.

The 4-D annual reference temperature profile is merely an arithmetic average of the 12 monthly temperature profiles. After determination of the temperature profile then the hydrostatic balance condition, assuming constant temperature gradient over the 1 km intervals of the profiles, means that a known or previously computed pressure p_0 at level z_0 can be used to compute pressure p_1 at level z_0 + 1 km, by the relation

$$p_1 = p_0(T_0/T_1)^{g/R\gamma} \tag{6.1}$$

where $T_1 = T_0 + \gamma\Delta z$, γ is the constant temperature gradient, Δz is 1 km, g is the acceleration of gravity and R is the gas constant for air. If $\gamma = 0$ then (6.1) becomes

$$p_1 = p_0 \exp[-g\Delta z/RT_0] \tag{6.2}$$

The surface pressure and the first valid pressure above the surface (generally at 1 km) are taken to be the arithmetic average of the 12 monthly values. Equation (6.1) or (6.2) is then used to generate a profile from the starting pressure value at the first valid height. Once the annual reference period temperature and pressure profiles are established, then the annual reference period density is computed from the perfect gas law.

Each monthly profile has an associated variance profile which is also averaged. However, the variance to be associated with the annual mean values will be more than the mean of the monthly variances. The variance due to variation of each of the monthly means must also be accounted for. It can easily be shown that these two variances add linearly (i.e. since the variance is the square of the standard deviation, the standard deviations add as the sum of the squares). Thus the variance v_a for a parameter y for the annual reference period is given by

$$v_a = \langle v_m \rangle + \langle y_m^2 \rangle - \langle y_m \rangle^2 \tag{6.3}$$

where $\langle v_m \rangle$ represents the annual mean of the monthly variances, $\langle y_m \rangle$ is the annual mean of the monthly means, and $\langle y_m^2 \rangle$ is the mean of the square of the monthly mean. The last two terms of (6.3) merely represent the variance of the monthly means about the annual mean for the parameter y.

Groves Annual Reference Period

The annual reference period data for the Groves data are handled in a similar manner to the 4-D data. The Groves monthly temperatures are averaged for an annual value, the annual mean pressures are computed from the hydrostatic relation, and the annual mean densities are computed from the perfect gas law.

The variance due to the variation of the monthly mean Groves values about the annual mean is added to the mean square of the standard deviations of the random component, discussed later in Section 8.

The stationary perturbation values are all averaged arithmetically to compute the annual mean stationary perturbation. Thus the 25-110 km range has a latitude-longitude variable monthly mean consisting of the annual mean Groves modified by the annual mean stationary perturbation, as in equation (4.10).

7. WINDS IN THE MODEL

Conceptually an independent wind model, such as the E-W wind model of Groves (1971), could be added to the pressure, density, and temperature model. However, the approach taken in the PROFILE program was to compute a mean wind from the geostrophic wind equations (which rely on horizontal pressure gradients) and a mean wind shear from the thermal wind equations (which rely on horizontal temperature gradients). Comparison of the computed winds and shears with each other and with measured wind data will then serve as a check on the consistency of the pressure and temperature fields. As will be shown in Section 10, sample results of the wind computations do show good agreement with measured results. Specific models for the random and quasi-biennial components of the wind are added to the mean wind, as discussed later in Sections 8 and 9.

Geostrophic Winds

The eastward (i.e. blowing toward the east) wind component u and northward component v can be evaluated from the geostrophic wind equations

$$u = -(1/\rho f)\ \partial p/\partial y \qquad (7.1)$$

$$v = (1/\rho f)\ \partial p/\partial x \qquad (7.2)$$

where ρ is the density, f is the coriolis parameter ($2\ \Omega \sin\phi$) and $\partial p/\partial x$ and $\partial p/\partial y$ are the eastward and northward components of the horizontal pressure gradient. For evaluation in the model, the pressure gradient terms must be approximated by finite differences.

If values of p are known at a rectangular (or square) array of latitude-longitude points (as with F in Figure 5.3) then $\partial p/\partial x$ and $\partial p/\partial y$ are evaluated by a linear interpolation of the finite differences at the edges of the latitude-longitude array.

$$(\partial p/\partial x)\Big|_{\phi,\ \lambda} = \frac{(p_0 - p_2) + [(p_1 - p_3) - (p_0 - p_2)](\phi - \phi_1)/(\phi_2 - \phi_1)}{(\lambda_2 - \lambda_1)\ R_e \cos\phi} \tag{7.3}$$

$$(\partial p/\partial y)\Big|_{\phi,\ \lambda} = \frac{(p_1 - p_0) + [(p_3 - p_2) - (p_1 - p_0)](\lambda - \lambda_1)/(\lambda_2 - \lambda_1)}{(\phi_2 - \phi_1)\ R_e} \tag{7.4}$$

where the subscripting is the same as for F, ϕ (latitude) and λ (longitude) as in Figure 5.3, and R_e is the radius of the Earth (required to convert latitude or longitude displacements to distance displacements).

Geostrophic wind values ·· also computed in the Jacchia height range by evaluating the Jacchia model at 5 degree increments of latitude and longitude and taking finite differences of the resulting pressure. This technique probably over extends the capabilities of the Jacchia model, however, and the computed winds in this height range should not be considered precise.

Thermal Wind Shear

The wind shear components $\partial u/\partial z$ and $\partial v/\partial z$ are evaluated by the thermal wind equations

$$\partial u/\partial z = -(g/fT)\ \partial T/\partial y \tag{7.5}$$

$$\partial v/\partial z = (g/fT)\ \partial T/\partial x \tag{7.6}$$

which is the usual form, leaving off a correction term in $\partial T/\partial z$, which is normally small. The horizontal temperature gradient terms in (7.5) and

(7.6) are estimated by finite differences in a similar manner to the pressure gradient components in equations (7.3) and (7.4).

Thermal wind shears are also computed in the Jacchia height range in a manner similar to that described for the wind calculations. Again, however, for the reasons already discussed, these values should not be taken as precise.

8. THE RANDOM VARIATIONS

In addition to the monthly means, two type of perturbations are considered in the model: random variations, and quasi-biennial oscillations, discussed in the following section. The random variations are considered to have a Gaussian distribution about the monthly mean with a standard deviation σ determined from empirically observed atmospheric variability. Tables of the random pressure, density, temperature and wind component as they are used on the program input tape appear in the users manual section of this report.

Random Pressure, Density, and Temperature

In the 4-D altitude range (below 25 km) the random σ's are taken directly from the 4-D data tapes as the square root of the tabulated variance values. For temperature and density in the 25-90 km range the extreme values tabulated by Youngblood (1972) were converted to equivalent standard deviations. In evaluating the extreme values, Youngblood relyed extensively on previous atmospheric variability studies by Cole (1970) and Theon (1972). Youngblood's tabulated extremes are taken to be 1% and 99% levels and the σ's for density and temperature computed from

$$(\sigma_T/\bar{T}) = (T_{HI} - T_{LO})/2(2.32)\ T_{AV} \quad (8.1)$$

and

$$(\sigma_\rho/\bar{\rho}) = (\rho_{HI} - \rho_{LO})/2(2.32)\ \rho_{AV} \quad (8.2)$$

where the subscripts HI and LO refer to the 1% and 99% extremes; ρ_{AV} in

Youngblood's report is taken from the Groves (1970) model. The factor 2.32 in equations (8.1) and (8.2) results from the fact that the 1% and 99% levels occur at $\pm$ 2.32σ from the mean in a Gaussian distribution. The σ's from Youngblood's data were evaluated at 5 km height intervals (25-90 km) and at latitudes 10^0, 30^0, 50^0, 70^0, and 90^0. Interpolation and extrapolation over the pole, similar to the method employed on the Groves data, was used to fill in values which were not available in Youngblood's report. The standard deviation for pressure in the 25-90 km range is computed from the relation

$$(\sigma_p/\bar{p})^2 = (\sigma_\rho/\bar{\rho})^2 + (\sigma_T/\bar{T})^2 + 2(\sigma_\rho/\bar{\rho})(\sigma_T/\bar{T})\ r(\rho T) \tag{8.3}$$

which is a condition derived by Buell (1970) which must result from the restrictions imposed on the atmospheric variation by the perfect gas law. The factor $r(\rho T)$ is the correlation between the density and temperature perturbations, and was evaluated by using Table 14.9 in Smith et al. (1971). (These tabulated values of $r(\rho T)$, strictly speaking, apply only to Cape Kennedy, but they were used for lack of appropriate correlation values at all latitudes). Relation (8.3) was used to evaluate $\sigma_p/\bar{p}$, rather than direct observational data, because the model used to generate the correlated random perturbations, described later in this section, requires consistant σ's and correlations as described by Buell (1970). In some cases the 4-D values of the σ's, when used in equation (8.3), would result in an unrealistic value for $r(\rho T)$, i.e. $|r(\rho T)| > 1$. When this occurred a default value of $r(\rho T)$ was also evaluated from Table 14.9 of Smith et al. (1971).

Above 90 km, the standard deviations for temperature and density were assumed to be independent of latitude and were taken from Figure 7 of Justus and Woodrum (1973). The standard deviations for pressure above 90 km were evaluated from equation (8.3) using a value for the density temperature correlation of $r(\rho T) = -0.75$, which is a consistent extrapolation from Table 14.9 of Smith et al. (1971).

Random Winds

An estimate of the amplitude of irregular winds as a fuction of height, latitude, and month of year is needed in order to combine with mean wind profiles to give realistic atmospheric wind profiles. Irregular winds will consist of all wind deviations from the monthly mean wind profile. Major contributions to the irregular winds are tides, gravity waves, and planetary waves.

As the data tape and the PROFILE program are presently set up, the standard deviations for the two horizontal random wind components are assumed to be equal. However, if it is desired to revise the data tape input, the program can easily be modified to accommodate unequal values for σ_u and σ_v. (These modifications are described in the programmers manual portion of this report).

Groves (1970) developed a mean model of the eastward wind and then calculated a standard deviation of experimental data from his mean model.

These standard deviations represent good estimates of the amplitudes of the irregular winds.

Tables 7-10 of Groves (1971) give his empirical model for the eastward wind component for the 25-130 km height range. Tables 13-17 of Groves (1971) include the measured standard deviation of the observed winds about the Groves model values. For some latitudes the Groves values for σ_u were available up to 120 km, for other latitudes only up to 80 km.

Thus from the Groves data, irregular eastward wind amplitudes were obtained for each month of the year at heights of 25 km up to about 100 km in steps of 5 km and for latitudes of 10, 30, 50, and 70 degrees. The amplitudes at 90 degrees latitude were found be extrapolating over the poles as explained in Section 4.

The irregular wind amplitudes above 100 km were estimated by considering the amplitudes of their main constituents. Planetary waves were assumed to be negligible in this height range. Thus, gravity waves and tides were assumed to be mainly responsible for the irregular winds at these heights. Amplitudes of the gravity waves were obtained from Figure 5 of Justus and Woodrum (1973). Amplitudes of the semidiurnal tides were estimated from Lindzen and Chapman (1969), Woodrum and Justus (1968), and Woodrum, Justus, and Roper (1969). Lindzen predicted theoretical amplitudes of the semidiurnal tide for heights above 100 km. However, his predicted values seemed to be much too large when compared with experimental data at altitudes from 100 to about 120 km. Thus, the values used in the present analysis were the theoretical values of Lindzen which had been scaled-down to agree with the experimental data. Diurnal tides were not included in the irregular winds because the diurnal variations were already contained in the Jacchia Model, which was used to calculate the "mean" wind. Latitude variations of the gravity waves and the semidiurnal tides were assumed to be negligible. The amplitudes of the gravity waves and the tides were combined to give an irregular wind amplitude in the following manner.

$$\sigma_{irr} = (\sigma_{GW}{}^2 + \sigma_{Tide}{}^2)^{1/2} \tag{8.4}$$

Amplitudes below 25 km were obtained by combining the above results from Groves and results from Figure 2 of Kantor and Cole (1964). Mean eastward wind profiles below 25 km were obtained from Kantor and Cole (1964) for the months of January and July at all latitudes except 90°. Then by assuming that the irregular wind amplitudes are proportional to the mean wind ampltidues, one can estimate the irregular wind amplitudes by the following method.

Since values of the irregular wind amplitudes and the mean wind amplitudes both exist at heights of 25 km, monthly varying normalizing factors between the irregular winds and the mean winds are calculated at this height as follows:

$$\text{Normalizing Factor} = \frac{\text{Irregular Wind Amplitude}}{\text{Mean Wind Amplitude}} \tag{8.5}$$

However, the values for the mean wind amplitudes are given only for the months of January and July. Thus, the normalizing factors were calculated for the months of November, December, January, February, and March by using the mean wind amplitude value of January only, and the monthly values of the irregular wind amplitudes from Groves (1971). Similarly, the normalizing factors for the months of May, June, July, August, and September were calculated by using the July value of the mean wind amplitude. Two normalizing factors were calculated for each of the months, April and October, by using both the January and July values of the mean wind amplitudes. This method of calculating the normalizing factors assumes that during a half-year interval, the major variations in the monthly values of the normalizing factor are caused mainly by the monthly variations of the irregular wind amplitudes. Then, the monthly irregular wind amplitudes below 25 km were calculated by multiplying the January and July mean wind values at the various heights by corresponding monthly normalizing factors, where the grouping of the months were the same as above. Two irregular winds were calculated for April and October. The average of the two values for each of these two months was the value that was used in the analysis.

Again, the irregular winds for the latitude of 90^{0} were found by extrapolation over the poles, and the northward irregular wind amplitudes were assumed to be equal to the eastward component.

The 4-D model does not include wind values or variances, and so other data sources had to be sought for random wind standard deviations below 25 km. Statistics on wind components are available for several test ranges in the IRIG Document 104-63 series of range reference atmospheres. The extreme wind (1% and 99% levels) could be used to compute monthly mean values of wind σ's at each of these test range sites by relations similar to (8.1) and (8.2)

$$\sigma_u = (U_{HI} - U_{LO})/2(2.32) \quad (8.6)$$

and

$$\sigma_v = (V_{HI} - V_{LO})/2(2.32) \quad (8.7)$$

where the HI and LO subscripts refer to the 1% and 99% levels. However, time did not permit the development of the global climatology of wind σ's from the test range σ's. Instead the simple method just described (based on assuming the wind σ was proportional to the mean zonal wind) was used below 25 km.

As an example of the validity of the simple method used here, Figure 8.1 shows the annual mean standard deviation for the wind at 30^0 compared with the profile of zonal wind standard deviation, computed from equation (8.6), for the test range at Eglin Air Force Base (latitude 30.5^0 N). Of course the agreement on a month-by-month basis would not be nearly so good as that indicated in Figure 8.1. Nevertheless, the results of the simplified model should be adequate for many design applications.

Alternate Random Magnitude Data

If it is desired to use alternate random data standard deviations in the program, then a revised input data tape could easily be created containing the revised data. The program also has options to by-pass the random data on the data tape and read instead an alternate data set from some other input. Details of how this can be done are given in the Users Manual Section of this report.

Two examples of possible alternate random standard deviation data are the new pressure, density, and temperature variation results of Cole (1972),

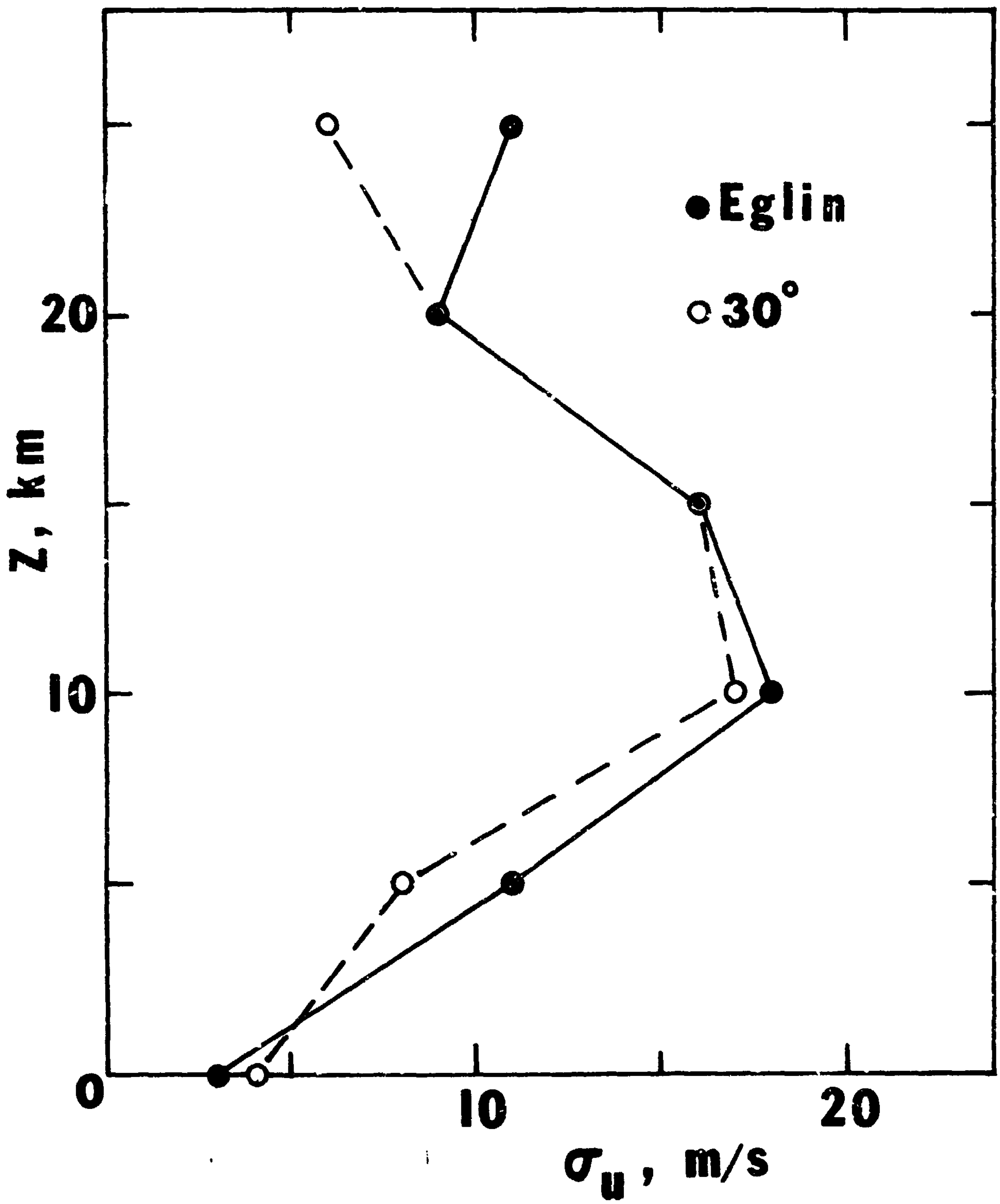


Figure 8.1 Comparison between the wind σ (annual mean) computed from equation (8.4) for Eglin AFB, latitude 30.5 N, with the 30° latitude annual mean wind σ computed by the simplified method.

and the above mentioned method to devise a set of random wind σ's from the range reference data.

