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THREE-DIMENSIONAL RANDOM EARTH ATMOSPHERES FOR MONTE CARLO TRAJECTORY ANALYSES

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16. Abstract

A set of four computer tapes containing random three-dimensional Earth atmospheres is available for Monte Carlo trajectory analyses. The four tapes - one for each season - contain sufficient atmospheric tables to allow over 1400 replications of any trajectory below an altitude of 99 km. The atmospheres were provided by an empirical model designed to generate random atmospheres whose distributions match those in a data base of over 6000 sounding-rocket measurements. A readily implementable means of linking the tapes to any existing trajectory simulation computer program is described. It involves the addition of three subroutines which are listed in an appendix.

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THREE-DIMENSIONAL RANDOM EARTH ATMOSPHERES FOR MONTE CARLO TRAJECTORY ANALYSES

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SUMMARY

A set of four magnetic computer tapes containing random global Earth atmospheres is available for Monte Carlo trajectory analyses below an altitude of 99 km. The four tapes - each representing a different season - contain atmospheres in sufficient quantity to permit over 1400 independent replications of any trajectory.

The atmospheres were generated by a statistical atmosphere model based on over 6000 rocket and high-altitude soundings. The model was constructed empirically to generate temperatures, densities, and pressures whose distributions match those in the data, and whose vertical gradients are likewise statistically similar to gradients in the data.

A readily implementable means of interfacing the tapes with an existing trajectory simulation program is described. The method involves the addition of three subroutines, which are linked to the trajectory program through simple calling statements. The core storage required for the subroutines is approximately 4000 (octal) words.

INTRODUCTION

There is a recognized need among aircraft and spacecraft designers for a means of estimating the impact of atmospheric variability on a vehicle's performance. Standard Atmospheres (refs. 1 to 3) are commonly used to calculate trajectories, but the Earth's atmosphere is variable and always differs from any standard. For example, high-altitude densities at a fixed location can vary by over 100 percent within the same season. Densities vary by at least 10 percent at all altitudes.

The Random Earth Atmosphere Computer Tapes (REACT) are a set of four magnetic tapes containing typical nonstandard densities and temperatures for a three-dimensional global atmosphere. The tapes are intended to be used along with a trajectory simulation program to generate samples of trajectories passing through different random atmospheres. Such samples can help define the variability in a vehicle's performance parameters resulting from atmospheric variations. Any vehicle (spacecraft or aircraft) can be studied by using the tapes in the flight regime where the altitude is below 99 kilometers.

The REACT atmospheres are profiles of temperatures and densities generated by the empirical random atmosphere (ERA) statistical model (ref. 4) which was developed empirically from over 6000 meteorological rocket and high-altitude soundings. Pressure and other atmospheric properties (e.g., viscosity, speed of sound, etc.) can be calculated from the temperatures and densities. The atmospheres on the tapes are described as typical in that their statistical distributions match those of the sounding data at corresponding altitudes, latitudes, and seasons.

The tapes represent four seasons as follows:

Tape	Months	Tape identification
1	March to May	SPRING
2	June to August	SUMMER
3	September to November	AUTUMN
4	December to February	WINTER

(The season designation refers to that of the northern hemisphere. For example, the "SPRING" tape actually contains autumn atmospheres for southern hemisphere locations.)

Each tape contains sufficient atmospheric data to permit up to 361 independent replications of the same trajectory, the actual number depending on the range of longitudes covered by that trajectory. The trajectory's performance parameters (for example, range, surface heating rates, dynamic pressures, structural loads, etc.), which are of interest to the vehicle designer, will vary from one replication to the next because of the atmosphere's variability. The collection of parameter values resulting from the simulations forms a random statistical sample which can be used to estimate that parameter's underlying probability distribution. Such distributions are needed in estimating the probability of exceeding existing design values, in establishing new design values, and in designing adequate guidance and control systems. Sources of error other than the atmosphere can be incorporated and a thorough error analysis performed.

Because the three-dimensional REACT atmospheres introduce certain density gradient effects which are not provided by the standard atmospheric models, a discussion of horizontal and vertical density gradients is included. Density gradients on the tapes are compared with those in the data and with proposed "design" gradients in reference 5. Vertical density gradients are consistent with those found in the data. Since the data base consists of isolated vertical profiles, inferences about horizontal density gradients cannot be made directly from the data. Horizontal gradients were controlled by assuming a minimum distance between uncorrelated profiles of 600 nautical miles (ref. 6). A fairly high percentage of the REACT density gradients exceeded the "design" gradients of reference 5, even though the latter were based on this same assumption. It is believed, however, that the REACT density gradients are more representative of realistic gradients.

Three subroutines which can be used to link REACT to a trajectory program are described and a listing of the subroutines is given in appendix A. Appendix B presents a brief description of the empirical atmosphere model (ref. 4) used to generate the tapes.

SYMBOLS AND ABBREVIATIONS

ATMOS — one of three subroutines used to interface REACT with trajectory program

COMMON/LINK/ — common storage area containing block information from TAPE10 - shared by ATMOS, INITBLK, and READBLK subroutines

D — atmospheric density, kg/m^3

DL — increment used to convert longitude to "longitude" on TAPE10, deg

g — acceleration due to gravity, m/sec^2

INITBLK — one of three subroutines used to interface REACT with trajectory program

k — refers to a season in northern hemisphere; $k = 1$ (spring), $k = 2$ (summer), $k = 3$ (autumn), and $k = 4$ (winter)

N — in subroutine READBLK, refers to next block to be read from TAPE10

NBR — simulation or replication number

NBRO — number of trajectories already simulated from TAPE10 on previous run of program

NMAX — maximum number of independent trajectories which can be simulated by using TAPE10

NO — number of TAPE10 block currently stored in COMMON/LINK/

P — atmospheric pressure, N/m^2

P_{62} — 1962 Standard Atmosphere pressure, N/m^2

R — gas constant used in equation of state, 8314.34 $J\text{-}kmol^{-1}\text{-}K^{-1}$

REACT — Random Earth Atmosphere Computer Tapes

READBLK — one of three subroutines used to interface REACT with trajectory program

RHO — three-dimensional array containing random atmospheric densities from TAPE10, kg/m^3

S — speed of sound, m/sec

SEASON	alphanumeric word used to identify REACT tape (first record on each tape)
s	standard deviation of atmospheric temperature estimated from sounding data, K
T	atmospheric temperature, K
$\bar{T}$	mean atmospheric temperature estimated from sounding data, K
TAPE10	REACT tape linked to a trajectory program at any given time
TAU	three-dimensional array containing random atmospheric temperatures from TAPE10, K
W	mean molecular weight of air, 28.964 kg-kmol^{-1}
XLAT	latitude, deg
XLATI	initial latitude of trajectory, deg
XLATO	latitude locating RHO and TAU arrays, deg
XLOMAX	maximum longitude of trajectory, deg
XLOMIN	minimum longitude of trajectory, deg
XLONG	"longitude" on TAPE10, deg
XLONGI	initial longitude of trajectory, deg
XLONGO	"longitude" locating RHO and TAU arrays, deg
Z	altitude, m
z	altitude, km
λ	longitude, deg
ρ	atmospheric density, kg/m^3
ρ_{62}	1962 Standard Atmosphere density, kg/m^3
ϕ	latitude, deg

TAPE SPECIFICATIONS

The tapes are 1.27-cm (0.5-in.) nine-track magnetic tapes written in binary (odd parity) mode, using a density of 629.9 characters per cm (1600 characters per in.), and labeled with ANSI standard labels. They were generated on a CONTROL DATA CYBER 175 computer which uses a physical record size of 512 60-bit words.

If it is necessary to read the tapes in double precision (for example, where the computer being used has a word size smaller than 60 bits), the information should be converted to single precision and transferred to a tape compatible with the computer to be used. Since the densities and temperatures are random, the degree of accuracy lost in reducing word size would not be significant.

GENERAL CONTENTS OF EACH TAPE

The Standard Atmosphere tables (refs. 1 to 3) are one-dimensional tables giving atmospheric properties as functions of altitude. The REACT atmospheres are three-dimensional tables which give densities and temperatures as functions of altitude, latitude, and longitude. REACT properties at a given altitude and latitude are modeled after data taken at the same altitude and latitude. Thus, these two coordinates, altitude and latitude, correspond exactly to the same coordinates of the trajectory. The "longitude" coordinate used in the REACT tables does not correspond to physical Earth longitudes but, instead, represents a longitudinal measure, in degrees, from the midnight meridian; that is, the zero "longitude" is interpreted as midnight and is not the Greenwich meridian. Moving eastward, each increase of 15° in "longitude" represents the passage of 1 hour in local time as determined by the Sun angle. At a "longitude" of 180°, for example, the atmospheres are characteristic of those at noon. The term referring to a coordinate on the REACT tapes will henceforth be placed in quotation marks to distinguish it from the physical longitude of the trajectory.

It is assumed that only one of the four tapes is linked to the trajectory simulation program at a given time, and this tape will be called TAPE10. Since the four tapes have identical formats, the sequence of statements used to read TAPE10 is appropriate for reading any of the four tapes.

Each tape contains one file which is composed of 2161 logical binary records. That is, in order to read the entire tape, 2161 unformatted READ statements must be executed. The first record contains one Hollerith word SEASON which is one of the following:

$$\text{SEASON} = \begin{cases} \text{10HSPRINGbbbb} \\ \text{10HSUMMERbbbb} \\ \text{10HAUTUMNbbbb} \\ \text{10HWINTERbbbb} \end{cases} \qquad (b = \text{blank}) \qquad (1)$$

depending on the tape.

The remaining 2160 records contain blocks of density and temperature tables, each extending to an altitude of 99 km and covering a specific geographical region, which is $30^{\circ} \times 30^{\circ}$ in latitude and "longitude." The 2160 blocks form 30 complete global atmospheres when pieced together. In general, many replicates of a given trajectory can be made by using the same global atmosphere by translating the trajectory 30° eastward (2 hours in time). This procedure is explained in more detail in a later section.

Each of the blocks must be read with a statement of the form

```
READ (10) NO,XLATO,XLONGO,RHO,TAU
```

where NO is the block number (NO = 1, . . ., 2160); XLATO and XLONGO are a reference latitude and longitude which locate the block geographically; and RHO is an array of densities and TAU is an array of temperatures, both dimensioned $34 \times 4 \times 4$. The elements RHO(I,J,K) and TAU(I,J,K) are, respectively, atmospheric density, in kg/m^3, and atmospheric temperature, in K, at

$$\left.\begin{array}{lll} \text{Altitude, km:} & z = 3(I - 1) & (I = 1, \ldots, 34) \\ \text{Latitude, deg:} & \phi = \text{XLATO} + 10(J - 1) & (J = 1, \ldots, 4) \\ \text{"Longitude," deg:} & \lambda = \text{XLONGO} + 10(K - 1) & (K = 1, \ldots, 4) \end{array}\right\} \quad (2)$$

Within each array the values are located every 3 km in altitude and every 10° in latitude and "longitude." From the dimensions of the RHO and TAU arrays, it follows that these tables cover the three-dimensional volume defined by

$$\left.\begin{array}{l} 0 \leqq z \leqq 99 \text{ km} \\ \text{XLATO} \leqq \phi \leqq \text{XLATO} + 30^\circ \\ \text{XLONGO} \leqq \lambda \leqq \text{XLONGO} + 30^\circ \end{array}\right\} \quad (3)$$

Figure 1 shows how the 2160 blocks fit together to cover the "longitude"-latitude plane. The number appearing in each block indicates the block number NO. The reference point (XLONGO,XLATO) for a block is the grid point in the lower left-hand corner of that block. Blocks were stored on the tapes beginning at XLATO = -90° and XLONGO = 0°, and proceeding northward, keeping XLONGO fixed and increasing XLATO in increments of 30° until XLATO = 60°. Then XLONGO is increased by 30° and the same six values of XLATO are repeated. As the blocks encompass the Earth 30 times, the value of XLONGO goes from 0° to $10\,770^\circ$ ($= 30 \times 360^\circ - 30^\circ$). It was more expedient from a programing standpoint to allow XLONGO to increase monotonically rather than set it back to 0° after each revolution. Near the equator the blocks cover an area approximately 3300 km by 3200 km and near the poles they cover an area approximately 3300 km by 860 km.

The computer core storage required to read each block is 1091 words or slightly more than 2000 octal words. It should only be necessary to read and store one block at a time. As the trajectory enters the three-dimensional region associated with a particular block, a subroutine should be called to read the appropriate block from TAPE10. The trajectory simulation can then continue through this region until a boundary is reached. As the trajectory passes into a new region, the subroutine should be called again to read the next appropriate set of RHO and TAU values.

REPLICATION OF TRAJECTORIES

It is assumed that the user will want to maximize the number of independent replicates of a trajectory which can be simulated by using TAPE10. That is, the user will have a specific trajectory, such as a space shuttle entry trajectory, and will want to replicate this trajectory as many times as possible by using different random atmospheres from TAPE10.

Figure 2 shows the ground track of an entry trajectory from a 28.5° inclined orbit. The initial longitude and latitude, when $z = 99$ km, are -175° and -5°, respectively, and the final longitude and latitude are -119° and 36°, respectively. Figure 3 shows a set of independent replicates of this trajectory relative to the atmospheres on TAPE10. Notice that the first trajectory begins at a "longitude" of 0°. The second begins at 30°, the third at 60°, and so forth. In simulating trajectories using different atmospheres from TAPE10, replicates will be independent provided that no two simulations use the same element of a RHO or TAU array to compute atmospheric properties. A 30° translation in "longitude" should result in trajectory replicates which are essentially independent. If ground tracks for different replicates approach or intersect one another when plotted on a latitude-"longitude" plane such as that in figure 3, the two replicates are not strictly independent. However, if their altitudes at points of intersection are substantially different, the dependence should be weak and can be ignored.