The Correlated Random Perturbation Model

The random perturbations to the monthly means are assumed to have a Gaussian distribution with a standard deviation determined as described above. However, to represent realistic perturbations, there must be correlation maintained between perturbations at successive positions along the profile or trajectory. This section describes the model used to maintain these realistic correlations.

Consider two successive positions along a trajectory, labeled 1 and 2 in Figure 8.2, with horizontal separation Δx and vertical separation Δz. We assume that the perturbations at position 1 are known either because 1 is the starting position at which some initial perturbation is assumed, or because a perturbation has already been computed for this location. Given the relative perturbation values (e.g. $\rho'/\bar{\rho}$ and $T'/\bar{T}$) at position 1 and the correlations that must be maintained, the problem is to compute the perturbations at position 2. The model assumes that the relative density perturbation at position 2 can be evaluated by

$$(\rho_2'/\bar{\rho}_2) = A(\rho_1'/\bar{\rho}_1) + B\, r_1 \qquad (8.8)$$

where r_1 is a Gaussian random number with mean zero and standard deviation one, and the A and B coefficients are to be determined by the correlations which must be maintained between $\rho_2'/\bar{\rho}_2$ and $\rho_1'/\bar{\rho}_1$. If we let $\sigma_{\rho 1}$ and $\sigma_{\rho 2}$ represent the standard deviations of $\rho_1'/\bar{\rho}_1$ and $\rho_2'/\bar{\rho}_2$ respectively, and we let R represent the correlation between $\rho_1'/\bar{\rho}_2$ and $\rho_2'/\bar{\rho}_2$, then multi-

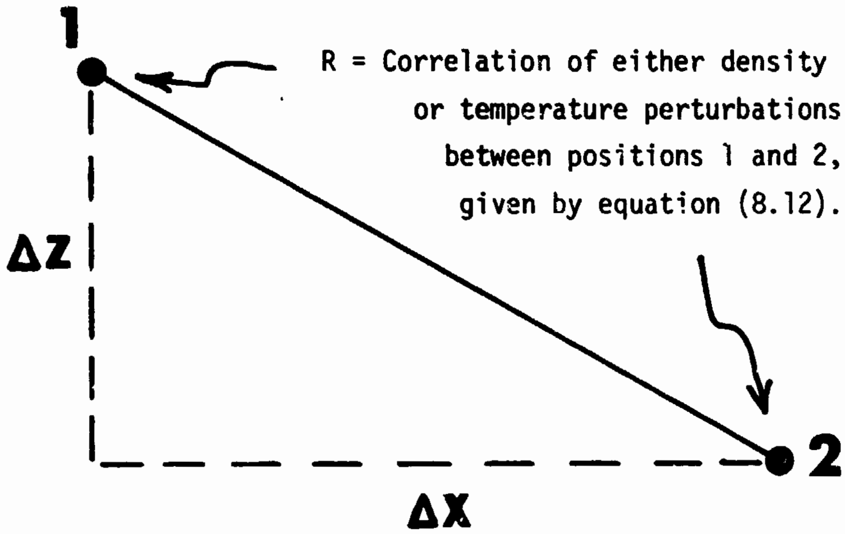


Figure 8.2 Successive positions 1 and 2 along a trajectory. Relative perturbations $p_1'/\bar{p}_1$, $T_1'/\bar{T}_1$ and $T_2'/\bar{T}_2$ are known at position 1. Relative perturbations at position 2 are computed from equation (8.8), (8.13), and (8.14) after evaluation of the coefficients by methods described in this section and in Appendix B.

plication of (8.6) by $\rho_1'/\bar{\rho}_2$ and averaging, yields

$$R\,\sigma_{\rho 1}\,\sigma_{\rho 2} = A\,\sigma_{\rho 1}^{\;2} \tag{8.9}$$

and squaring both sides of (8.6) and averaging yields

$$\sigma_{\rho 2}^{\;2} = A^2\,\sigma_{\rho 1}^{\;2} + B^2 \tag{8.10}$$

Combination of (8.9) and (8.10) allows A and B to be evaluated in terms of the known σ_1, σ_2, and R.

$$A = R\,\sigma_{\rho 2}/\sigma_{\rho 1} \tag{8.11}$$

$$B = \sigma_{\rho 2}(1 - R^2)^{1/2} \tag{8.12}$$

The model next assumes that the temperature perturbation at position 2 is given by

$$(T_2'/\bar{T}_2) = C(T_1'/\bar{T}_1) + D(\rho_2'/\bar{\rho}_2) + E\,r_2 \tag{8.13}$$

where r_2 is a Gaussian random similar to r_1 and coefficients C, D, and E are to be determined by the required correlation conditions. The correlation between $T_1'/\bar{T}_2$ and $T_2'/\bar{T}_2$ is assumed to be the same value R as for the density correlation. The solution for the C, D, and E coefficients is more complicated than for the A and B coefficients, and is outlined in Appendix B. With the density and temperature perturbations at position 2 determined, via equations (8.8) and (8.13) with their coefficients evaluated, then the pressure perturbation is given by

$$(p_2'/\bar{p}_2) = (\rho_2'/\bar{\rho}_2) + (T_2'/\bar{T}_2) \tag{8.14}$$

This solves the problem of evaluating pressure, density, and temperature perturbations in terms of the given standard deviations and the correlation R (the correlation between density or temperature perturbations over the displacement from position 1 to position 2). In the model used, the correlation R is taken to be

$$R = \exp\left\{ - [(\Delta x/L_H)^2 + (\Delta z/L_V)^2]^{1/2} \right\} \tag{8.15}$$

where Δx and Δz are the horizontal and vertical displacements, illustrated in Figure 8.2, and L_H and L_V are the horizontal and vertical correlation scales.

The values of the correlation scales in the correlation relation (8.15) must be chosen so that the correlation field approximately represents the major features of all of the phenomena which cause deviations from the monthly mean. There are actually many physical processes which could contribute to the total departure being modeled by the random variations: synoptic weather patterns in the troposphere and stratosphere, and gravity waves, planetary waves, and tides, especially at the higher altitudes. In the present implementation of the model the correlation scales are given by the linear relations plotted in Figure 8.3. The values for L_H near the surface were determined from the correlation studies of Buell (1971, 1972a) who found the horizontal correlation scale to be approximately 800 km at the 500 mb (6 km) level. The value of 1500 km for L_H at 100 km altitude was estimated as a dominate scale for the large scale tidal and planetary wave perturbations. Vertical scales of 5-10 km, increasing with height are

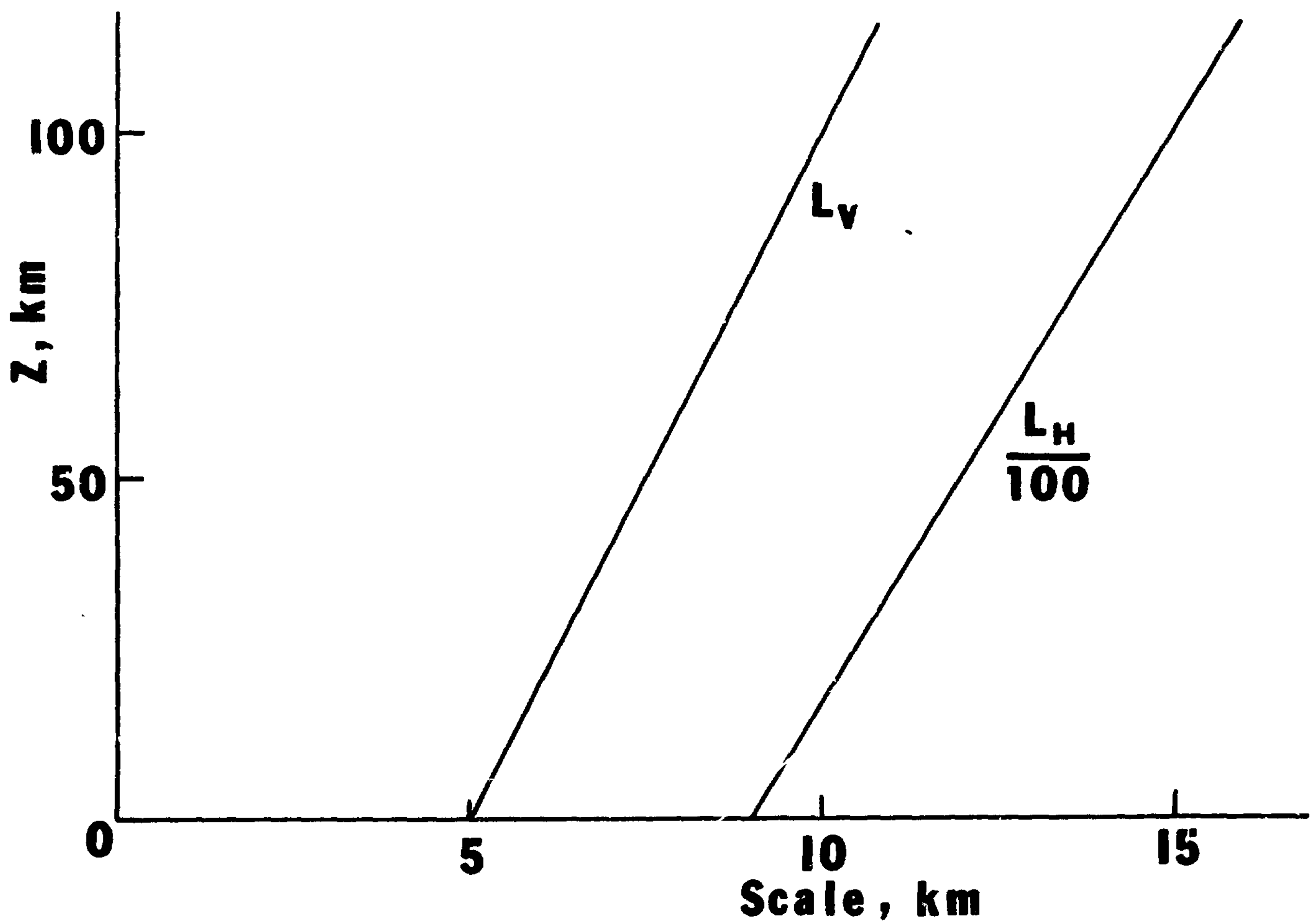


Figure 8.3 Correlation scales for the random perturbation correlation function, equation (8.15).

common to synoptic weather variations (for example the "depth of pressure perturbations" parameter of Buell, 1972b), and gravity wave and planetary wave systems (Justus and Woodrum, 1972, 1973).

The random perturbation model used here is an extension of one originally developed for simulation of turbulence (Justus, 1971, Justus and Hicks, 1971). The perturbations generated by the model are not only correlated with each other over successive times, but also a time series of such perturbations can be Fourier transformed and has a spectrum which agrees with that expected from the correlation function (e.g. equation (8.15)) used to generate the time series (e.g. by equation (8.8)). Figure 8.4 shows the fast Fourier transform power spectrum of one such time series of perturbations along with the theoretical spectrum which corresponds to the exponential correlation function.

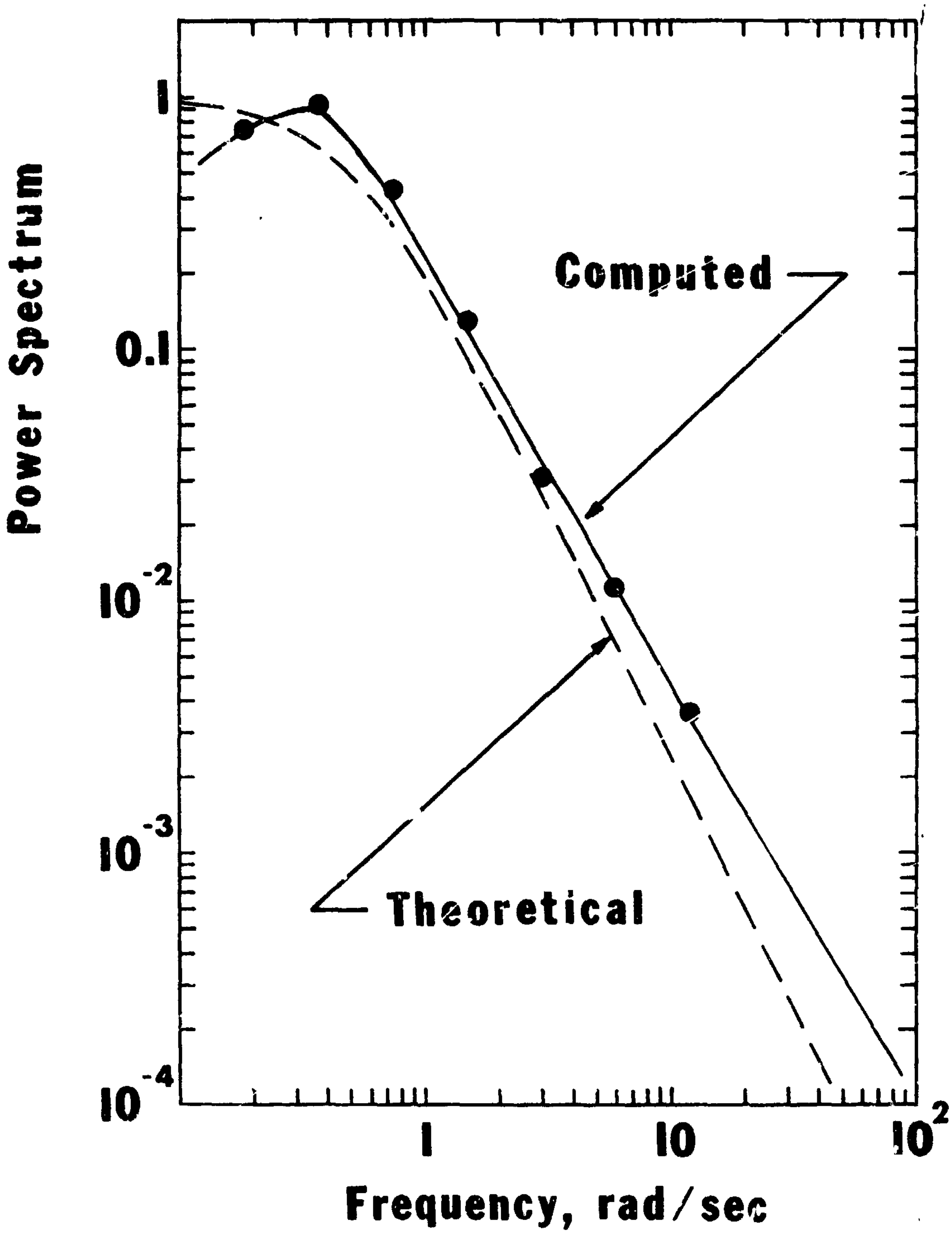


Figure 8.4 Computed and theoretical power spectrum of a time series of perturbations, such as would be generated from equation (8.8). Theoretical spectrum is computed from transform of correlation function (equation (8.15)).

9. VARIATIONS DUE TO THE QUASI-BIENNIAL OSCILLATION (QBO)

It was shown from periodogram calculations by Justus and Woodrum (1973) that quasi-biennial oscillations of the wind, pressure, density, and temperature were significant in the height range 45 to 60 km. In many instances the amplitudes of the quasi-biennial oscillations were comparable to the annual and semi-annual oscillations. Other publications have indicated the same. Belmont and Dartt (1973), Cole (1968), and Rahmatullah (1968). Consequently, in modeling the winds and thermodynamic variables of the atmosphere, the quasi-biennial oscillations should definitely be considered.

In the present work, the amplitudes and phases of the quasi-biennial oscillations were found by first performing a harmonic analyses on MRN data from three sites. The data were chosen for each site such that the data values occurred at the same time of day, plus or minus ten minutes, for a time interval covering about six years, 1964 through 1969. Thus, solar radiation errors would be minimized. The sites and local times of day were Ascension Island, A.F.B., 1345 hours; Cape Kennedy, Florida, 1000 hours; and Fort Greely, Alaska, 1000 hours. Then the data for each site were averaged over one month intervals. The data average for each month was weighted by the number of values in the average and the time used for each month was the averaged time.

Harmonic analysis was performed on the data by computing a mean, a quasi-biennial, an annual, and semiannual oscillation according to the following equation.

$$Y(t) = A_1 + A_2 \sin\left(\frac{2\pi t}{T_1} + \theta_1\right)$$

$$+ A_3 \sin\left(\frac{2\pi t}{T_2} + \theta_2\right) + A_4 \sin\left(\frac{2\pi t}{T_3} + \theta_3\right) \quad (9.1)$$

where Y is the wind or thermodynamic variable, A_1 is the mean, A_2, A_3, and A_4 are amplitudes, t is the time, T_1, T_2, T_3 are the periods of the semi-annual, annual, and quasi-biennial oscillations respectively, θ_1, θ_2, and θ_3 are phase angles.

First, calculations were performed on each data set by varying the quasi-biennial period from 600 days to 1,080 days in steps of 30 days. Variances for each calculation were computed. The periods causing minimum variances were somewhat scattered but the period equal to 870 days seems to best minimize the variances for all the data. This result agreed well with the value of [illegible] months found by Belmont and Dartt (1973) and reasonably well with the value of 32 months found by Groves (1973).

For computer purposes it is desired to have values of the amplitude and phase of the quasi-biennial oscillations at 10, 30, 50, 70, and 90 degrees latitudes and for heights from 0 to 90 km. The present work gives values for heights 25 to 60 km and at three latitudes: 7° 59'S (Ascension Island) 28° 27'N (Cape Kennedy) and 64° 00'N (Fort Greely). The values for the desired latitudes were obtained by considering the above results and results from Cole (1968), Rahmatullah (1968), Groves (1973), Shah and Godson (1966), Reed (1965), and Angell and Korshover (1963), (1964), (1965), (1962). Curves were drawn graphically to best fit the available data as a function of latitude. Then values were read at the appropriate latitudes. For data values below 25 km and above 60 km, it was assumed that the quasi-biennial amplitude approached zero at 10 km and 90 km altitude for each latitude. Then, curves were extrapolated to these points and values were read at appropriate heights. These values are given in the following table.