Since "longitudes" on TAPE10 actually represent time lines, the first trajectory in figure 3 starts at midnight, the second at 2 a.m., the third at 4 a.m., and so forth. If a large sample of replicates is generated or if the number of replicates is a multiple of 12, then the effect of local time will average out.

INCORPORATING REACT INTO A TRAJECTORY SIMULATION PROGRAM

In order to interface a trajectory program with REACT, it is suggested that three subroutines, such as those listed in appendix A, be added. A flow chart utilizing these subroutines is shown in figure 4. The first INITBLK is called once at the beginning of each trajectory simulation to initialize the block. It determines the trajectory's initial latitude and "longitude" relative to the blocks on TAPE10, and then calls the second subroutine READBLK which reads the correct block of information from TAPE10.

A third subroutine ATMOS is called at each point along a trajectory whenever atmospheric properties (i.e., density, temperature, pressure, and speed of sound) are needed. Presumably, ATMOS will replace any atmospheric model already in the trajectory program and, as it will be called frequently, it should be as efficient as possible. ATMOS interpolates in the RHO and TAU arrays to give an atmospheric density and temperature at the altitude, latitude, and longitude specified in its calling statement. Atmospheric pressure is then obtained from the equation of state, and the speed of sound is calculated from the temperature. (See formulation of ATMOS.) Before interpolating, a test is made to determine whether the trajectory's altitude, longitude, and latitude are still within the range covered by the block currently stored. If it is outside the longitude-latitude range, ATMOS calls READBLK to locate and read the correct block. If the altitude is above 99 km, ATMOS calls an alternate atmosphere model which the user must supply. In most instances it is sufficient to let this be the nonrandom atmosphere previously used to calculate trajectories.

The subroutines are written so as to be readily incorporated into an existing trajectory program. The only link between the trajectory program and the subroutines is through the calling statements to the subroutines INITBLK and ATMOS whose arguments are in terms of true longitudes. Conversion to "longitudes" relative to the coordinates on TAPE10 is handled automatically by the subroutines. Replication of trajectories is also handled automatically in that INITBLK calculates the initial "longitude" of each successive replicate, translating it 30° eastward from its previous initial "longitude." A more detailed description of the formulation of each subroutine follows.

SUBROUTINE INITBLK - FORMULATION

INITBLK must be called once prior to each replication of a trajectory. The basic purpose of INITBLK is to initialize the COMMON storage area

```
COMMON/LINK/ DL,NO,XLATO,XLONGO,RHO(34,4,4),TAU(34,4,4)
```

which is shared by all three subroutines. (See appendix A.) During a simulation, NO, XLATO, XLONGO, RHO, and TAU will contain the most recent block of information read from TAPE10, and DL is an increment used to convert longitudes to "longitudes" on TAPE10 by the translation

$$\text{"Longitude"} = \text{Longitude} + \text{DL} \tag{4}$$

The calling statement for INITBLK is

```
CALL INITBLK(NBR,NMAX,XLATI,XLONGI,XLOMIN,XLOMAX)
```

where NBR = 1, 2, 3, . . . is the number of the replication about to be simulated; NMAX is an output variable which gives the maximum number of independent replications which can be simulated using TAPE10; XLATI and XLONGI are the initial latitude and longitude, respectively, of the trajectory; and XLOMIN and XLOMAX are the minimum and maximum longitudes, respectively, of the trajectory. All arguments except NBR should remain constant throughout the simulations.

The first time INITBLK is called, the calling program must set NBR = 1. At this time, DL is initialized so that the minimum longitude XLOMIN corresponds to a "longitude" on TAPE10 of 0.001°. (This value is effectively zero but a small positive increment is used to prevent a negative zero "longitude" from occurring because of machine round-off error.) Thus, the increment DL is calculated as

$$\text{DL} = 0.001 - \text{XLOMIN} \tag{5}$$

The initial longitude XLONGI becomes the "longitude"

$$XLONG = XLONGI + DL \tag{6}$$

on TAPE10, and the maximum number of independent replicates is calculated as

$$NMAX = \left[\frac{10\ 800 - XLOMAX - DL}{30}\right] + 1 \tag{7}$$

where here and in later formulas the brackets indicate the "greatest integer" function defined by

$$[x] = \begin{cases} \text{greatest integer} \leq x & \text{if} \quad x \geq 0 \\ \text{smallest integer} \geq x & \text{if} \quad x < 0 \end{cases} \tag{8}$$

INITBLK then sets NO = 0 and calls READBLK to read the block covering the point (XLATI, XLONG), where XLONG is defined in equation (6).

On subsequent calls to INITBLK, NBR must be greater than 1. At this time DL is increased by 30° and the new XLONG is calculated by equation (6). After each replication is simulated and before calling INITBLK for the next replication, NBR should be tested to make sure it does not exceed NMAX.

As an example, consider the trajectory shown in figure 2. The first call to INITBLK would be

```
CALL INITBLK(1,NMAX,-5.0,-175.0,-175.0,-119.0)
```

When INITBLK returns control to the calling program, the value of NMAX will be 359 and will remain constant throughout the run. Thus, a sample of 359 independent replications of this trajectory can be generated from each tape or 1436 replications by using all four tapes. Of course, the user can always make fewer replications.

As another example, figure 5 shows the groundtrack of an entry trajectory from a 104° inclined orbit. The first call to INITBLK for this trajectory would be

```
CALL INITBLK(1,NMAX,73.0,4.0,-123.0,4.0)
```

Note that the minimum longitude (-123°) is neither the initial nor the final longitude in this case. Here INITBLK returns with NMAX = 356, and the possible replications are illustrated in figure 6.

SUBROUTINE READBLK - FORMULATION

READBLK is called both from INITBLK, to initialize RHO and TAU at the beginning of each trajectory replication, and from ATMOS whenever the trajectory enters a region requiring new RHO and TAU arrays. The calling statement to READBLK is

CALL READBLK(XLAT,XLONG)

where $-90^o \leq XLAT \leq 90^o$ and $0^o \leq XLONG \leq 10\ 800^o$ are the present latitude and "longitude" relative to the blocks on TAPE10.

At the time READBLK is called, NO is the number of the previous block read from TAPE10. READBLK uses XLAT and XLONG to determine N, the number of the next block to be read, by the formula

$$N = 6\left[\frac{XLONG}{30}\right] + \left[\frac{XLAT + 90}{30}\right] + 1 \tag{9}$$

For example, if $XLAT = -18.6^o$ and $XLONG = 239.5^o$, then

$$N = 6[7.98] + [2.38] + 1 = 42 + 2 + 1 = 45 \tag{10}$$

READBLK now compares N to NO + 1. If N < NO + 1, READBLK backspaces over blocks NO to N, and then reads block N. If N = NO + 1, then it simply reads the next block on TAPE10. If N > NO + 1, READBLK skips blocks NO + 1 to N - 1 and then reads block N. In reading block N, a new set of values for NO, XLATO, XLONGO, RHO, and TAU is thereby stored in COMMON/LINK/.

SUBROUTINE ATMOS - FORMULATION

ATMOS is called at each step along a trajectory when atmospheric properties are needed. Its calling statement is

CALL ATMOS(Z,XLAT,XLONG,D,T,P,S)

where Z is the altitude in meters, XLAT and XLONG are the true latitude and longitude in degrees, and D, T, P, and S are output variables which upon returning to the calling program will contain, respectively, atmospheric density in kg/m^3, temperature in K, pressure in N/m^2, and speed of sound in m/sec for the location (Z,XLAT,XLONG).

ATMOS first tests to see whether Z is in the range $0 \leq Z \leq 99\ 000$. If not, ATMOS calls a subroutine (which the user must supply) to get atmospheric properties outside this range. In the version of ATMOS in appendix A, the subroutine called is AT62 which is a subroutine used to get 1962 Standard Atmosphere properties.

If Z is in the correct range, then ATMOS tests XLAT and XLONG to determine whether

$$XLATO \leq XLAT \leq XLATO + 30 \tag{11}$$

and

$$XLONGO \leq XLONG + DL \leq XLONGO + 30 \tag{12}$$

If either of these conditions is not satisfied, READBLK is called and the test is repeated.

Once Z, XLAT, and XLONG are found to be in the correct range, D and T are obtained by interpolation by using RHO and TAU as three-way tables. All interpolations are linear except in vertical planes of the RHO array. In this direction linear interpolation is performed on the logarithm of density.

Once D and T are obtained, P is computed from the equation of state

$$P = \frac{RDT}{W} \tag{13}$$

where R is the universal gas constant (8314.34 J-kmol^{-1}-K^{-1}) and W is the mean molecular weight of air. Although W begins to vary above about 90 km, for the purposes of REACT it was assumed constant (28.964 kg-kmol^{-1}).

The speed of sound is computed as

$$S = \left(1.4\ \frac{RT}{W}\right)^{1/2} \tag{14}$$

where the constant 1.4 is the ratio of the specific heat of air at constant pressure to that at constant volume. Equations (13) and (14) are the same as those used in the U.S. Standard Atmosphere (refs. 1 to 3).

RESUMING AN INTERRUPTED SET OF SIMULATIONS

Suppose a user wishes to run 350 replications of a trajectory where 350 $\leq$ NMAX, and for some reason only 100 replications were run the first time his program was executed. If the original program is resubmitted to run the remaining 250 replications, there will have to be some assurance that none of the previously run simulations are duplicated. To effect this, the 101st replication should begin on TAPE10 at a "longitude" 30° east of where the 100th replication began.

In general, let NBRO be the total number of replicates already run from TAPE10, and let XLATI, XLONGI, XLOMIN, and XLOMAX be the arguments of INITBLK as defined earlier. Before calling INITBLK for the first time, subtract 30 × NBRO from XLOMIN (that is, XLOMIN = XLOMIN - 30*NBRO). Then call INITBLK as usual with NBR = 1. Upon returning from INITBLK, the correct block from TAPE10 will have been read in order to resume simulations, and NMAX will be the maximum number of independent replications which can be simulated by using the remainder of TAPE10. That is, if NMAX were, for example, 359 when the first 100 trajectories were run, then this time NMAX will be 259. The user may wish to convert back to the original count after INITBLK is called the first time. This can be accomplished by setting NMAX = NMAX + NBRO, and numbering the first simulation of the present run NBR = NBRO + 1.

A general programing sequence which would work whether one is resuming simulations or starting a new set would be the following:

```
      .
      .
      .
      READ 400, NBRO,XLATI,XLONGI,XLOMIN,XLOMAX
  400 FORMAT(I5,4F10.3)
      REWIND 10
      READ(10) SEASON
      XLOMIN = XLOMIN - 30.*NBRO
      CALL INITBLK(1,NMAX,XLATI,XLONGI,XLOMIN,XLOMAX)
      NBR = NBRO + 1
      NMAX = NMAX + NBRO
   10 WRITE 401, NBR,SEASON
  401 FORMAT(20H1 SIMULATION NUMBER,I3,9H SEASON =, A10)
      .
      .
      .
      (complete trajectory simulation)
      .
      .
      .
      NBR = NBR + 1
      IF(NBR - NMAX) 20,20,30
   20 CALL INITBLK(NBR,NMAX,XLATI,XLONGI,XLOMIN,XLOMAX)
      GO TO 10
   30 .
      .
      .
      (wind up)
      .
      .
      .
      STOP
      END
```

Note that when NBRO = 0, this procedure is equivalent to starting a new set of simulations.

DENSITY GRADIENTS

Density gradients along a vehicle's flight path can be as important as the actual density. For example, an extreme positive density gradient during entry can create higher surface heating loads than either a uniformly high or low density atmosphere. A set of "design" gradients for horizontal and vertical changes in density has been published in reference 5 for use in studying the effects on a vehicle's performance of extreme gradients in atmospheric density along a flight path. The horizontal and vertical gradients in density found on the REACT tapes are compared with these design gradients and with measured gradients in the atmospheric data base described in appendix B.

The ERA (Empirical Random Atmosphere) model used to generate the REACT atmospheres was designed to provide atmospheric properties with realistic vertical gradients. That is, one of the objectives in developing the model was to imitate vertical density gradients in the data base. Thus, vertical density gradients in the REACT atmospheres are inherently similar to those found in the data. Figures 7(a) and 7(b) compare the mean and standard deviation of vertical density gradients in the data with corresponding properties of modeled gradients. Table I shows the percentage of vertical gradients in both the data and the model which exceed the "design" gradients of reference 5.

In the case of horizontal density gradients, the data base was of no use since it consists of isolated one-dimensional soundings. In creating the REACT tapes, control of horizontal gradients was exercised by the choice of longitude-latitude grid size and by correlating density profiles which are relatively close together. A telephone contact with one of the contributors[1] to reference 5 revealed that horizontal design gradients were based on the conclusion in reference 6 that hot and cold atmospheric regimes can occur within 1111.2 km (600 n. mi. or 10° of latitude) of one another. For the construction of the three-dimensional REACT atmospheres, this statement was interpreted as meaning that the minimum distance between two statisticlly independent profiles is 1111.2 km.

A spacing of 10° was chosen for the longitude-latitude grid. Accordingly, constant-latitude lines are 1111.2 km apart and, therefore, profiles on different latitude lines could be treated as independent. The longitude lines, on the other hand, are 1111.2 km apart at the equator but converge to a single point at each pole. Thus, profiles at some adjacent grid points were closer than 1111.2 km and these had to be correlated. This was accomplished by first generating independent profiles spaced 1111.2 km apart along a constant latitude line, and interpolating linearly between these to obtain profiles at the grid points. This procedure for correlating adjacent profiles is consistent with the overall scheme of interpolating between horizontal grid points to get a density or temperature at any arbitrary location.