It is assumed in the above analysis that the quasi-biennial variations have no longitude dependence and are symmetric about the equator.

Tables of the quasi-biennial pressure, density, temperature and wind component amplitudes and phases, as they appear in the input data tapes for the PROFILE program, can be found in the users manual section of this report.

10. SAMPLE RESULTS

The PROFILE program is designed to give two types of atmospheric parameters: (1) values along a simulated trajectory, whose positions must be input to the program one at the time for evaluation, and (2) a profile (such as a vertical profile at a single location) for which the positions are automatically computed by the program after the initial position is given (any constant increments in height, latitude, and longitude can be used).

Simulated Trajectory Parameters

Figure 10.1 shows the height and range versus time for the Space Shuttle ascent trajectory for mission 1, a launch from Cape Kennedy into a 28.5^{o} orbit. Figure 10.2 shows the computed density, in percent deviation from the U.S. 1962 Standard Atmosphere, for a typical run to simulate conditions along the trajectory for mission 1. The solid line and shaded area shows the January monthly mean and $\pm$ 2 standard deviations of the random density perturbation. The dashed line in Figure 10.2 shows a typical profile of mean density plus random density perturbation. Note that the random component exceeds the one sigma level for many times, but on this particular run the 2σ is not exceeded. One of the characteristics of the random model used is that the 1% exceedance level on the random perturbation should be exceeded 1% of the time, etc., i.e. the generated perturbations have a distribution which matches statistically the observed statistical parameters, which are used as the input data.

Figures 10.3 and 10.4 show the 0-2000 seconds and 2000-3000 second segments of the density values for the external tank disposal trajectory for mission 1. This trajectory starts zero time at the insertion point over the

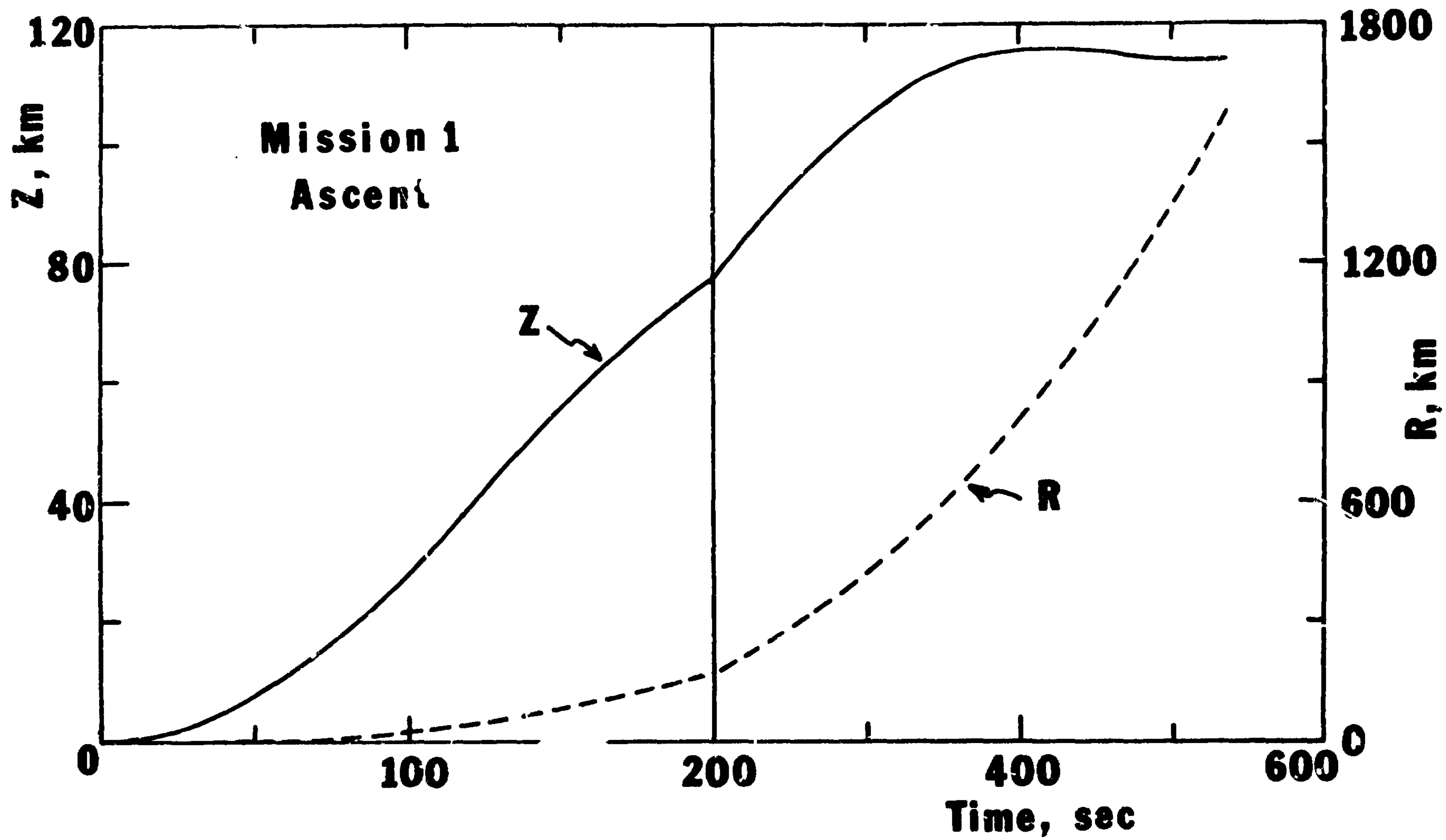


Figure 10.1 Altitude and range vs. time for Shuttle ascent trajectory on mission 1, a Cape Kennedy launch into a 28.5° orbit. Note the shift in time scale at 200 seconds, to correspond with a similar shift on Figure 10.2.

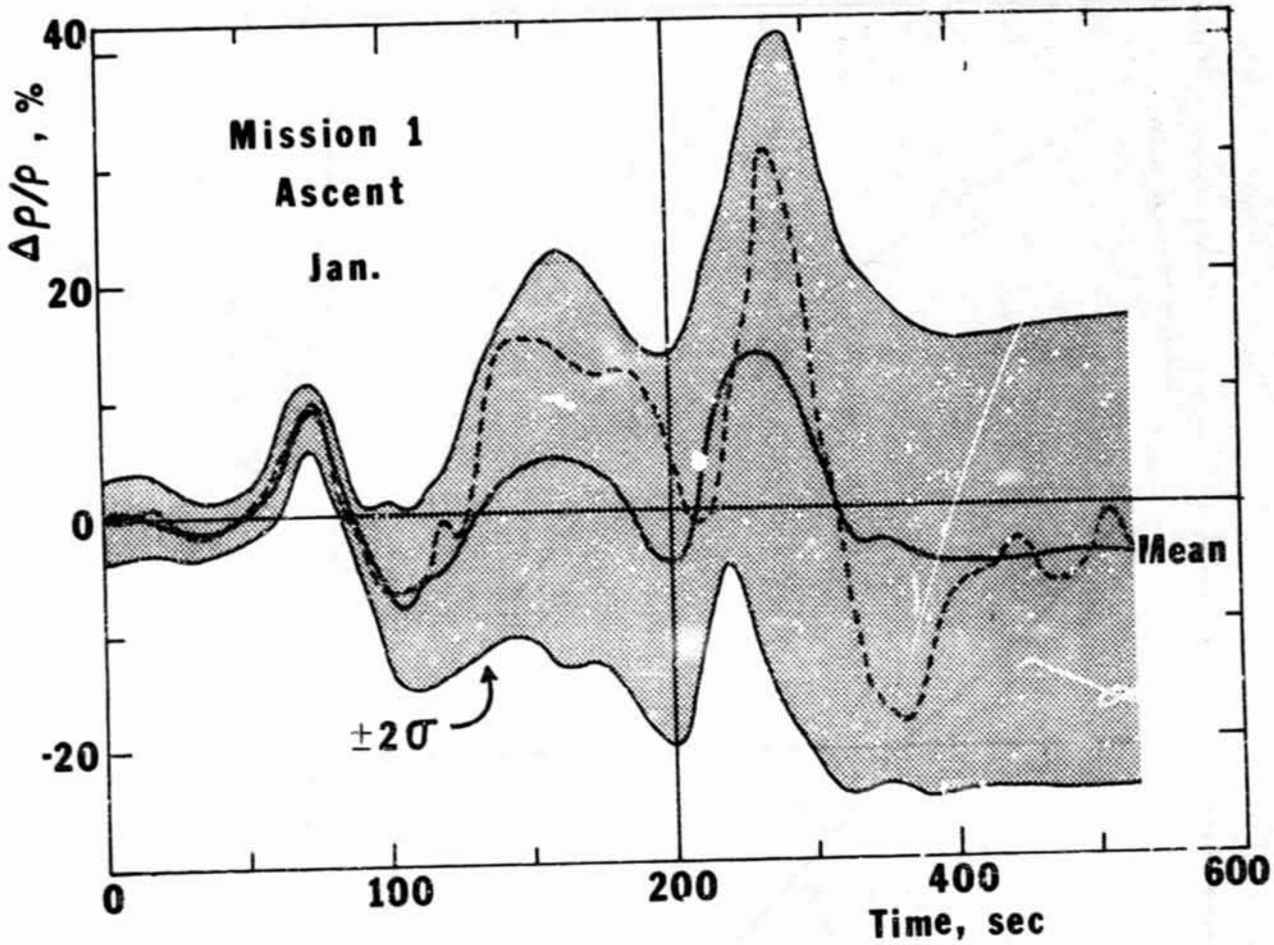


Figure 10.2 Density deviation from the U.S. 1962 Standard Atmosphere for Shuttle ascent trajectory, mission 1. The solid line and shaded area shows the January monthly mean and ±2 standard deviations of the random density perturbation. The dashed line shows a typical density profile of mean plus random component. Note time scale shift at 200 seconds.

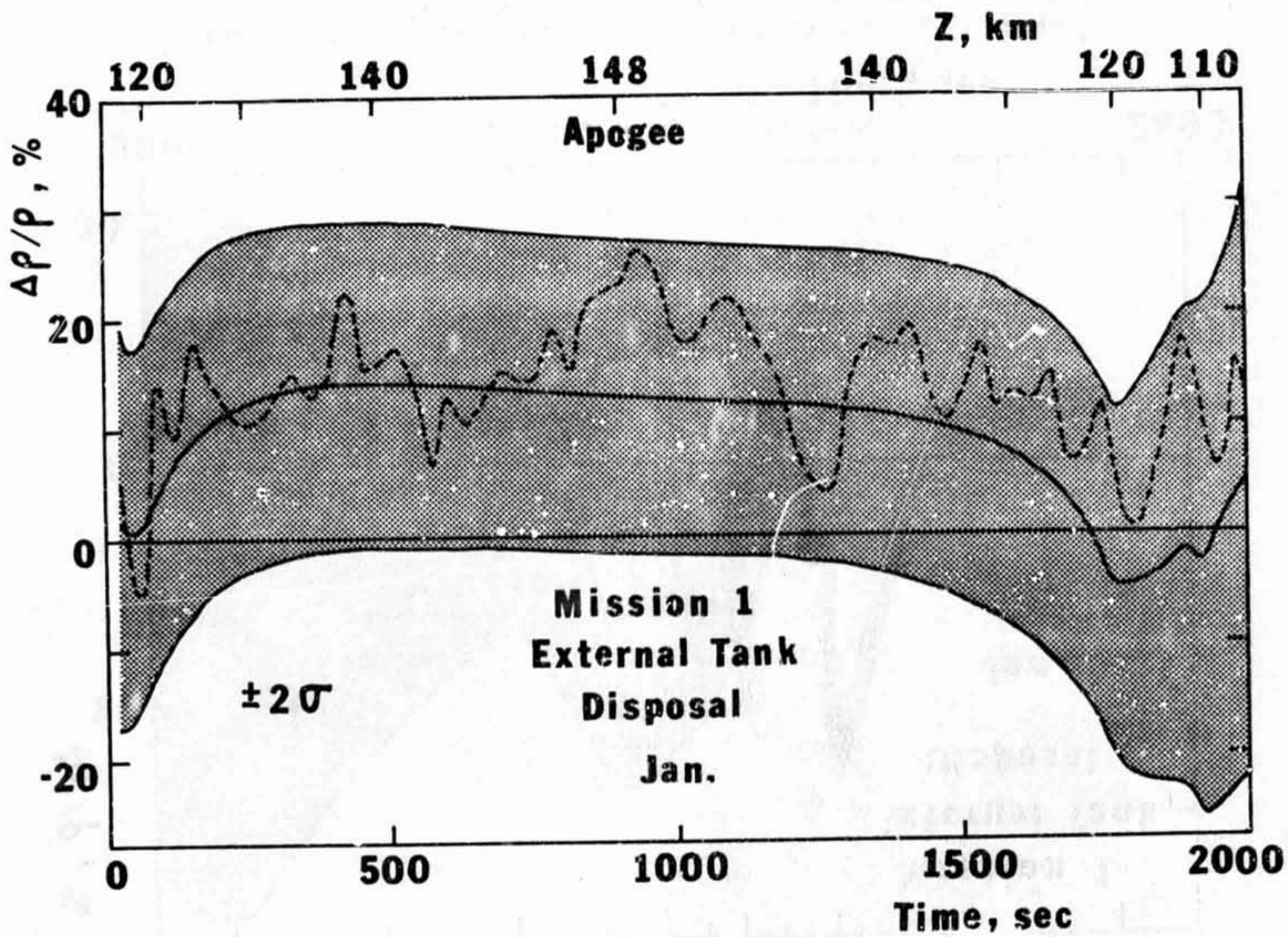


Figure 10.3 Density deviation from the 1962 U.S. Standard Atmosphere for the mission 1 external tank disposal trajectory - times 0 to 2000. Symbolism on the graph is the same as in Figure 10.2.

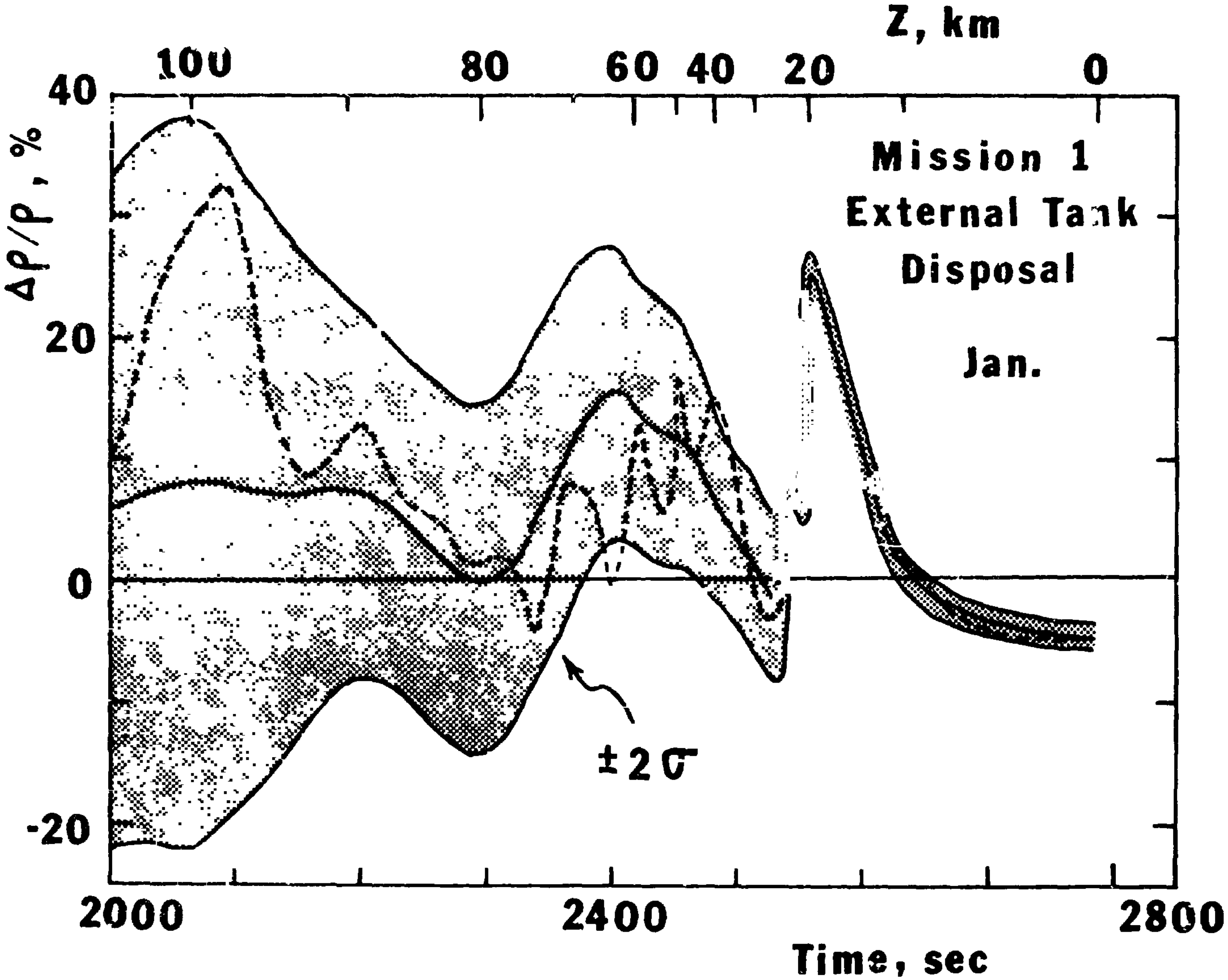


Figure 10.4 Density along the mission 1 external tank trajectory, time 2000 seconds to impact. This graph is a continuation of Figure 10.3 with a change in time scale.

Carribean (Latitude 27.8°N, Longitude 67.3°W) and terminates at the tank impact point in the Indian Ocean (Latitude 28.6°S, Longitude 89.4°E). Note the change in time scale between Figures 10.3 and 10.4. The heights are shown at the top of these two figures. The plots of Figures 10.3 and 10.4 show the January mean density, the ± 2σ envelope, and a typical curve of density deviation from the 1962 U.S. Standard Atmosphere for the mission 1 external tank disposal trajectory.