A comparison was made between the horizontal design density gradients of reference 5 and the horizontal density gradients in the REACT atmospheres. Table II lists the percentage of horizontal density gradients on the REACT tapes which exceed the design gradients. A significant disparity exists because there is a greater difference between hot and cold atmospheres in the REACT model, even within the same latitude-season category, than in the model used to construct the design gradients in reference 5. Since the REACT model is based on an extensive amount of data, it is believed to be more accurate in its representation of these differences.

CONCLUDING REMARKS

The Random Earth Atmosphere Computer Tapes (REACT) are a set of four magnetic tapes representing four different seasons which can be used to simulate spacecraft and aircraft trajectories through nonstandard atmospheres characteristic of their respective latitudes and seasons. The atmospheric temperatures and densities on any one tape (season) at the same latitude and altitude form a

[1] S. Clark Brown, NASA Marshall Space Flight Center, June 7, 1974.

random sample whose statistical properties match those of observed temperatures and densities in a data base of over 6000 sounding-rocket and high-altitude measurements.

A method is described whereby, with the addition of three subroutines involving approximately 4000 octal storage locations, the tapes can be linked to any existing trajectory simulation program. Depending on the longitudinal range of a particular trajectory, between 349 and 361 independent replications of that trajectory can be made with each tape. Thus, approximately 1400 replicates can be generated by using all four tapes.

As a trajectory is simulated, a series of "blocks" is read from one of the tapes. Each "block" contains arrays of atmospheric densities and temperatures which span a volume 99 km deep, 30° wide in longitude, and 30° long in latitude. Values in the arrays are located at grid points every 3 km in altitude, and every 10° in longitude and latitude. To obtain atmospheric properties at any arbitrary point on a trajectory, the subroutines interpolate by using the arrays as three-way tables. Interpolation is linear in all directions except in vertical planes of the density array, where linear interpolation is applied to the logarithm of density.

Vertical density gradients are consistent with those found in the data base. Horizontal density gradients are controlled by assuming a minimum distance between uncorrelated profiles of 1111.2 km. In the case of both horizontal and vertical density gradients, a significant percentage of the REACT atmospheres exceed the "design" gradients of reference 5. It is believed, however, that the REACT density gradients are more representative of realistic gradients.

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May 27, 1977

APPENDIX A

SUBROUTINE LISTINGS

The following listings are suggested versions of the three subroutines INITBLK, READBLK, and ATMOS:

SUBROUTINE INITBLK(NBR,NMAX,XLATI,XLONGI,XLOMIN,XLOMAX):

```
      COMMON/LINK/ DL,NO,XLATO,XLONGO,RHO(34,4,4),TAU(34,4,4)
      IF(NBR-1) 1,1,2
    1 DL = .001-XLOMIN
      XLONG=XLONGI+DL
      NMAX=(10800.-XLOMAX-DL)/30.+1.
      NO=0
      CALL READBLK(XLATI,XLONG)
      RETURN
    2 DL=DL+30.
      XLONG=XLONGI+DL
      CALL READBLK(XLATI,XLONG)
      RETURN
      END
```

SUBROUTINE READBLK(XLAT,XLONG):

```
      COMMON/LINK/ DL,NO,XLATO,XLONGO,RHO(34,4,4),TAU(34,4,4)
      NCOLS=XLONG/30.
      NM1=6.*NCOLS+(XLAT+90.)/30.
      N=NM1+1
      IF(NM1-NO) 1,5,3
    1 DO 2 I=N,NO
    2 BACKSPACE 10
      READ(10) NO,XLATO,XLONGO,RHO,TAU
      RETURN
    3 NEXT=NO+1
      DO 4 I=NEXT,NM1
    4 READ(10)
    5 READ(10) NO,XLATO,XLONGO,RHO,TAU
      RETURN
      END
```

SUBROUTINE ATMOS(Z,XLAT,XLONG,D,T,P,S):

```
      COMMON/LINK/ DL,NO,XLATO,XLONGO,RHO(34,4,4),TAU(34,4,4)
      DIMENSION ANS(4)
      ZKM=Z/1000.
      IF(Z) 1,2,2
    1 PRINT 401,Z,XLAT,XLONG
  401 FORMAT(/6(2H *)* ALTITUDE=*F10.1* OUTSIDE RANGE*/6(2H *)*AT LATI
    1 TUDE *F6.1* AND LONGITUDE *F7.1/)
C     USE ALTERNATE (1962 STANDARD) ATMOSPHERE MODEL
```

APPENDIX A

```
      ZFT=Z/.3048
      CALL AT62(ZFT,ANS)
      D=515.379*ANS(1)
      P=47.880258*ANS(2)
      T=ANS(3)
      S=.3048*ANS(4)
      RETURN
    2 IF(ZKM-99.) 4,3,1
    3 ZKM=98.9
    4 DXLAT=XLAT-XLATO
      IF(DXLAT) 11,5,5
    5 IF(DXLAT-30.) 7,6,11
    6 DXLAT=29.9
    7 DXLONG=XLONG+DL-XLONGO
      IF(DXLONG) 11,8,8
    8 IF(DXLONG-30.) 10,9,11
    9 DXLONG=29.9
   10 I=ZKM/3.+1.
      IP1=I+1
      J=DXLAT/10.+1.
      JP1=J+1
      K=DXLONG/10.+1.
      KP1=K+1
      R1=(3000.*I-Z)/3000.
      R2=1.-R1
      RHO1=EXP(R1*ALOG(RHO(I,J,K))+R2*ALOG(RHO(IP1,J,K)))
      RHO2=EXP(R1*ALOG(RHO(I,JP1,K))+R2*ALOG(RHO(IP1,JP1,K)))
      RHO3=EXP(R1*ALOG(RHO(I,J,KP1))+R2*ALOG(RHO(IP1,J,KP1)))
      RHO4=EXP(R1*ALOG(RHO(I,JP1,KP1))+R2*ALOG(RHO(IP1,JP1,KP1)))
      TAU1=R1*TAU(I,J,K)+R2*TAU(IP1,J,K)
      TAU2=R1*TAU(I,JP1,K)+R2*TAU(IP1,JP1,K)
      TAU3=R1*TAU(I,J,KP1)+R2*TAU(IP1,J,KP1)
      TAU4=R1*TAU(I,JP1,KP1)+R2*TAU(IP1,JP1,KP1)
      R1=(XLATO+10.*J-XLAT)/10.
      R2=1.-R1
      RHO12=R1*RHO1+R2*RHO2
      RHO34=R1*RHO3+R2*RHO4
      TAU12=R1*TAU1+R2*TAU2
      TAU34=R1*TAU3+R2*TAU4
      R1=(XLONGO+10.*K-XLONG-DL)/10.
      R2=1.-R1
      D=R1*RHO12+R2*RHO34
      T=R1*TAU12+R2*TAU34
      P=T*D/.00348362
      S=.069836*SQRT(T)
      RETURN
   11 RLONG=XLONG+DL
      CALL READBLK(XLAT,RLONG)
      GO TO 4
      END
```

APPENDIX B

EMPIRICAL RANDOM ATMOSPHERE MODEL

To construct the model used in generating the REACT atmospheres, a set of over 6000 rocket and high-altitude soundings of the atmosphere was modeled empirically. The soundings were divided into categories according to the latitude and season of the sounding. The five latitude categories

Band, deg	Latitudes covered
15	0° to 22.5° N or S
30	22.5° to 37.5° N or S
45	37.5° to 52.5° N or S
60	52.5° to 67.5° N or S
75	67.5° to 90.0° N or S

correspond to those used in the 1966 Supplemental Atmospheres (ref. 2). Soundings which fell into one of the four nonequatorial latitude categories were also classified by their season. The four season categories are:

Season	Northern hemisphere	Southern hemisphere
Spring	March to May	September to November
Summer	June to August	December to February
Autumn	September to November	March to May
Winter	December to February	June to August

Soundings in the equatorial (15°) band were not classified as to season since seasonal differences at these latitudes are negligible. Table III lists the resultant 17 latitude-season categories and the number of soundings which belongs to each category.

Each sounding was converted, by interpolation, to a temperature and/or density profile with observations every 3 km in altitude over the range of the sounding. Since the soundings did not always cover the same altitude range and, in fact, some did not even overlap, the number of observations at each altitude was always less than the number of profiles shown in table III. Table IV shows the actual number of temperature observations at each altitude, and table V shows the number of density observations at each altitude.

A drastic reduction in available data above 60 km is readily apparent. In categories where temperature data were completely missing, temperature means were estimated by using gradients from the 1966 Supplemental Atmospheres (ref. 2) and variances at the highest altitude where data were available were extended to 99 km. Missing pressure and density means were then filled in by using the hydrostatic equation and the equation of state, and their variances were also extended from lower altitudes. The modeling procedure is described in detail in reference 4. Only a brief description of the model statistics relative to the data is given here.

APPENDIX B

For the kth season ($k = 1, 2, 3,$ and 4) and any latitude ϕ, the model uses a random-number-generating scheme to produce a temperature-altitude profile. At any fixed altitude z the temperature is assumed to be a Gaussian random variable with a mean $\bar{T}(z,k,\phi)$ and a standard deviation $s(z,k,\phi)$; these values are estimated from the data. Thus, model-generated temperature profiles were provided, within the accuracy of the random number generator, the same means and standard deviations as the temperature data at corresponding altitudes, seasons, and latitudes. Furthermore, within the same profile, temperatures at different altitudes were correlated by using coefficients of correlation estimated from the data. This latter covariance property insures that modeled vertical temperature gradients are consistent with those in the data.

If $|\phi| \leq 15^{\circ}$, parameters from the 15° band data are used, and likewise, if $|\phi| \geq 75^{\circ}$, parameters from one of the 75° bands are used depending on the season. For $15^{\circ} < |\phi| < 75^{\circ}$, $\bar{T}(z,k,\phi)$ and $s(z,k,\phi)$ are obtained by linear interpolation over ϕ by using the tables for $\bar{T}$ and s in the "category" latitudes 15°, 30°, 45°, 60°, and 75°.

In order to calculate pressure and density profiles consistent with a particular random temperature profile, hydrostatic equilibrium is assumed to exist. Thus, pressures vary according to the hydrostatic equation

$$dP = -g\rho \, dz \tag{B1}$$

where g and ρ are gravitational acceleration and density, respectively, at altitude z. By relating temperature, pressure, and density by the equation of state

$$\rho = \frac{WP}{RT} \tag{B2}$$

one can calculate complete pressure and density profiles from a given temperature profile and a base pressure P_o. Base pressure P_o (at sea level) is selected by using a Gaussian random number generator and is correlated to sea-level temperature. Although it is known that hydrostatic equilibrium is not always maintained, means and standard deviations of model-generated pressures and densities (based on hydrostatic equilibrium) agree reasonably well with the data. (See ref. 4.)

Figure 8, which compares the mean and standard deviation of temperatures in the model and the data, illustrates the agreement between model and data. The results shown here for the 15° latitude-season category are typical of all the categories. Model statistics in figure 8 and in subsequent figures are based on a sample of 1000 model-generated atmospheres. Figure 9 compares model and data means and standard deviations of P/P_{62} where atmospheric pressure P is nondimensionalized by the 1962 Standard Atmosphere pressure P_{62}. Figure 10 compares means and standard deviations of nondimensionalized densities ρ/ρ_{62}.

REFERENCES

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3. U.S. Standard Atmosphere, 1976. NOAA, NASA, and U.S. Air Force, Oct. 1976.

4. Campbell, Janet W.: A Model for Simulating Random Atmospheres as a Function of Latitude, Season, and Time. NASA TN D-8470, 1977.

5. Daniels, Glenn E., ed.: Terrestrial Environment (Climatic) Criteria Guidelines for Use in Aerospace Vehicle Development, 1973 Revision. NASA TM X-64757, 1973.

6. Cole, Allen E.; and Kantor, Arthur J.: Horizontal and Vertical Distributions of Atmospheric Density, Up to 90 km. AFCRL-64-483, U.S. Air Force, June 1964. (Available from DDC as AD 605196.)

TABLE I.- PERCENTAGE OF VERTICAL DENSITY GRADIENTS IN DATA AND IN MODEL WHICH EXCEED DESIGN GRADIENTS (REF. 5)

[Design values for vertical density gradients are expressed as maximum and minimum percentage increases in density between altitude z and altitude z - 2 km (ref. 5). Exceedance rates are the percentage of times in the data and in the model that the design value is exceeded.]

(a) 15° Latitude (Design values interpolated from the July design values)

Altitude, km	Minimum increase, percent, in 2-km layer			Maximum increase, percent, in 2-km layer		
	Design value	Exceedance rate		Design value	Exceedance rate	
		Data	Model		Data	Model
30	28	0.0	0.0	39	2.8	1.5*
40	27	.0	.0	35	14.9	17.5
50	24	.2	.3	32	2.0	.6**
60	23	1.2	.3*	31	3.1	1.9
70	30	9.1	19.2*	43	20.0	17.9
80	34	25.0	27.9	47	15.0	13.9
90	36	25.5	18.2	49	25.5	21.3

*Exceedance rate in the model which is significantly different from that found in the data at the 0.05 level.

**Exceedance rate in the model which is significantly different from that found in the data at the 0.01 level.

TABLE I.- Continued

(b) 30° Latitude

Spring

Altitude, km	Minimum increase, percent, in 2-km layer			Maximum increase, percent, in 2-km layer		
	Design value	Exceedance rate		Design value	Exceedance rate	
		Data	Model		Data	Model
30	30	0.2	0.0	39	8.3	6.3
40	29	.3	.1	37	1.3	1.2
50	23	.3	.0	31	4.3	.9**
60	25	5.1	38.0**	33	.4	.0
70	33	66.7	76.0	41	.0	6.6
80	36	23.1	36.5	47	7.7	6.1
90	37	30.0	37.9	50	10.0	21.2

**Exceedance rate in the model which is significantly different from that found in the data at the 0.01 level.

Summer

Altitude, km	Minimum increase, percent, in 2-km layer			Maximum increase, percent, in 2-km layer		
	Design value	Exceedance rate		Design value	Exceedance rate	
		Data	Model		Data	Model
30	32	0.3	0.0	40	0.0	0.0
40	28	.0	.0	35	11.3	10.5
50	25	1.1	1.6	32	2.2	.6
60	24	4.0	3.1	34	2.5	.6
70	30	37.5	71.2*	45	.0	6.2
80	30	10.0	10.7	47	.0	5.7
90	40	.0	.2	50	33.3	43.2

*Exceedance rate in the model which is significantly different from that found in the data at the 0.05 level.