Figure 10.5 shows a ground plot of mission 3 re-entry and return trajectory. This mission is a 104° obrital inclination with launch from and return to Vandenburg AFB. The height and time along the trajectory ground plot are also shown in Figure 10.5. Figures 10.6-10.8 show density variation plots similar to those previously given. Figures 10.6 and 10.7 are for a January mission, and Figure 10.8 is the upper altitude section of a July mission trajectory. The polar orbit trajectory, such as plotted in Figures 10.5-10.8, is the situation for which the PROFILE program is most valuable. Notice that the - 2σ envelope for the January trajectory in Figure 10.6 reaches - 80% deviation from the 1962 Standard Atmosphere, while the + 2σ envelope for the July trajectory reaches + 70% deviation. Therefore, monthly variations are extremely large for the polar orbit re-entry trajectory. Figures 10.6 and 10.8 also show that very large deviations, first positive then negative (or vice-versa), could be expected within the ± 2σ limits of variability, even on a single trajectory.

The PROFILE program gives output for monthly mean and mean plus perturbations of pressure, density, temperature, and Northward and Eastward wind components. The wind shear for the monthly mean wind, the stationary per-

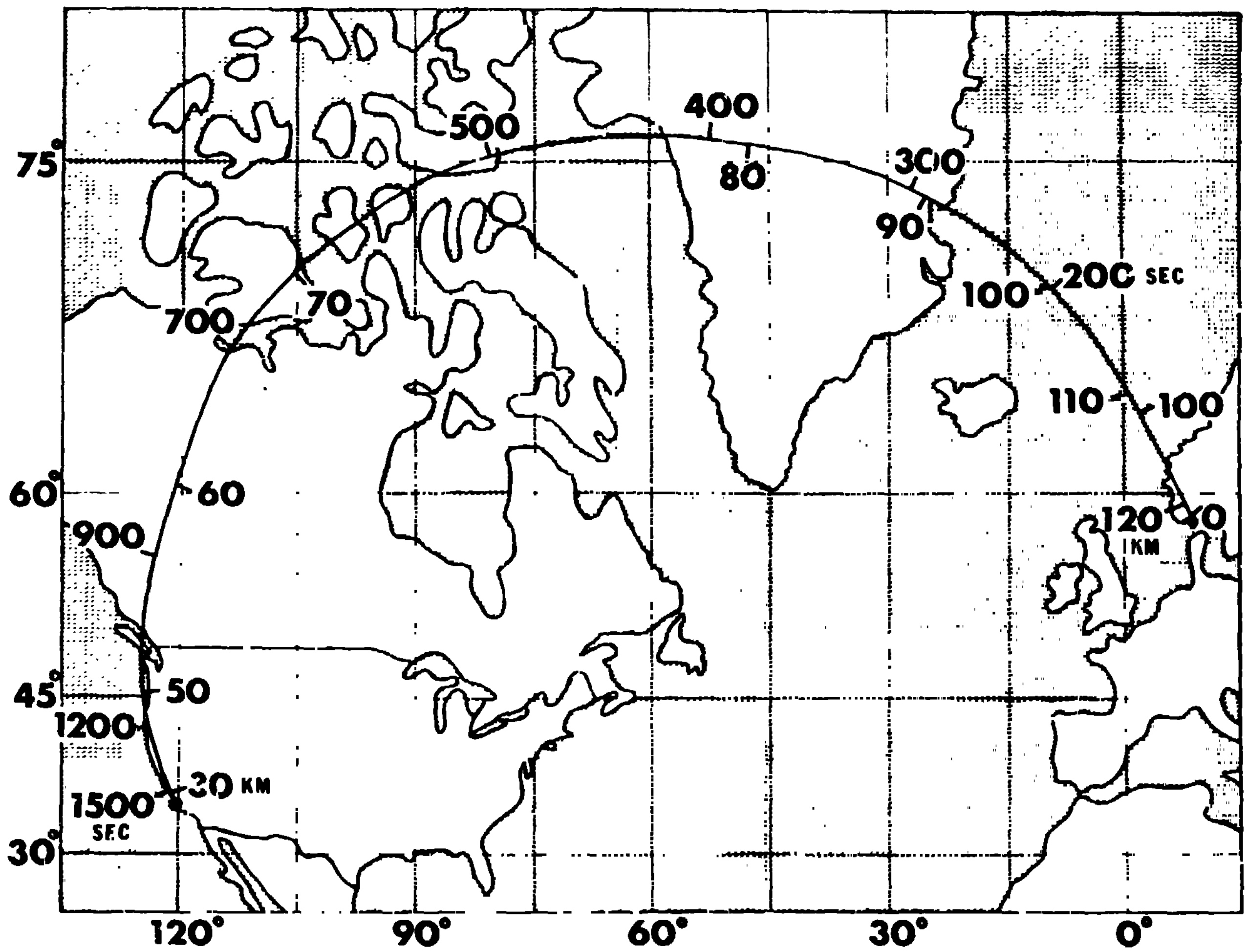


Figure 10.5 Ground plot of the re-entry and return trajectory for mission 3, a 104^{0} inclination polar orbit launched from and returning to Vandenburg AFB. The altitude in km is plotted on the inner side of the orbital plot and the time in seconds is plotted on the outer side.

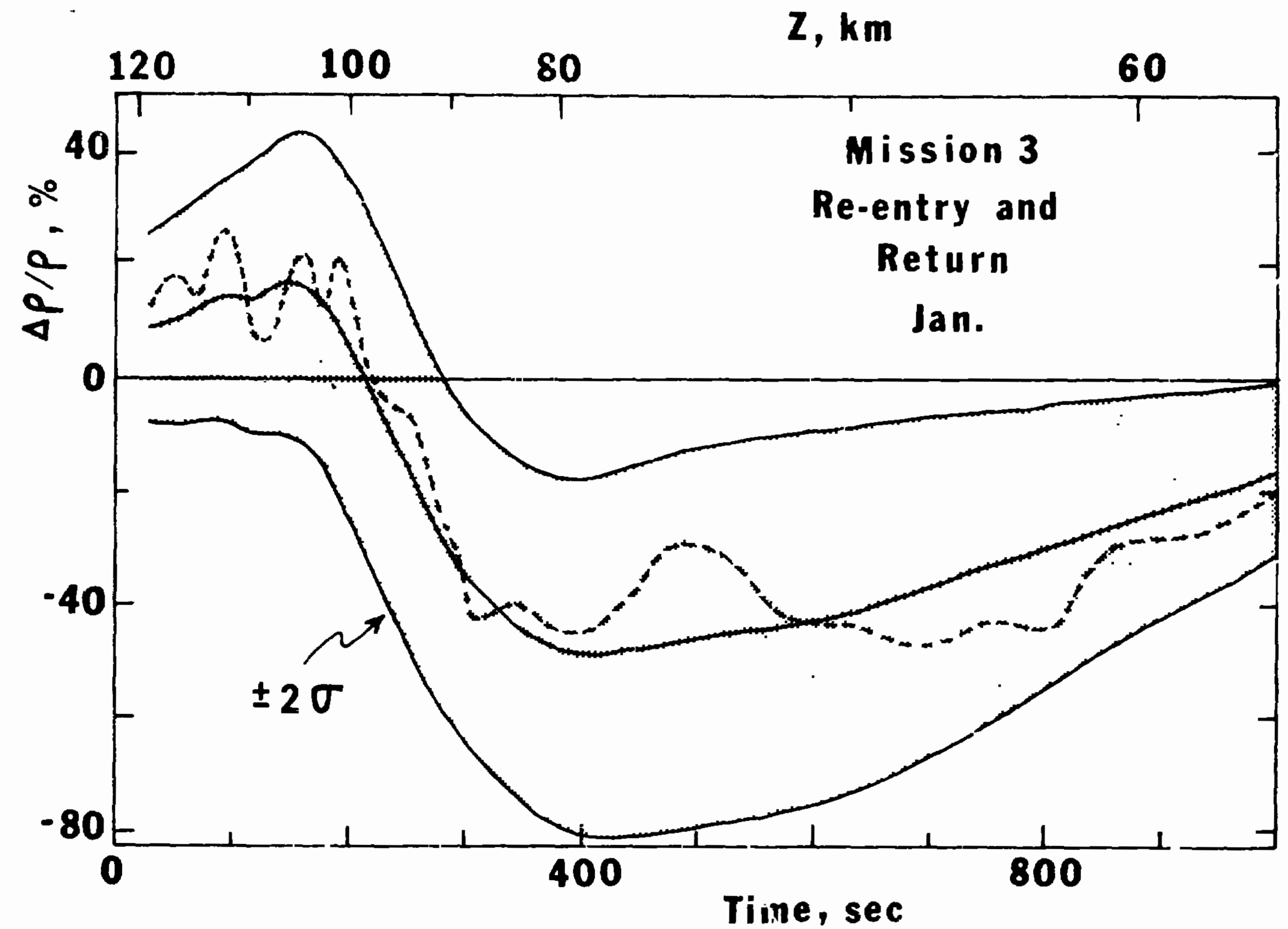


Figure 10.6 Density along a January mission 3 (Vandenburg polar orbit) re-entry and return trajectory. Density deviations are with respect to the 1962 U.S. Standard Atmosphere Graph symbolism as in Figure 10.2.

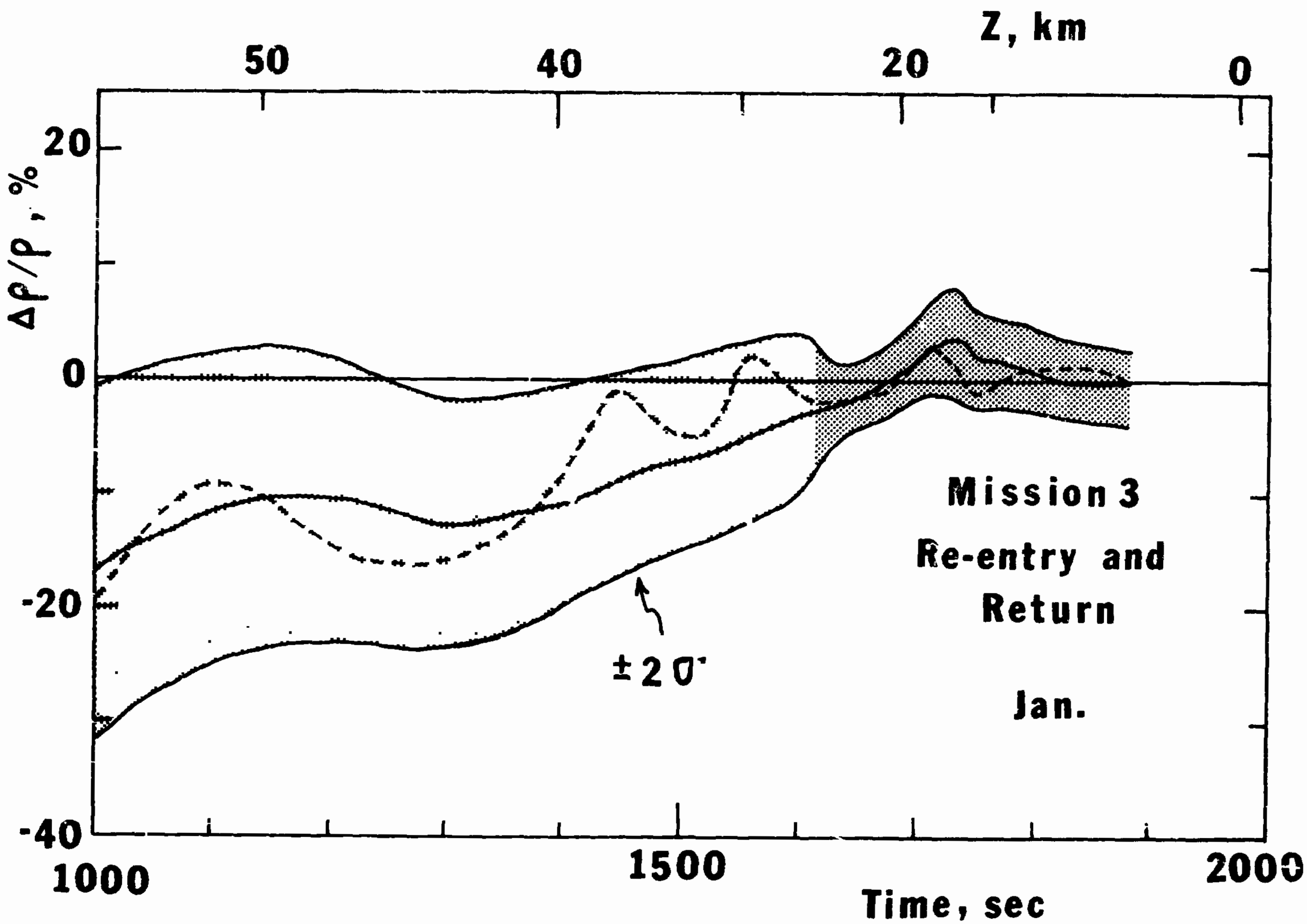


Figure 10.7 Continuation of Figure 10.6. Note shift in density deviation scale.

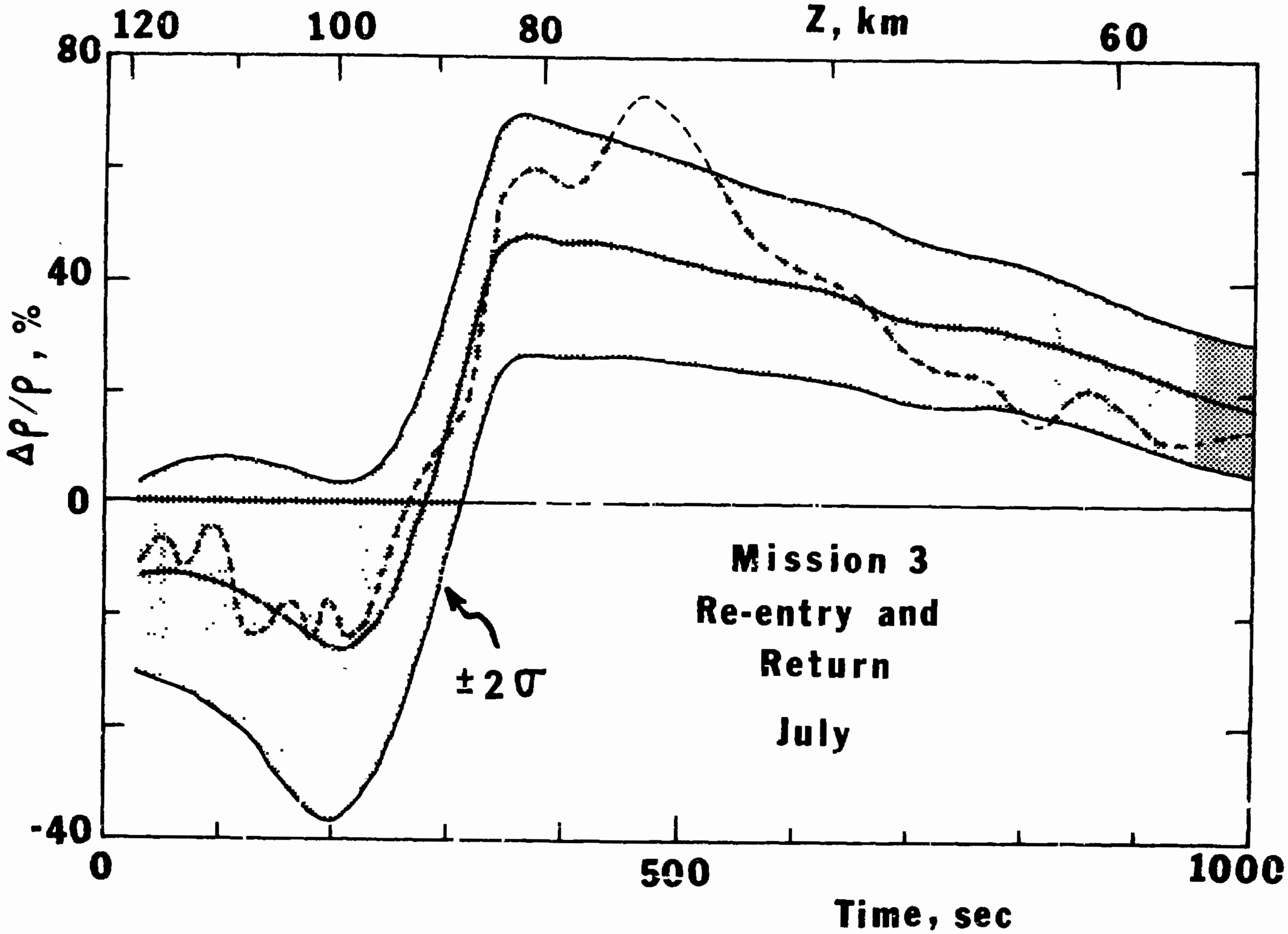


Figure 10.8 Density along a July mission 3 re-entry and return trajectory, as in Figure 10.6

turbations and the random and quasi-biennial perturbations and their magnitudes are also printed out. The percent deviations from the U.S. Standard Atmosphere for mean and total values of pressure, density, and temperature are also evaluated and output. Therefore variation of any or all of these parameters along any simulated trajectory could be evaluated and plotted for analysis. The output can also optionally be punched as well as printed, so that the card output could go directly into a plot routine.

Sample Vertical Profiles at Range Locations

Profiles of all of the parameters just discussed in the previous section can also be easily computed along any linear path in height, latitude, longitude coordinates. The most useful such profile would be a vertical profile at a given location. Figures 10.9-10.11 show the PROFILE program computed Cape Kennedy January monthly mean profiles of temperature, density, and eastward wind component, along with the January range reference atmosphere values (from the IRIG Documents 104-63). The monthly mean wind was taken to be the 50 percentile value given for the zonal wind distribution. These curves indicate reasonably good agreement between the monthly mean profiles generated by the PROFILE program and the range reference atmosphere data.

Further indication of how well the model works is provided by Figure 10.12. This figure compares the mean wind shear computed by the thermal wind equation with direct evaluation of wind shear by numerical differentiation of the mean geostrophic wind. Since the thermal wind equation makes use of horizontal temperature gradients, and the geostrophic wind equation relies on horizontal pressure gradient values, then the agreement shown by

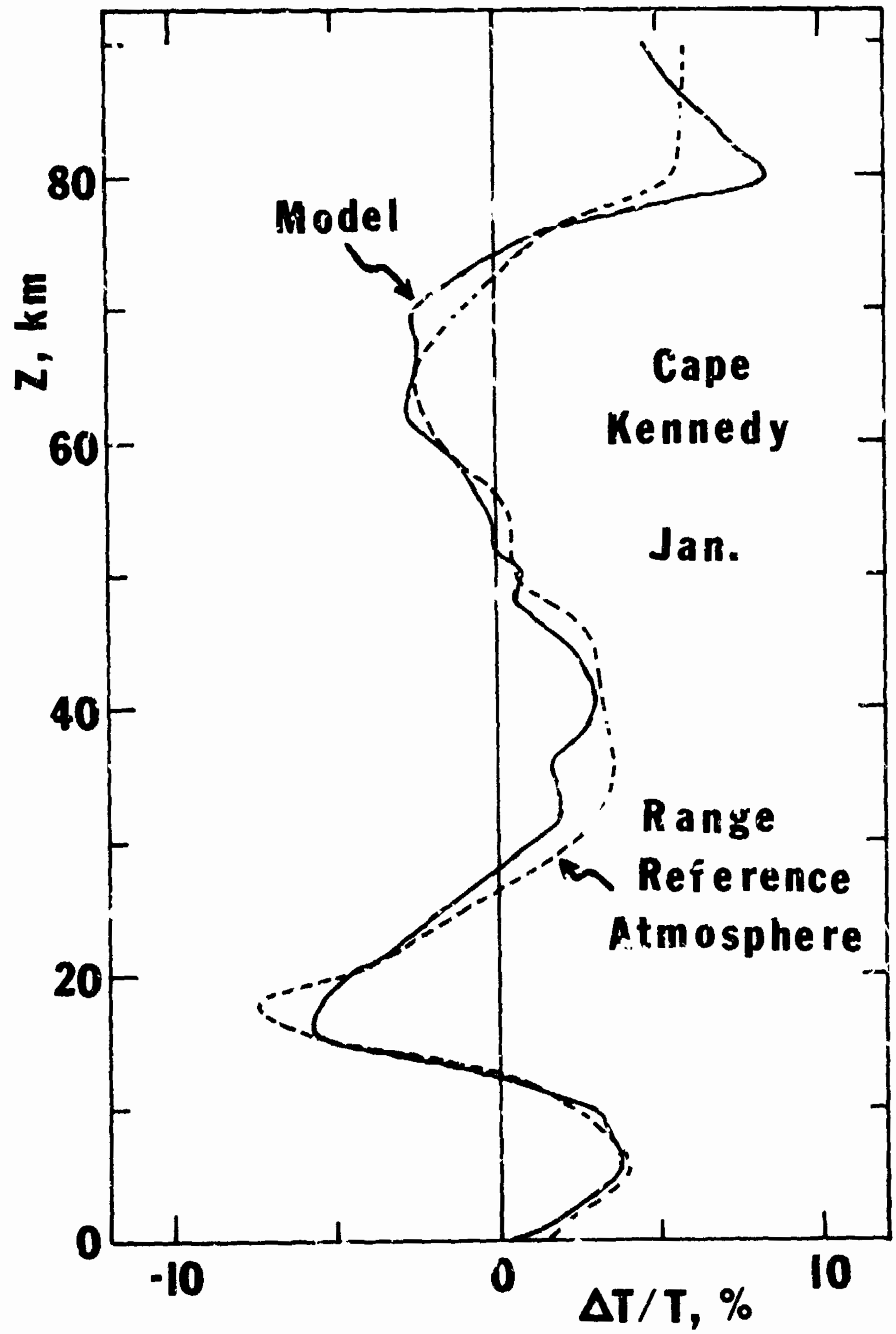
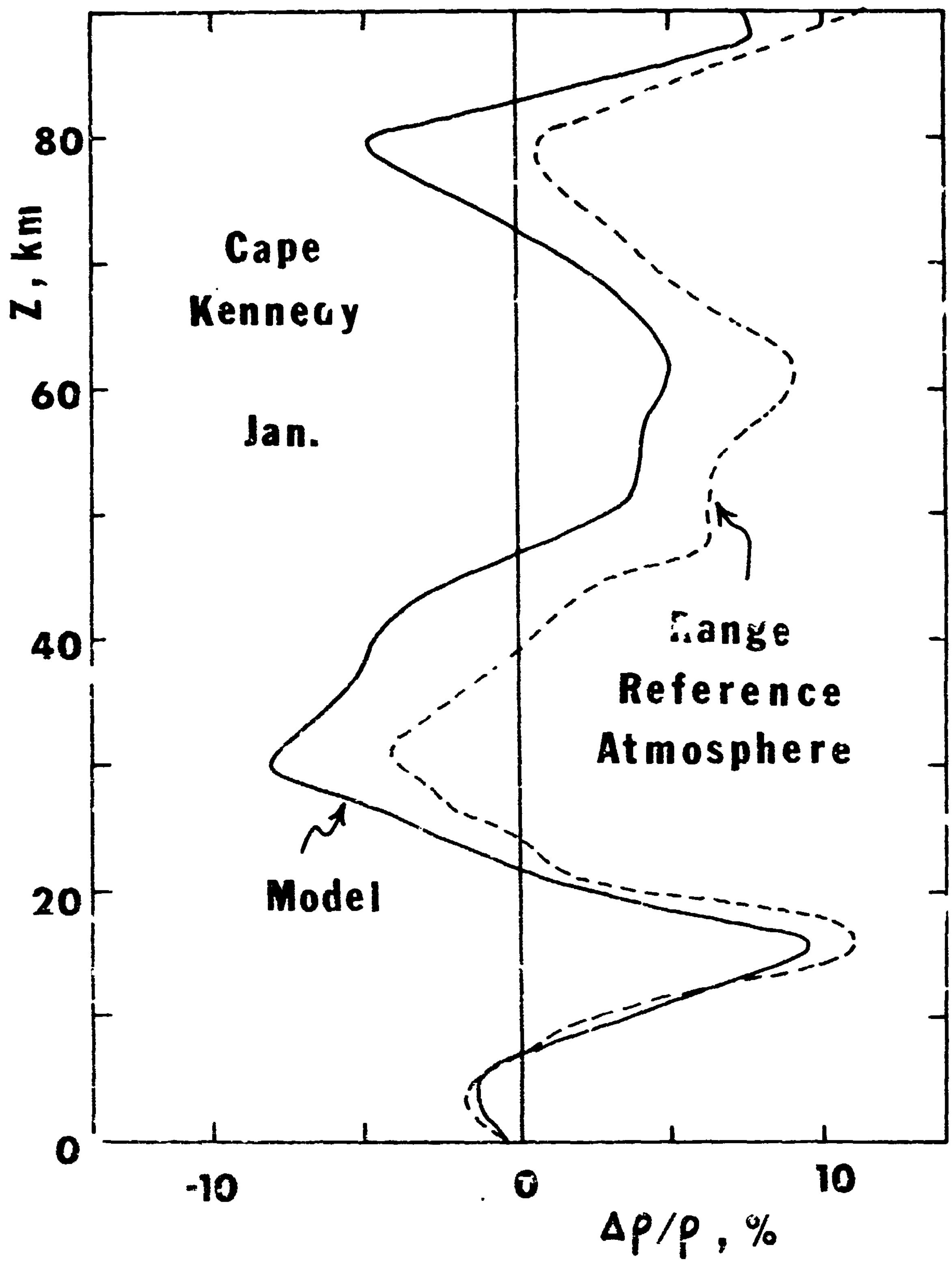


Figure 10.9 PROFILE generated monthly mean temperature for Cape Kennedy in January, compared to the Kennedy January range reference atmosphere. Percent deviations are with respect to the 1962 U.S. Standard Atmosphere.



Figur 10.10 As in . gure 10.9 for density.

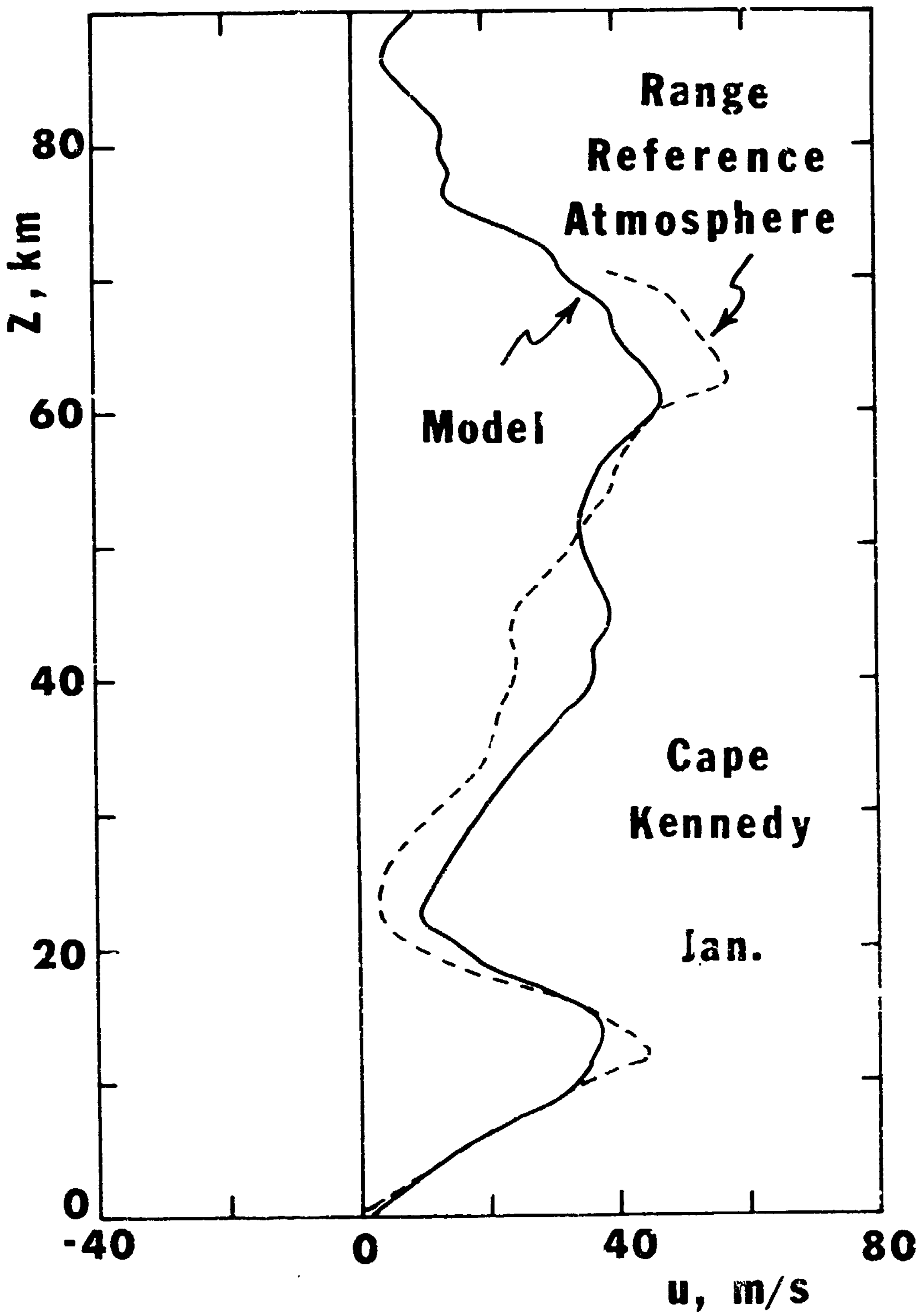


Figure 10.11 As in Figure 10.9 for zonal wind.

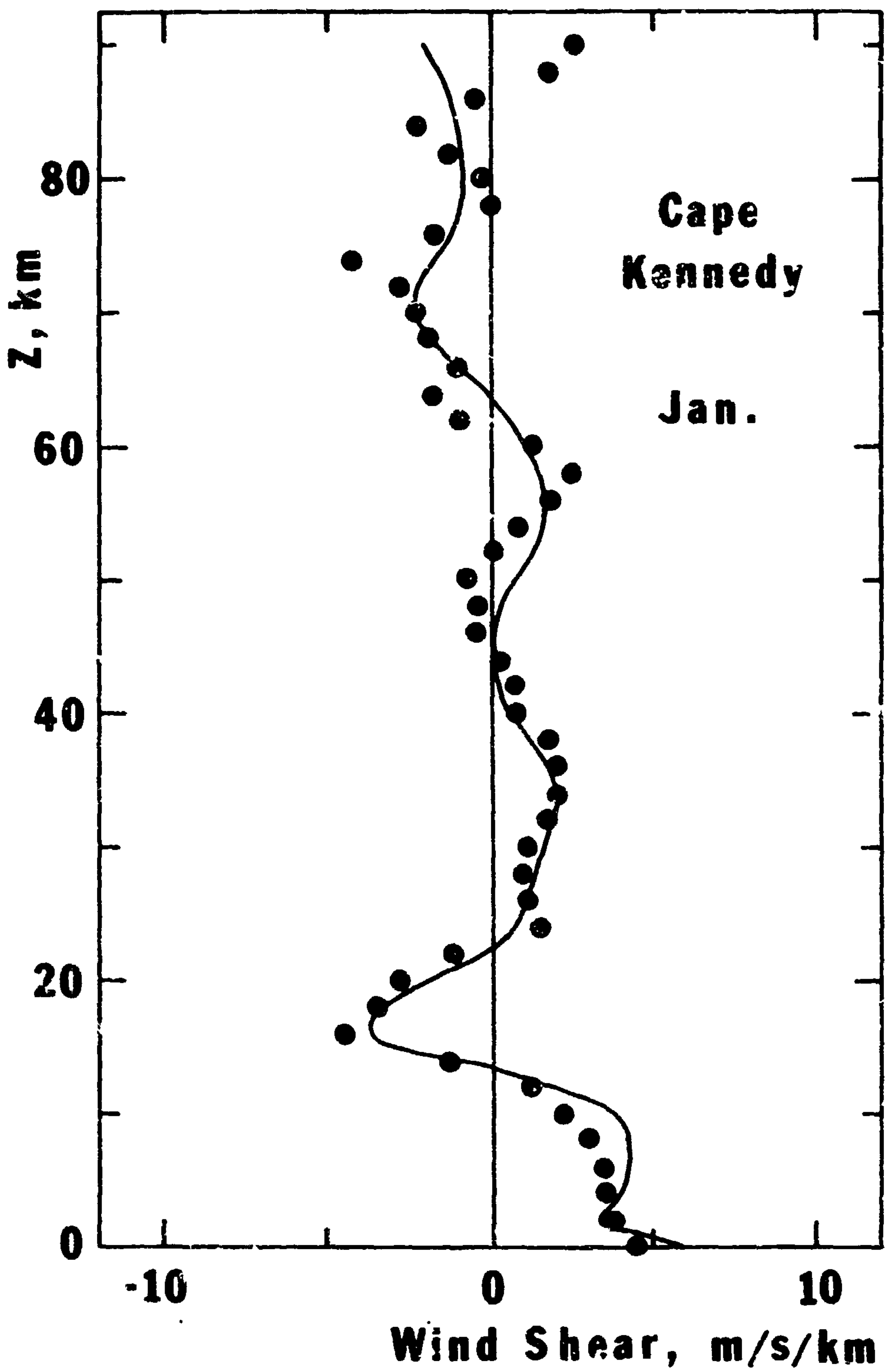


Figure 10.12 The line is the mean wind shear evaluated by the thermal wind equation. The dots are wind shear values computed by numerical differentiation of the geostrophic winds. The agreement indicates good consistency exists in the mean temperature and mean pressure fields.

Figure 10.12 indicates good consistency between the fields of mean pressure and mean temperature in the model.

Comparisons between PROFILE generated January monthly mean temperature, density, and zonal wind profiles for three other locations (Wallops Island, White Sands, and Fort Greely) are given in Figures 10.13 to 10.21. The temperature and density data are presented as percent deviation from the U.S. 1962 Standard Atmosphere. Each graph also shows the January range reference atmosphere for the site location. Generally good agreement between the PROFILE program mean parameter results and the range reference atmosphere is seen in all of these plots.

As a test that the model also works well in the southern hemisphere, see Figures 10.22 and 10.23. These figures show the monthly mean temperature and density and the $\pm$ 1σ envelope for Woomera, Australia (31°S, 137°E) in July. A typical profile, (HAD 174, July 7, 1965, Pearson and Johnson, 1973) is also shown, and is found to fall generally well within the $\pm$ 1σ levels.

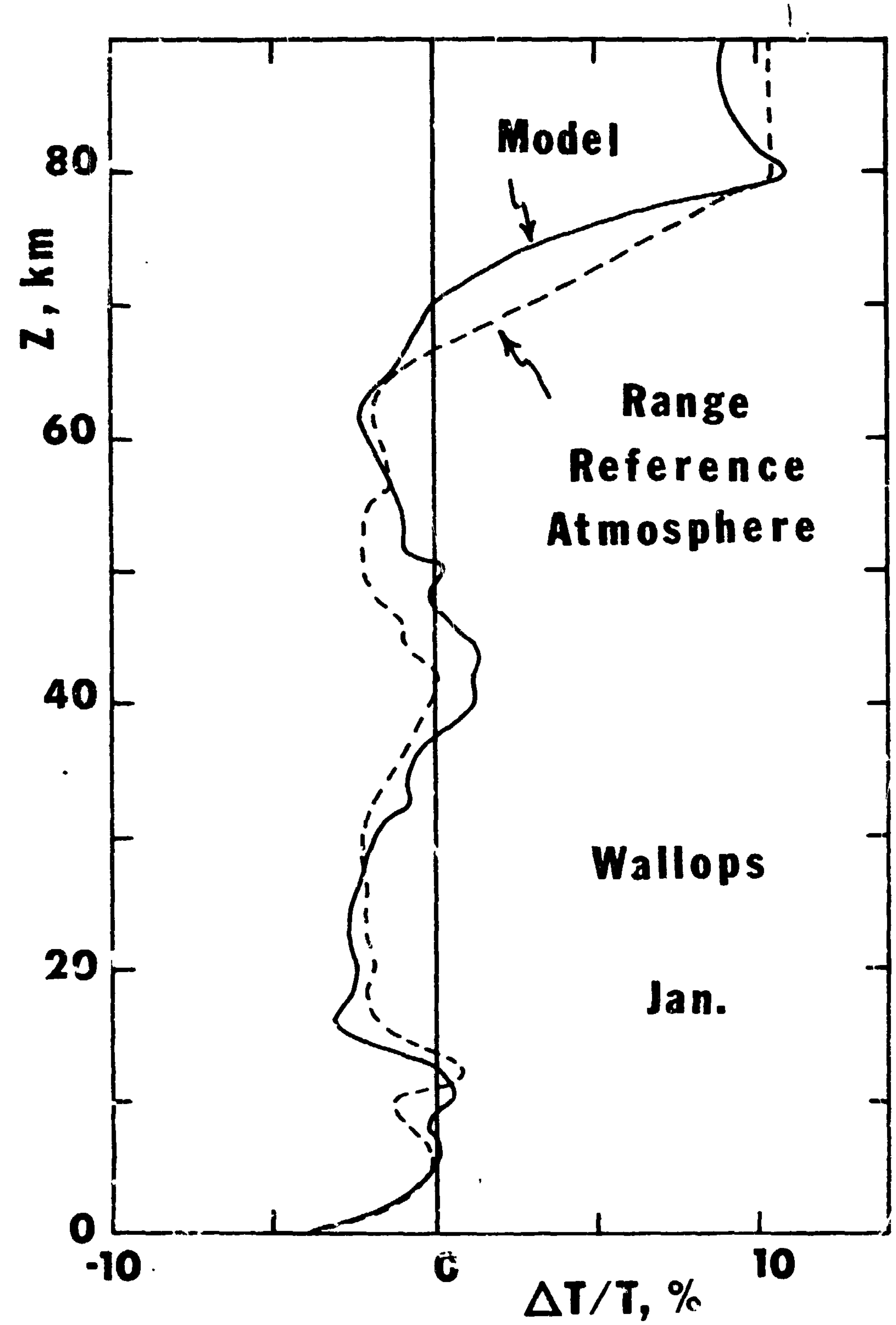


Figure 10.13 PROFILE generated monthly mean temperature for Wallops Island in January, compared to the Wallops January range reference atmosphere. Percent deviations are with respect to the 1962 U.S. Standard Atmosphere.