TABLE I.- Continued

(b) 30° Latitude - Concluded

Autumn

Altitude, km	Minimum increase, percent, in 2-km layer			Maximum increase, percent, in 2-km layer		
	Design value	Exceedance rate		Design value	Exceedance rate	
		Data	Model		Data	Model
30	33	1.0	0.0	42	0.0	0.0
40	27	.0	.0	39	3.3	1.8
50	22	.3	.0	32	2.8	.7*
60	26	10.0	11.5	31	4.8	2.0*
70	32	50.0	67.0	36	30.0	19.3
80	35	25.0	17.2	39	25.0	33.4
90	40	38.1	39.4	50	4.8	3.6

*Exceedance rate in the model which is significantly different from that found in the data at the 0.05 level.

Winter

Altitude, km	Minimum increase, percent, in 2-km layer			Maximum increase, percent, in 2-km layer		
	Design value	Exceedance rate		Design value	Exceedance rate	
		Data	Model		Data	Model
30	31	0.2	0.0	43	2.0	0.1**
40	28	1.2	.6	40	1.5	1.1
50	23	.3	.5	34	.0	.0
60	23	.0	.3	35	1.2	.0
70	29	10.0	29.3**	41	15.0	11.2
80	30	4.8	8.9	47	.0	.1
90	26	.0	.0	60	.0	.0

**Exceedance rate in the model which is significantly different from that found in the data at the 0.01 level.

TABLE I.- Continued

(c) 45° Latitude

Spring

Altitude, km	Minimum increase, percent, in 2-km layer			Maximum increase, percent, in 2-km layer		
	Design value	Exceedance rate		Design value	Exceedance rate	
		Data	Model		Data	Model
30	32	0.0	0.0	38	35.7	35.3
40	31	12.2	13.0	34	26.7	27.1
50	25	.0	1.3	29	28.5	30.6
60	25	9.1	2.7	30	11.7	4.7
70	27	10.0	8.5	41	.0	.4
80	35	55.6	38.5	53	22.2	11.8
90	38	.0	29.6	58	50.0	7.7

Summer

Altitude, km	Minimum increase, percent, in 2-km layer			Maximum increase, percent, in 2-km layer		
	Design value	Exceedance rate		Design value	Exceedance rate	
		Data	Model		Data	Model
30	34	0.0	0.0	38	6.1	4.6
40	30	.0	.9	35	11.5	14.7
50	25	2.3	6.6*	31	2.3	5.0
60	25	5.6	3.0	30	4.2	4.0
70	26	.0	14.9	45	7.1	16.0
80	30	30.8	27.3	53	.0	.5
90	38	.0	33.9*	56	37.5	24.5

*Exceedance rate in the model which is significantly different from that found in the data at the 0.05 level.

TABLE I.- Continued

(c) 45° Latitude - Concluded

Autumn

Altitude, km	Minimum increase, percent, in 2-km layer			Maximum increase, percent, in 2-km layer		
	Design value	Exceedance rate		Design value	Exceedance rate	
		Data	Model		Data	Model
30	35	2.9	3.7	50	0.0	0.0
40	26	.0	.0	40	1.9	.1*
50	24	.0	.0	34	.0	.0
60	24	2.0	.1*	34	.0	.0
70	28	42.9	27.5	41	.0	.4
80	35	50.0	65.2	44	.0	1.1
90	40	50.0	66.0	56	.0	.1

*Exceedance rate in the model which is significantly different from that found in the data at the 0.05 level.

Winter

Altitude, km	Minimum increase, percent, in 2-km layer			Maximum increase, percent, in 2-km layer		
	Design value	Exceedance rate		Design value	Exceedance rate	
		Data	Model		Data	Model
30	35	3.3	2.9	47	0.0	0.0
40	27	.0	.3	45	.0	.0
50	23	2.2	.7	42	.0	.0
60	22	3.8	.8	38	.0	.2
70	19	.0	.8	48	13.3	2.8
80	19	.0	2.2	55	.0	.9
90	23	.0	4.5	62	.0	2.3

TABLE I.- Continued

(d) 60° Latitude

Spring

Altitude, km	Minimum increase, percent, in 2-km layer			Maximum increase, percent, in 2-km layer		
	Design value	Exceedance rate		Design value	Exceedance rate	
		Data	Model		Data	Model
30	32	0.0	0.0	37	50.5	50.3
40	31	1.2	3.6*	34	50.9	47.4
50	26	2.0	7.6**	30	16.4	10.8
60	25	5.3	4.3	30	8.5	8.3
70	26	.0	11.2	40	.0	.0
80	36	---	100.0	51	----	.0
90		---	85.8	61	----	.0

*Exceedance rate in the model which is significantly different from that found in the data at the 0.05 level.

**Exceedance rate in the model which is significantly different from that found in the data at the 0.01 level.

Summer

Altitude, km	Minimum increase, percent, in 2-km layer			Maximum increase, percent, in 2-km layer		
	Design value	Exceedance rate		Design value	Exceedance rate	
		Data	Model		Data	Model
30	34	1.9	8.7**	37	1.9	4.0
40	30	.0	.1	35	2.4	.8
50	25	2.5	3.9	31	.0	.2
60	25	.0	1.3	28	7.1	3.7
70	26	---	55.2	39	---	.0
80	34	---	70.4	53	---	.0
90	39	---	8.0	58	---	.0

**Exceedance rate in the model which is significantly different from that found in the data at the 0.01 level.

TABLE I.- Continued

(d) 60° Latitude - Concluded

Autumn

Altitude, km	Minimum increase, percent, in 2-km layer			Maximum increase, percent, in 2-km layer		
	Design value	Exceedance rate		Design value	Exceedance rate	
		Data	Model		Data	Model
30	33	0.0	0.5	51	0.0	0.0
40	28	.0	.0	41	6.7	5.8
50	26	.0	2.0	34	11.5	12.0
60	22	.0	.0	33	3.0	.9
70	27	.0	61.3	40	.0	.1
80	33	---	63.6	48	----	.1
90	40	---	73.5	58	----	.0

Winter

Altitude, km	Minimum increase, percent, in 2-km layer			Maximum increase, percent, in 2-km layer		
	Design value	Exceedance rate		Design value	Exceedance rate	
		Data	Model		Data	Model
30	33	1.4	5.4**	48	0.7	0.0
40	26	.0	.0	44	.5	1.1
50	23	.0	.1	43	.5	.5
60	24	.0	1.7	38	.0	.2
70	20	.0	.0	52	.0	.0
80	15	---	.0	59	---	.0
90	19	---	.0	63	---	.0