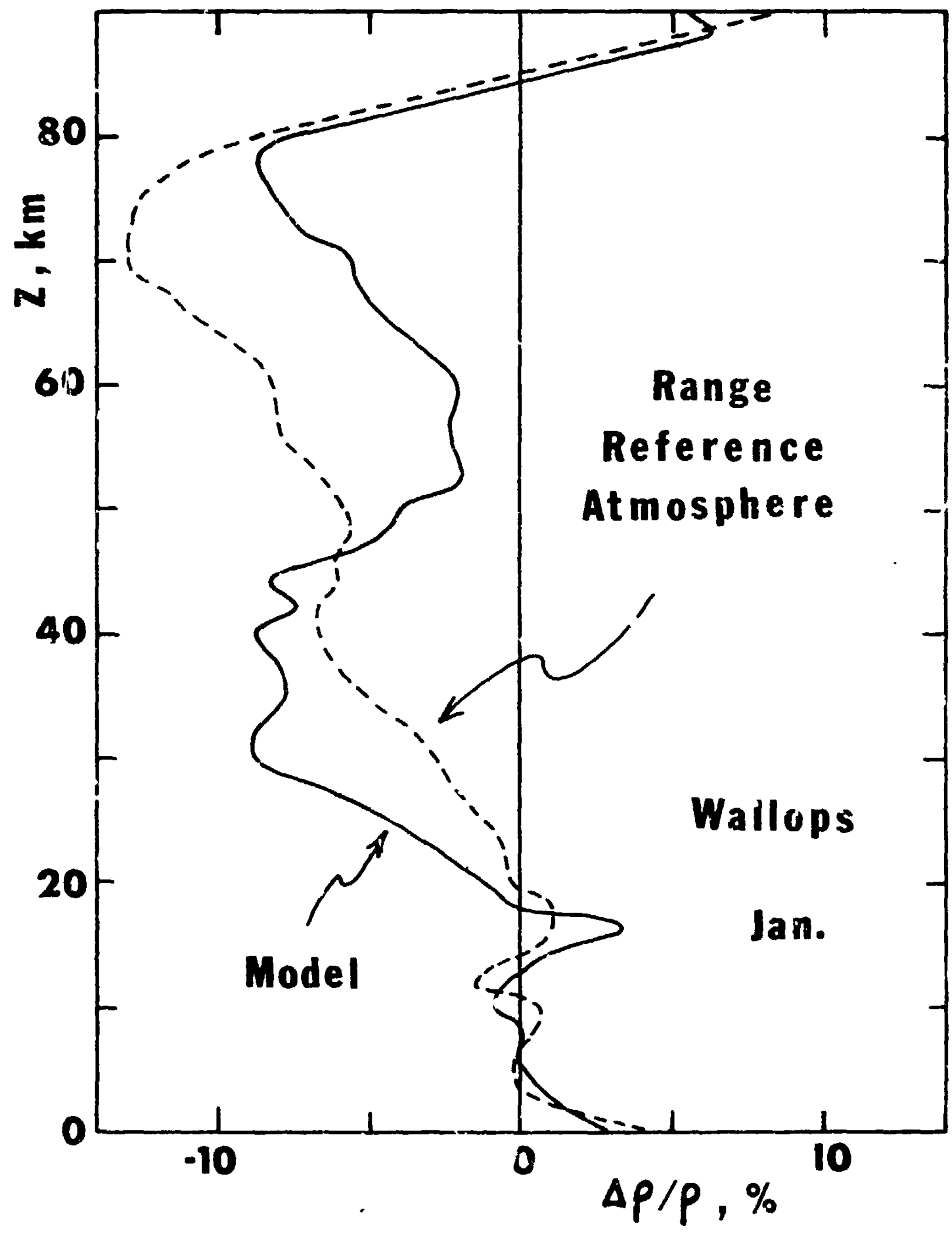


Figure 10.14 A. in Figure 10.13 for density.

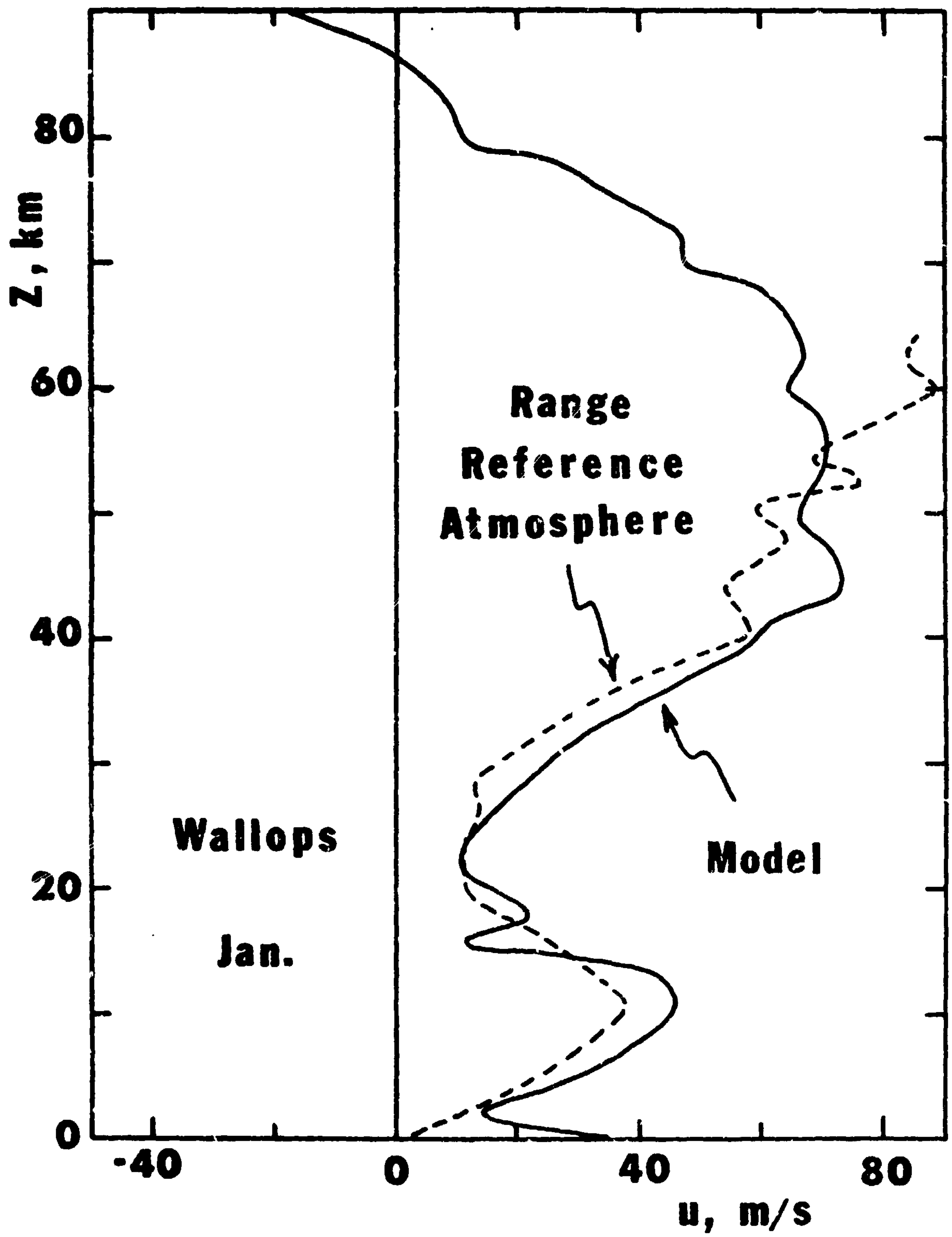


Figure 10.15 As in Figure 10.13 for zonal wind.

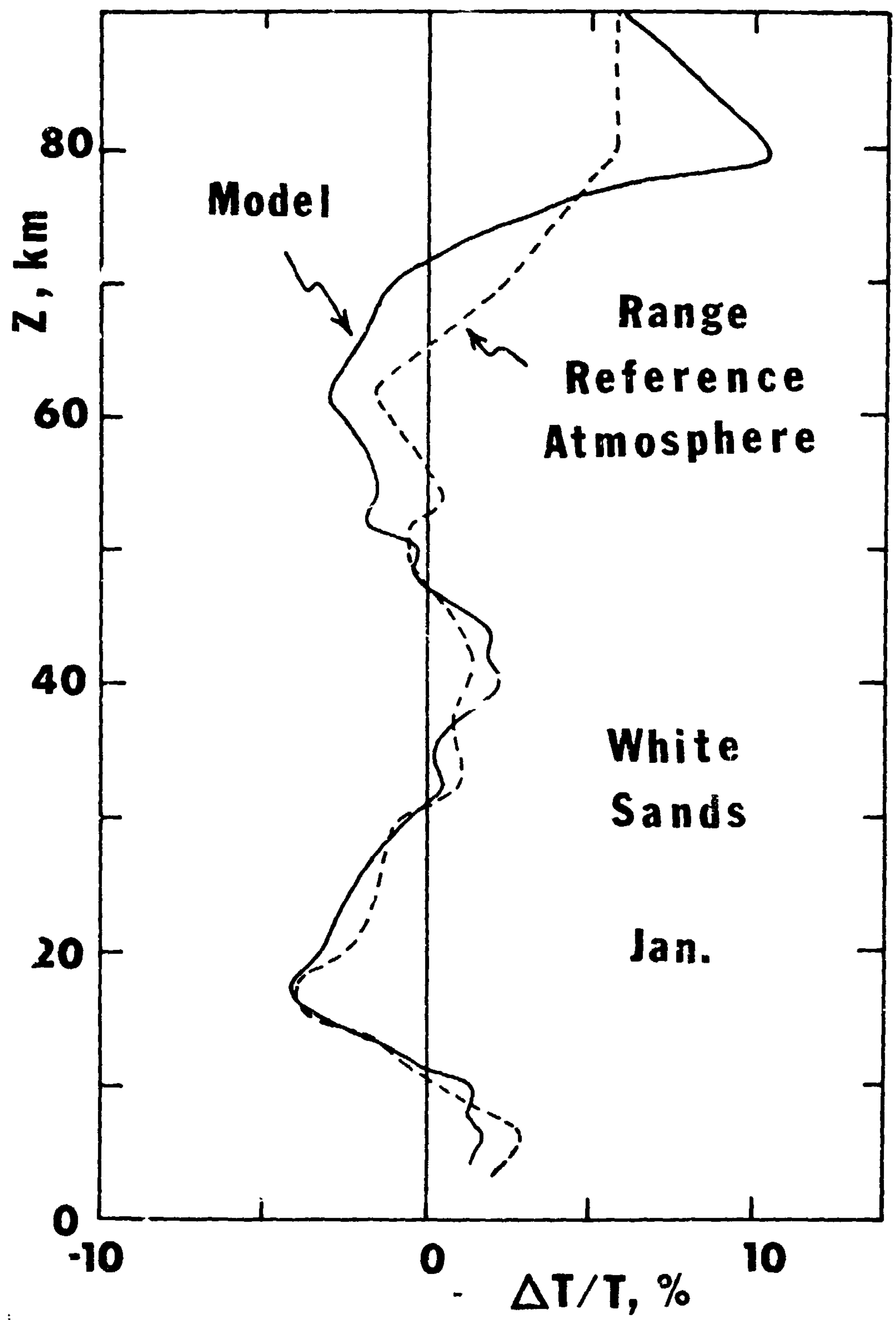


Figure 10.16 PROFILE generated monthly mean temperature for White Sands in January, compared to the White Sands January range reference atmosphere. Percent deviations are with respect to the 1962 U.S. Standard Atmosphere.

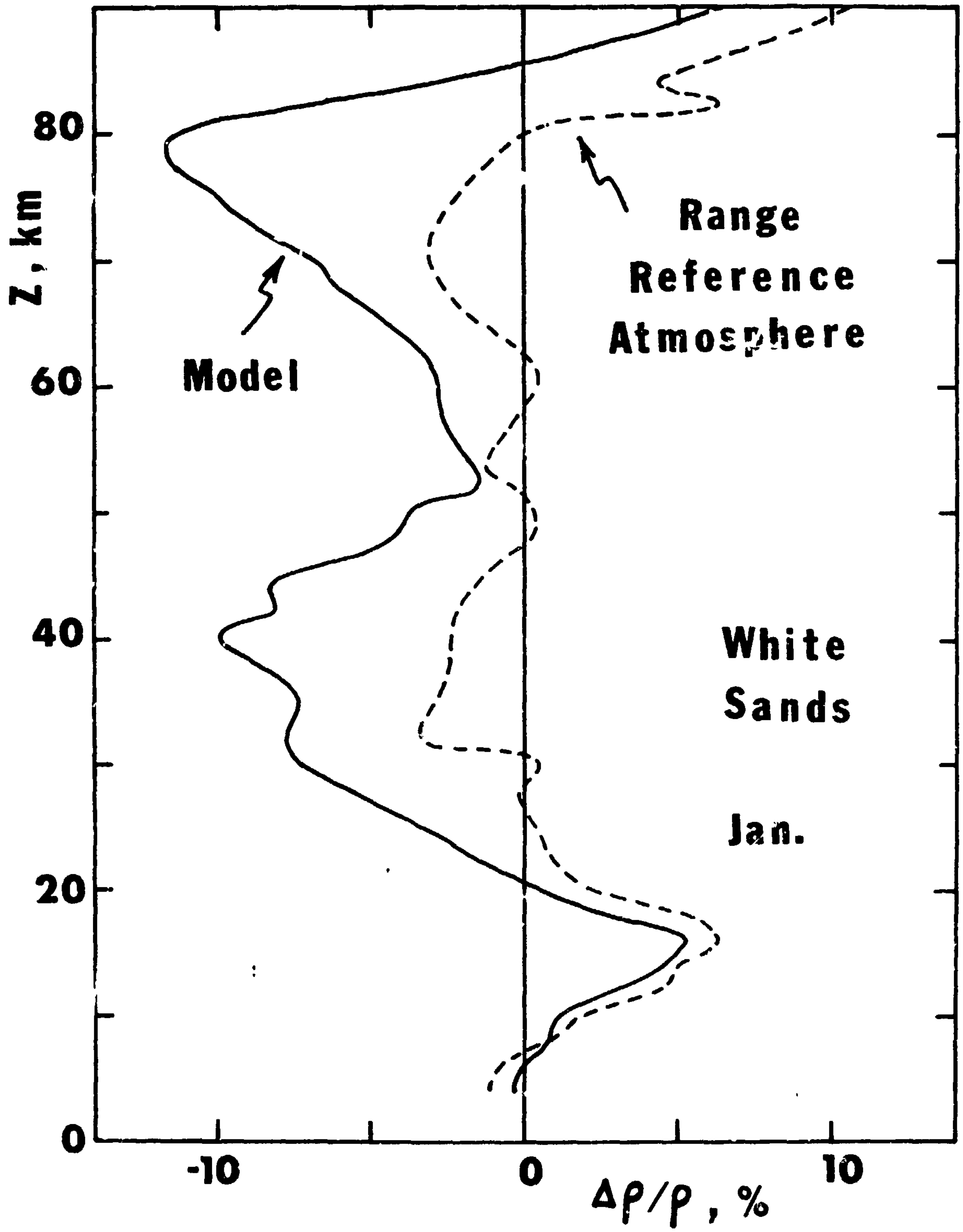


Figure 10.17 As in Figure 10.16 for density.

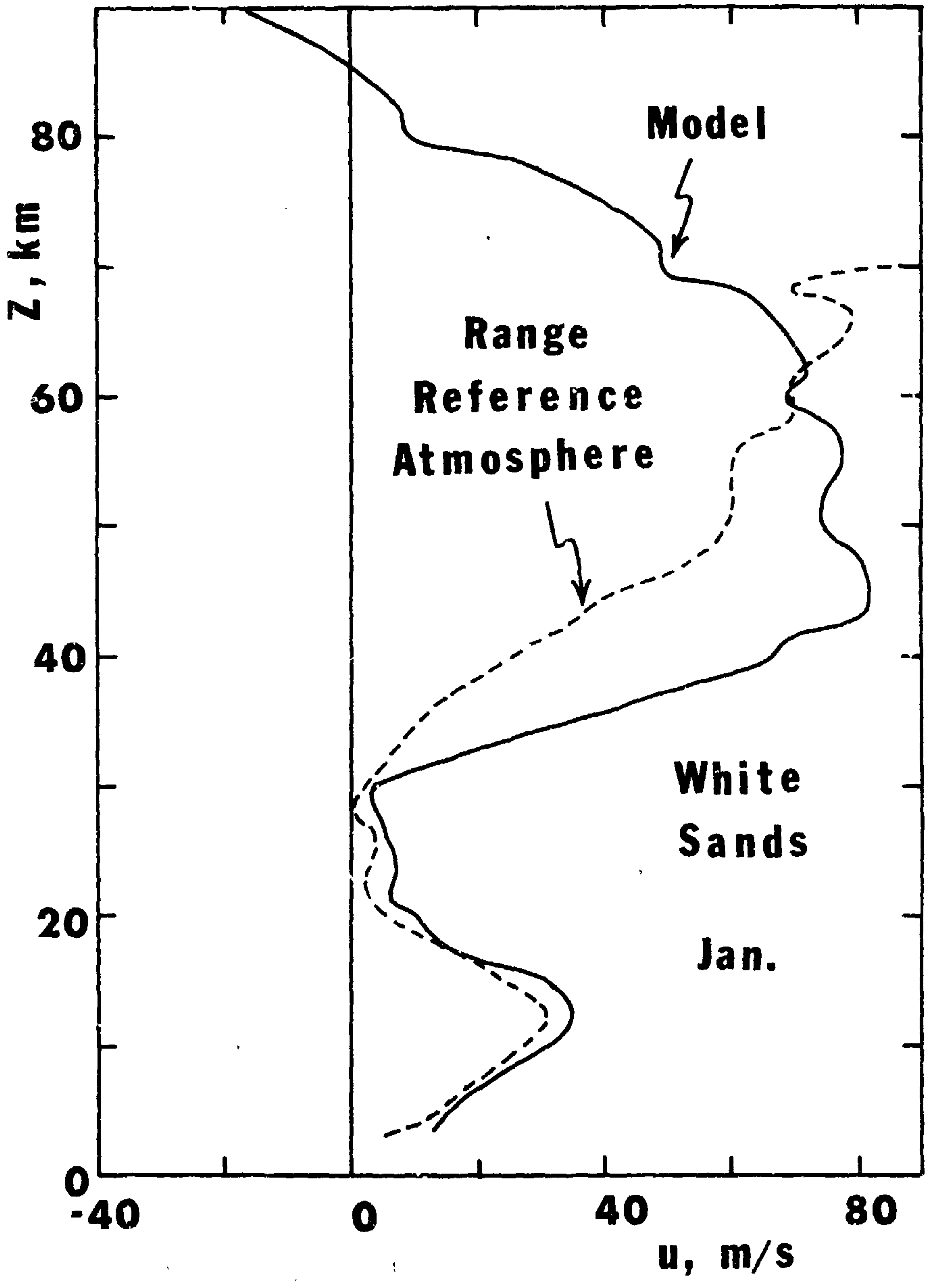


Figure 10.18 As in Figure 10.16 for zonal wind.

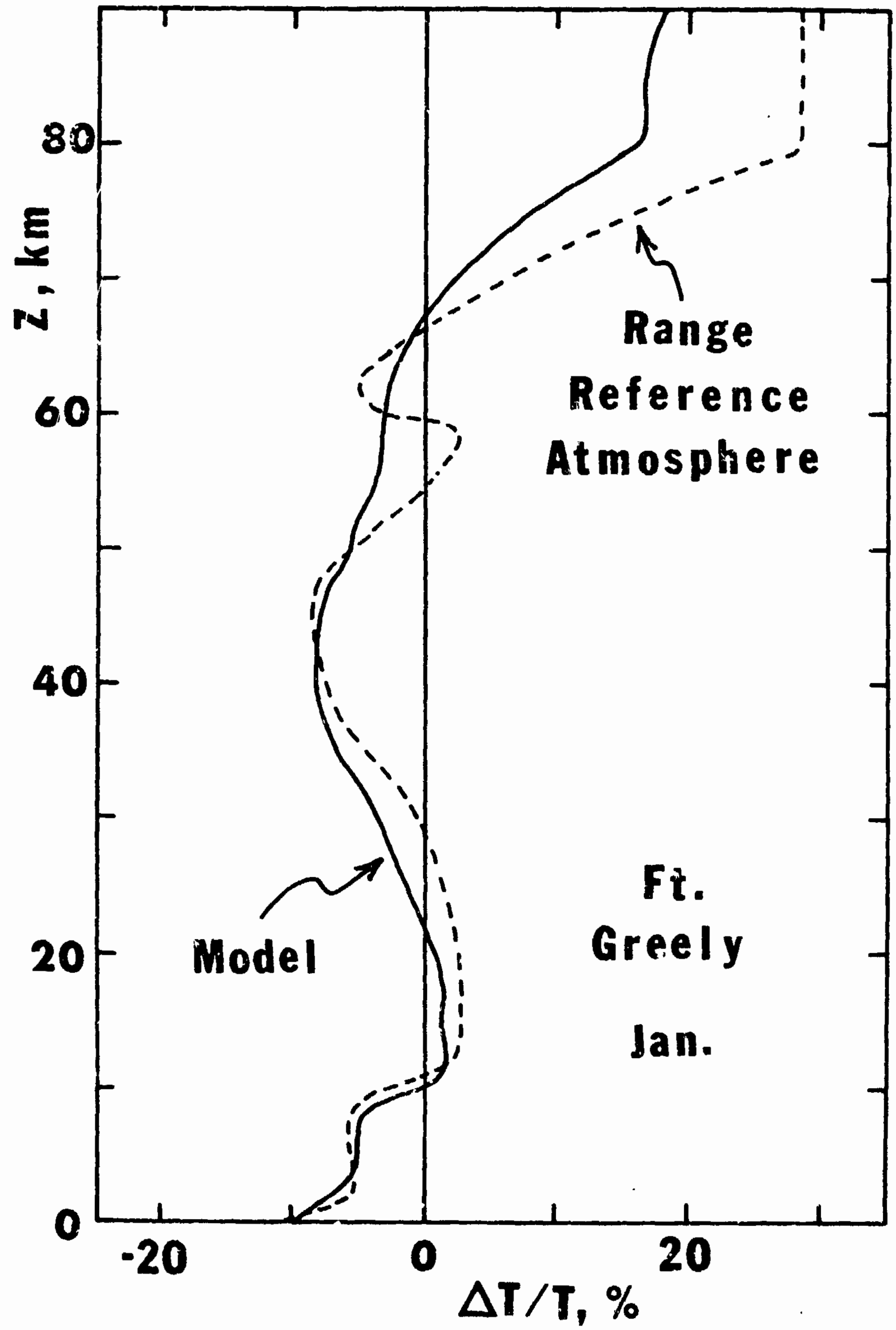


Figure 10.19 PROFILE generated monthly mean temperature for Fort Greely in January, compared to the Fort Greely January range reference atmosphere. Percent deviations are with respect to the 1962 U.S. Standard Atmosphere.

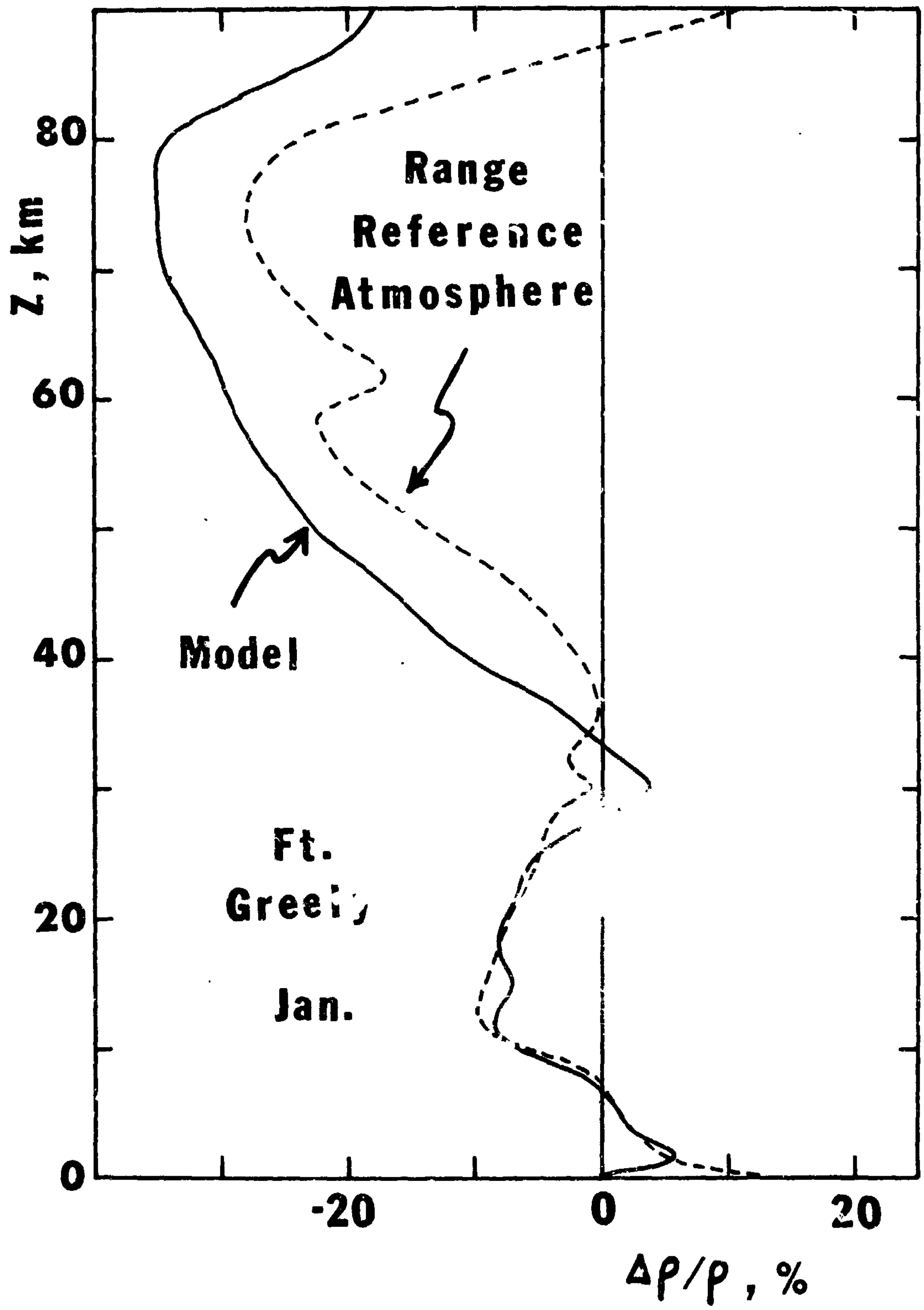


Figure 10.20 As in Figure 10.19 for density.

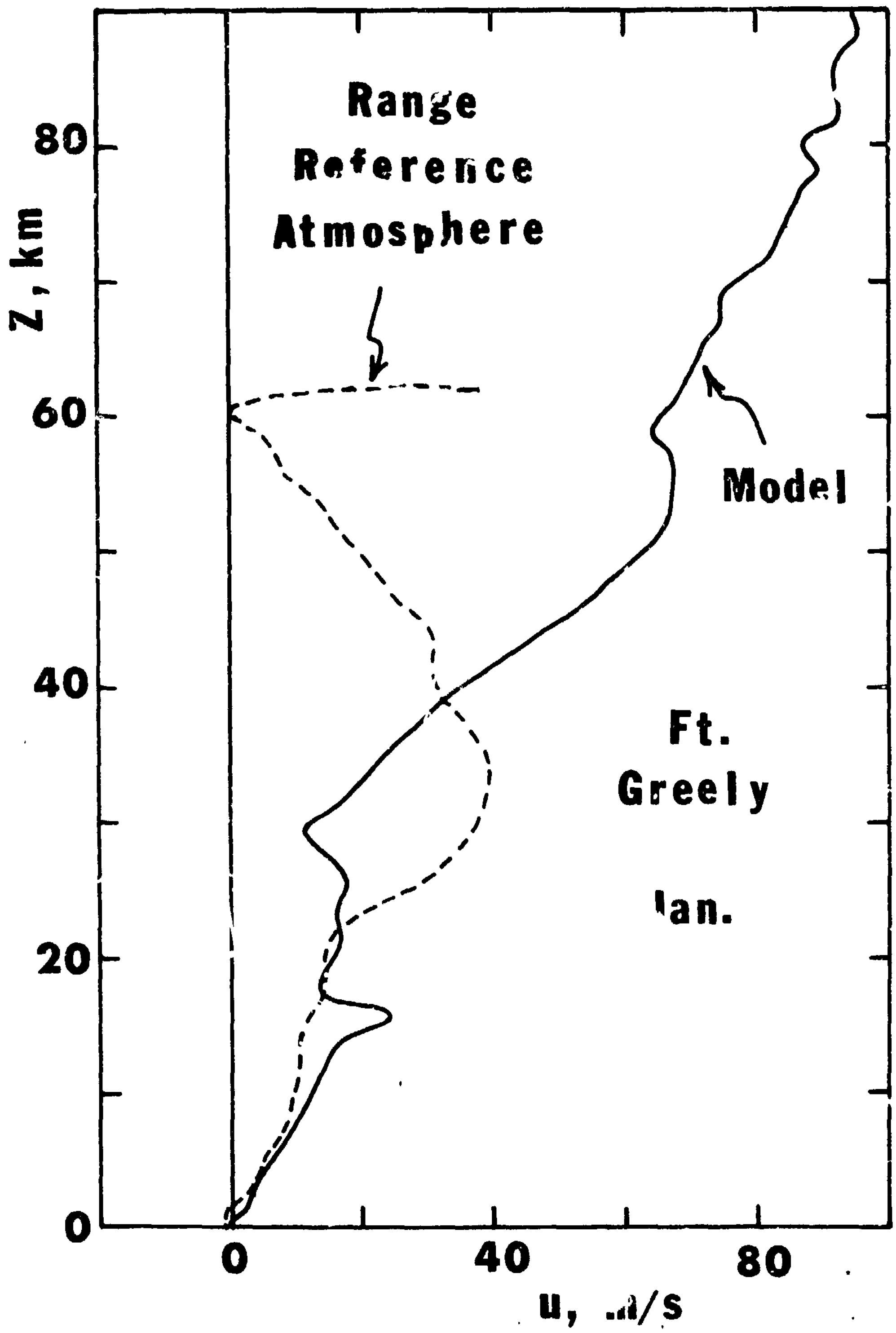


Figure 10.21 As in Figure 10.19 for zonal wind

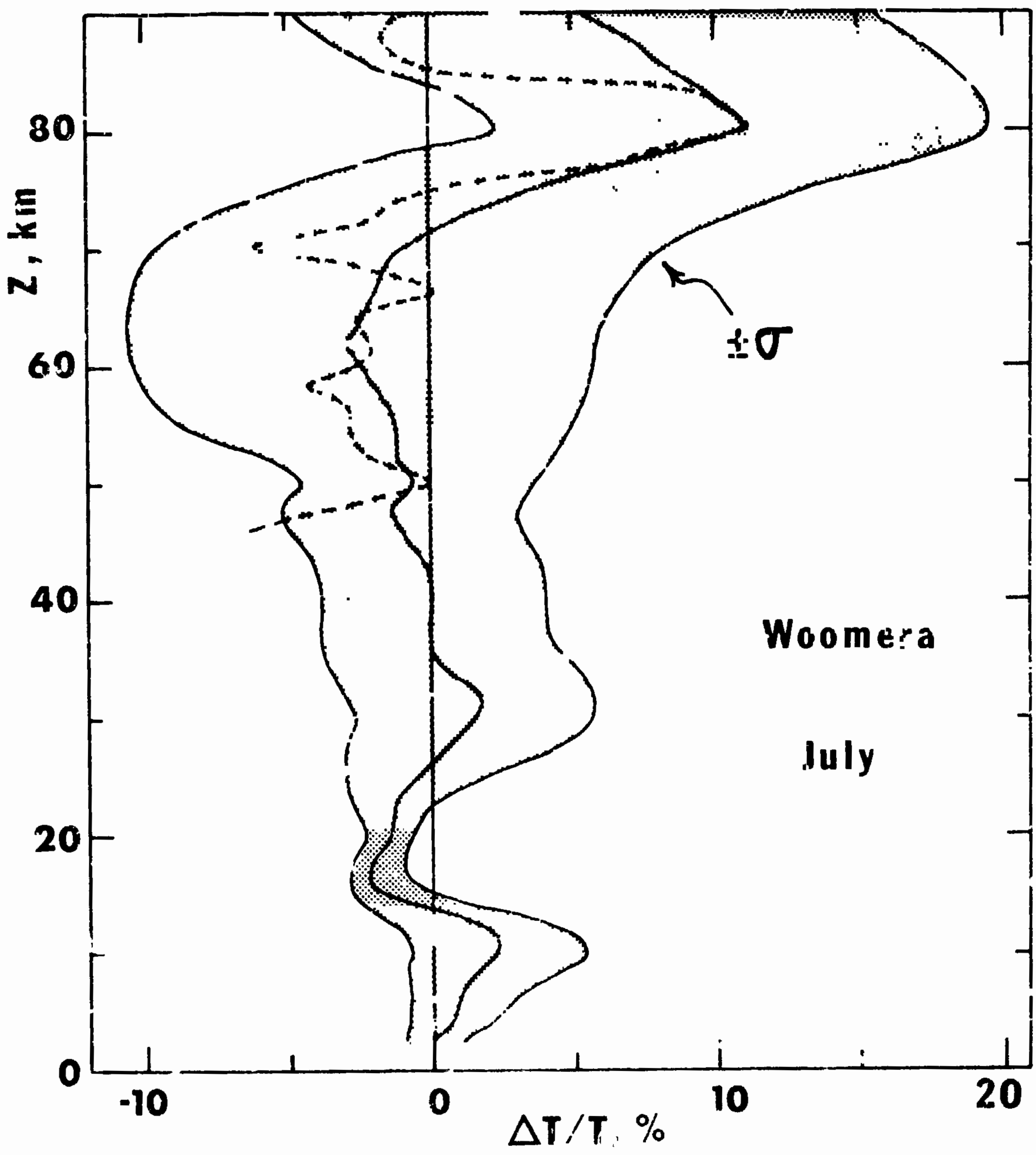


Figure 10.22 Monthly mean temperature and the ± 1σ envelope for Woomera, Australia (31 °S) in July. Percent deviation are with respect to the 1962 U. S. Standard Atmosphere. A typical observed profile is also shown for comparison (HAD 174, July 7, 1965).

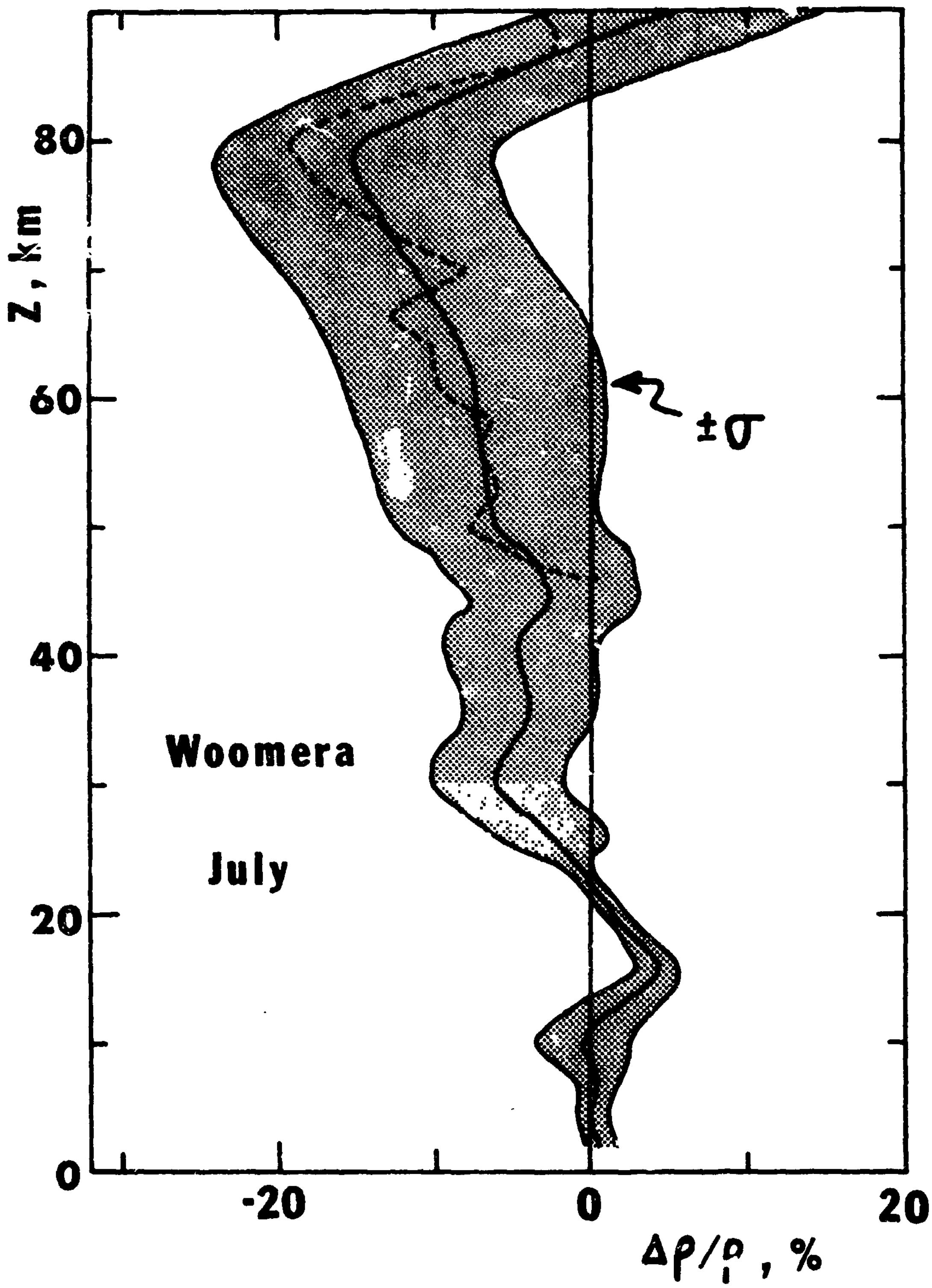


Figure 10.23 As in Figure 10.22 for density.

11. APPLICATIONS OF THE MODEL

A set of trajectory positions for any desired trajectory, ascent or re-entry, can be input to the PROFILE program for evaluation of atmospheric parameters for design purposes. Especially useful for Space Shuttle applications would be simulations of external tank re-entry trajectories, which come in over the Indian Ocean, a region somewhat sparse in direct observations. The PROFILE program, and its accompanying input data tapes, should prove very valuable in many phases of design and mission analysis for the Space Shuttle and other manned or un-manned space missions. When locations near test ranges are to be simulated, the PROFILE program produces atmospheric parameter values close to those of the appropriate range reference atmosphere. Yet when a region, not near any test range, is to be studied, the PROFILE program produces values more consistent and realistic than previously available Standard Atmospheres (e.g. 1966 U.S. Standard Atmosphere supplements) or models (e.g. Groves, 1971).

In addition to applications in spacecraft design and in trajectory and mission analysis applications, the PROFILE program has many other potential uses. Some of these possible alternate applications are outlined below.

In certain atmospheric measuring techniques an iteration scheme is made, starting from some assumed profile and converging on the final result. Two examples of this type of analysis are infrasonic measurements of wind and satellite temperature profiles. Infrasonic waves are affected by the wind profile, and adjustment of an assumed wind profile to yield optimum agreement among observations of natural infrasound at an array of locations is a possible ground based technique for determining wind conditions in the upper atmosphere (Donn and Rind, 1972). If more accurate wind profiles could be used to start with, the optimization process could be speeded up. Infrared scanners in satellites are used to determine atmospheric temperature profiles and total water column by means of an inversion process applied to the spectrum of infrared radiation received at the satellite. The process to determine the integrated water column requires an assumed or a measured temperature profile. Reasonably accurate assumed temperature profiles for this purpose could be generated by the PROFILE program. The satellite infrared radiometer method for measuring temperature profiles also relies somewhat on an interation process. A portion of the radiative transfer matrix is weakly dependent on the temperature profile, so that its solution to determine a temperature profile must be interated once or twice from an initial guess (Wark and Hilleary, 1969). A satellite remote sounding method developed by Rodgers (1970) is based on selecting among equal radiance temperature profiles by picking the one with maximum probability of occurrence. The PROFILE program results (surface to about 50 km), especially if coupled with cloud statistics (for example from Greaves, et al., 1971) could provide good information concerning the relative probability of various temperature profiles.

PROFILE program generated profiles of atmospheric parameters would make meaningful comparison data for measurements obtained by many different sounding or measuring techniques.

For many purposes it is useful to know some details of the mean global circulation patterns which would affect horizontal transport and dispersion in the atmosphere. The mean monthly horizontal winds computed by the PROFILE program would be a useful latitude-longitude-height dependent wind field for global diffusion estimations. A method to estimate the latitude-longitude-height dependent mean monthly vertical winds from slopes of isentropic surfaces is now being investigated. All of the necessary parameters to compute these isentropic surface slopes are now being computed or are available for computation in the PROFILE program. These cm/sec magnitude mean vertical winds are not detectable directly, but could play an important part in constituent mixing or in global scale diffusion in the atmosphere.

12. LIMITATIONS OF THE MODEL AND POSSIBLE FUTURE REFINEMENTS

The major shortcoming of the present model is due to the lack of adequate observational data over certain regions and altitude ranges (especially eastern and southern hemispheres in the 25-120 km range). The limited southern hemisphere observations above 25 km forced the six-month displaced northern hemisphere data to be used for the southern hemisphere in the modified Groves region (25-110 km). Note, however, that the southern hemisphere 4-D data (surface to 25 km) is based on actual southern hemisphere measurements, for each of the 12 months.

Two areas where further improvement could be made in the data on the input data tape are in the stationary perturbations and the random perturbation and random wind magnitudes. Due to time limitations only two or three years of upper air charts were read at the 10, 2, and 0.4 mb level. Two more years of 10 mb monthly means are available for reading. Only the first week of each month was read for three years at the 2 and 0.4 mb levels. The other weeks and two other complete years are available for reading. More recent random perturbation magnitudes than those used are now available (Cole, 1972) and the range reference atmosphere wind statistics could be used to improve the random wind magnitude data.

A revised model of the random perturbations to consider a large vertical scale systemmatic deviation from the monthly mean plus a smaller magnitude small vertical scale random component could improve the model profile correspondence to observed conditions. However, improvements in the stationary perturbation and random parameter data without changing the random perturbation model could be accomplished by changing only the input data tape. No program alterations would be required. There are also program options for reading in alternate random (or QBO) parameters from another data file instead of those values on the data tape (see the users manual section of this report).

The 1970 version of the Jacchia model was purposely selected over the later refinements made by Jacchia (1971) as being better suited for the Space Shuttle design applications. However, the Jacchia subroutines were kept separate in the program so that easy substitution of any alternate thermosphere-exosphere model could be made if desired (see the users and programmers manual section of this report for further details).

Although many scientific, engineering, and technical applications require atmospheric parameters not included in the PROFILE program (humidity, cloud cover, atmospheric constituents, electron densities, etc.) the presently constituted program is already rather large (about 32K on the UNIVAC 1108 FORTRAN compiler), and it requires about one minute of time on the UNIVAC 1108 as a minimum for data lookup on the data tape and 4-D tape (computation of parameters on the trajectory takes almost insignificant time after the data lookup from the tapes has been completed). Therefore, there are probably not many applications for which major new additions to the present program would be beneficial, from a program size standpoint. However, if modification or additions are required for specific applications, the program was written in a modular form with adequate subdivision into subroutine sections so that deletions, modification, and additions to the sections where alterations are desired could be accomplished with a minimum of difficulty. (Again, consult the users and programmers manual sections of this report for more details).

APPENDIX A
Latitude and Longitude Interpolation Method

Consider a function $f(x, y)$ of which there are four known values f_0, f_1, f_2, and f_3 at the rectangularly spaced points (x_1, y_1), (x_2, y_1), (x_1, y_2), and (x_2, y_2) respectively (see Figure A-1). The values of $f(x, y)$ over the interval $x_1 < x < x_2$ and $y_1 < y < y_2$ can be found from the following approximate series expansion

$$f(x, y) = f(x_1, y_1) + \left.\frac{\partial f}{\partial x}\right|_{(x_1, y_1)} (x - x_1) + \left.\frac{\partial f}{\partial y}\right|_{(x_1, y_1)} (y - y_1) + \left.\frac{\partial^2 f}{\partial x \partial y}\right|_{(x_1, y_1)} (x - x_1)(y - y_1) \tag{A-1}$$

where $f(x_1, y_1) = f_0$. The following finite difference approximations for the partial derivatives in (A-1) can be made (where $\Delta x = x_2 - x_1$ and $\Delta y = y_2 - y_1$).

$$\left.\frac{\partial f}{\partial x}\right|_{(x_1, y_1)} \approx \frac{f_1 - f_0}{\Delta x} \tag{A-2}$$

$$\left.\frac{\partial f}{\partial y}\right|_{(x_1, y_1)} \approx \frac{f_2 - f_0}{\Delta y} \tag{A-3}$$

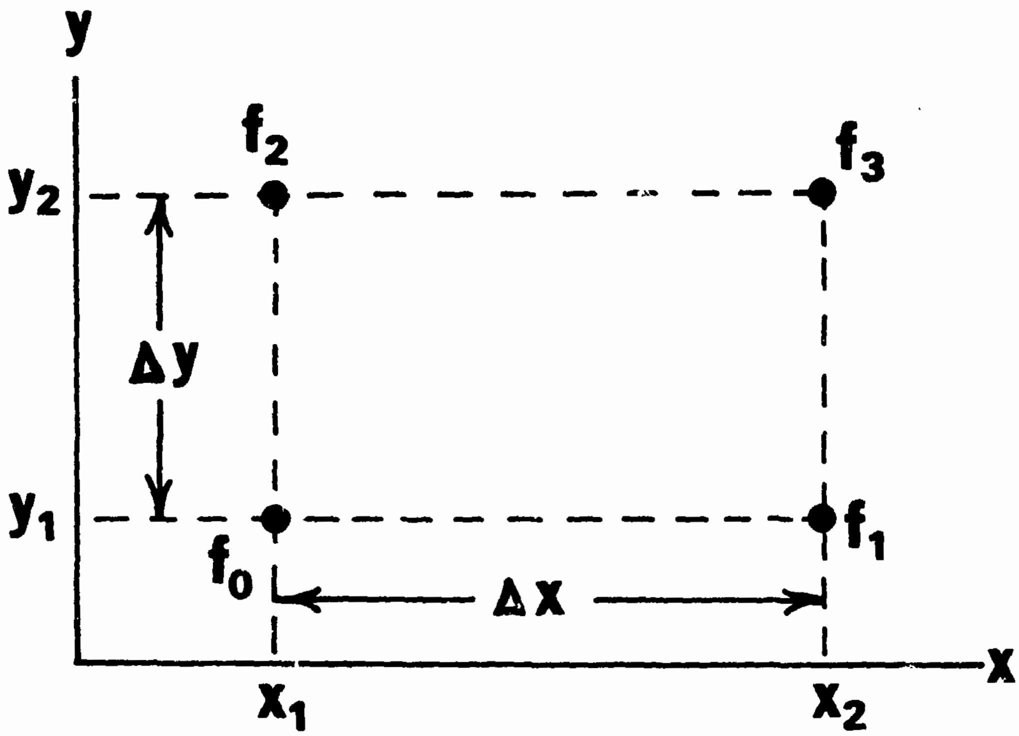


Figure A-1 Illustration of the interpolation geometry

$$\left.\frac{\partial^2 f}{\partial x \partial y}\right|_{(x_1,\, y_1)} \simeq \frac{\frac{f_3 - f_1}{\Delta x} - \frac{f_2 - f_o}{\Delta y}}{\Delta x}$$

$$= \frac{\frac{f_3 - f_2}{\Delta x} - \frac{f_1 - f_o}{\Delta x}}{\Delta y}$$

$$= \frac{f_3 - f_1 - f_2 + f_o}{\Delta x \Delta y} \qquad \text{(A-4)}$$

With these approximations (A-1) becomes

$$f(x, y) = f_o + (f_1 - f_o)\,\delta x + (f_2 - f_o)\,\delta_y$$

$$+ \ (f_3 - f_1 - f_2 + f_o)\,\delta x \delta y \qquad \text{(A-5)}$$

where $\delta x = (x - x_1)/\Delta x$ and $\delta y = (y - y_1)/\Delta y$. Equation (A-5) is seen to correspond to equation (1) page 32 in the 4-D model report (Spiegler and Fowler, 1972) except for the introduction of the cosine-of-latitude factors in the 4-D report. Equation (A-5), with an appropriate change in variables, is equivalent to the NMC grid four point interpolation technique of Jenne, (1970). The interpolation formula (A-5) is used in the PROFILE program whenever latitude-longitude interpolation is required between a rectangular array (in latitude-longitude coordinates) of positions.

APPENDIX B
Derivation of Coefficients C, D, and E in Equation (8...)

Multiplication of equation (8.10) successively by $T_1'/\bar{T}_1$, $\rho_2'/\bar{\rho}_2$ and by itself, and then averaging, yields the three equations

$$R\,\sigma_{T_1}\,\sigma_{T_2} = C\,\sigma_{T_1}^{\;2} + D\,r(T_1\,\rho_2)\,\sigma_{T_1}\,\sigma_{\rho_2} \tag{B-1}$$

$$r(T_2\,\rho_2)\,\sigma_{T_2}\,\sigma_{\rho_2} = C\,r(T_1\,\rho_2)\,\sigma_{T_1}\,\sigma_{\rho_2} + D\,\sigma_{\rho_2}^{\;2} \tag{B-2}$$

$$\sigma_{T_2}^{\;2} = C^2\,\sigma_{T_1}^{\;2} + D^2\,\sigma_{\rho_2}^{\;2} + 2\,C\,D\,r(T_1\,\rho_2)\,\sigma_{T_1}\,\sigma_{\rho_2} + E^2 \tag{B-3}$$

which can be solved for the coefficients C, D, and E once the correlation parameters $r(T_1\,\rho_2)$ and $r(T_2\,\rho_2)$ are determined. From Buell (1970), $r(T_2\,\rho_2)$ must be given by

$$r(T_2\,\rho_2) = (\sigma_{p_2}^{\;2} - \sigma_{\rho_2}^{\;2} - \sigma_{T_2}^{\;2})/(2\,\sigma_{\rho_2}\,\sigma_{T_2}) \tag{B-4}$$

where, according to the notation here, σ_{T_2} is the standard deviation of $T_1'/\bar{T}_2$. Multiplication of equation (8.6) by $T_1'/\bar{T}_1$ and averaging yields

$$r(T_1\,\rho_2)\,\sigma_{\rho_2}\,\sigma_{T_1} = A\,\sigma_{\rho_1}\,\sigma_{T_1}\,r(T_1\,\rho_1) \tag{B-5}$$

which, after substitution of (8.8), yields

$$r(T_1\,\rho_2) = R\,r(T_1\,\rho_1) \tag{B-6}$$

and $r(T_1\,\rho_1)$ is given by a relation similar to (B-4), so

$$r(T_1\ \rho_2) = R\ (\sigma_{\rho_1}{}^2 - \sigma_{\rho_2}{}^2 - \sigma_{T_2}{}^2)/(2\sigma_{\rho_1}\ \sigma_{T_2}) \qquad \text{(B-7)}$$

With equations (B-4) and (B-7) to use in equations (B-1 - B-3) they can be solved for C, D, and E. C and D can be solved first from (B-1 and B-2), yielding

$$C = \frac{R(\sigma_{T_2}/\sigma_{T_1})\ [1 - r(T_2\ \rho_2)\ r(T_1\ \rho_1)]}{1 - R^2\ r(T_1\ \rho_1)} \qquad \text{(B-8)}$$

$$D = \frac{(\sigma_{T_2}/\sigma_{\rho_2})\ [r(T_2\ \rho_2) - R^2\ r(T_1\ \rho_1)]}{1 - R^2\ r(T_1\ \rho_1)} \qquad \text{(B-9)}$$

where the $r(T_1\ \rho_1)$ and $r(T_2\ \rho_2)$ factors are evaluated by (B-4) and its companion equation for position 1. Coefficient E can then be sc[illegible]y using relations (B-8) and (B-9) in (B-3)

$$E = [\sigma_{T_2}{}^2 - C^2\ \sigma_{T_1}{}^2 - D^2\ \sigma_{\rho_2}{}^2 - 2\ C\ D\ R\ r(T_1\ \rho_1)\ \sigma_{T_1}\ \sigma_{\rho_2}]^{1/2} \qquad \text{(B-10)}$$

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APPROVAL

FOUR-D GLOBAL REFERENCE ATMOSPHERE TECHNICAL DESCRIPTION - PART I

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The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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