**Exceedance rate in the model which is significantly different from that found in the data at the 0.01 level.

TABLE I.- Continued

(e) 75^{o} Latitude

Spring

Altitude, km	Minimum increase, percent, in 2-km layer			Maximum increase, percent, in 2-km layer		
	Design value	Exceedance rate		Design value	Exceedance rate	
		Data	Model		Data	Model
30	29	1.1	0.0	36	42.5	41.6
40	28	1.4	1.7	34	25.7	26.2
50	26	14.3	18.2	33	.0	2.0
60	25	32.4	41.5	30	18.9	9.9
70	28	4.3	22.0**	37	34.8	21.0
80	37	----	51.1	45	----	7.9
90	38	----	35.4	61	----	5.2

**Exceedance rate in the model which is significantly different from that found in the data at the 0.01 level.

Summer

Altitude, km	Minimum increase, percent, in 2-km layer			Maximum increase, percent, in 2-km layer		
	Design value	Exceedance rate		Design value	Exceedance rate	
		Data	Model		Data	Model
30	34	23.6	19.0	37	3.8	1.1
40	30	3.3	1.0	35	3.3	1.2
50	25	24.3	16.3	33	.0	.0
60	24	5.1	19.1**	27	40.7	40.0
70	26	5.4	29.0**	29	83.8	42.7**
80	39	----	27.9	49	----	26.4
90	41	----	35.9	57	----	26.6

**Exceedance rate in the model which is significantly different from that found in the data at the 0.01 level.

TABLE I.- Concluded

(e) 75° Latitude - Concluded

Autumn

Altitude, km	Minimum increase, percent, in 2-km layer			Maximum increase, percent, in 2-km layer		
	Design value	Exceedance rate		Design value	Exceedance rate	
		Data	Model		Data	Model
30	30	0.0	0.0	48	1.3	0.0
40	30	2.9	1.1	41	19.1	18.3
50	26	3.9	2.6	33	47.1	47.4
60	19	.0	.0	30	50.0	26.3**
70	27	9.5	17.2	36	28.6	24.0
80	29	25.0	27.5	51	12.5	15.4
90	40	----	47.7	57	----	11.0

**Exceedance rate in the model which is significantly different from that found in the data at the 0.01 level.

Winter

Altitude, km	Minimum increase, percent, in 2-km layer			Maximum increase, percent, in 2-km layer		
	Design value	Exceedance rate		Design value	Exceedance rate	
		Data	Model		Data	Model
30	29	0.0	0.0	36	2.4	5.1
40	25	5.5	.4	34	13.7	24.9**
50	22	.0	1.0	33	16.3	9.5
60	27	22.9	32.5	30	.0	.8
70	26	3.8	6.2	37	.0	.7
80	15	5.9	.1	61	5.9	1.1
90	14	----	.1	65	----	3.2

**Exceedance rate in the model which is significantly different from that found in the data at the 0.01 level.

TABLE II.- PERCENTAGE OF REACT HORIZONTAL DENSITY GRADIENTS WHICH EXCEED DESIGN GRADIENTS (REF. 5)

[Horizontal gradients measured along lines of constant latitude. Design values for horizontal density gradients are expressed as maximum change in percent departure from 1962 Standard Atmosphere density per 110 km (ref. 5).]

(a) Spring tape

Altitude, km	REACT density gradients, percent, at latitude -							
	10° N		30° N		50° N		70° N	
	Design value	Exceedance rate	Design value	Exceedance rate	Design value	Exceedance rate	Design value	Exceedance rate
30	0.30	19	0.30	23	0.60	12	1.10	18
33	.30	24	.36	23	.60	17	1.04	24
36	.30	27	.42	20	.60	24	.98	32
39	.30	33	.48	15	.60	30	.92	43
42	.30	39	.52	15	.66	30	.84	52
45	.30	41	.55	16	.75	29	.75	60
48	.30	41	.58	19	.84	31	.66	69
51	.31	46	.58	22	.90	34	.58	71
54	.34	44	.52	29	.90	36	.52	77
57	.37	42	.46	43	.90	39	.46	80
60	.40	41	.40	54	.90	39	.40	85
63	.46	39	.52	43	1.02	35	.46	82
66	.52	48	.64	36	1.14	37	.52	81
69	.58	55	.76	39	1.26	38	.58	79
72	.60	57	.86	45	1.32	37	.62	81
75	.60	63	.95	48	1.35	43	.65	81
78	.60	64	1.04	51	1.38	48	.68	81
81	.59	68	1.07	54	1.37	55	.66	83
84	.56	74	.98	60	1.28	61	.54	90
87	.53	76	.89	70	1.19	64	.42	92
90	.50	79	.80	78	1.10	69	.30	94

TABLE II.- Continued

(b) Summer tape

Altitude, km	REACT density gradients, percent, at latitude -							
	10° N		30° N		50° N		70° N	
	Design value	Exceedance rate	Design value	Exceedance rate	Design value	Exceedance rate	Design value	Exceedance rate
30	0.40	9	0.40	3	0.40	8	0.40	26
33	.40	12	.40	4	.40	9	.37	35
36	.40	17	.40	9	.40	14	.34	48
39	.40	19	.40	13	.40	19	.31	59
42	.44	22	.44	13	.42	24	.36	59
45	.50	18	.50	13	.45	30	.45	57
48	.56	16	.56	13	.48	32	.54	57
51	.61	16	.61	15	.54	35	.62	53
54	.64	17	.64	18	.66	31	.68	50
57	.67	17	.67	18	.78	27	.74	49
60	.70	17	.70	24	.90	22	.80	45
63	.76	16	.76	21	.99	23	.89	50
66	.82	30	.82	23	1.08	23	.98	58
69	.88	37	.88	28	1.17	30	1.07	62
72	.88	40	.88	60	1.24	33	1.10	69
75	.85	50	.85	49	1.30	36	1.10	69
78	.82	52	.82	48	1.36	38	1.10	71
81	.75	59	.75	62	1.36	46	1.05	75
84	.60	72	.60	73	1.24	61	.90	84
87	.45	80	.45	80	1.12	67	.75	88
90	.30	87	.30	86	1.00	78	.60	93

TABLE II.- Continued

(c) Autumn tape

Altitude, km	REACT density gradients, percent, at latitude -							
	10° N		30° N		50° N		70° N	
	Design value	Exceedance rate	Design value	Exceedance rate	Design value	Exceedance rate	Design value	Exceedance rate
30	0.30	19	0.30	25	0.90	2	1.10	21
33	.30	24	.30	31	.90	5	1.07	28
36	.30	27	.30	40	.90	9	1.04	36
39	.30	33	.30	47	.90	15	1.01	45
42	.34	33	.40	39	.96	19	1.00	48
45	.40	27	.55	31	1.05	19	1.00	51
48	.46	23	.70	24	1.14	22	1.00	55
51	.52	22	.81	21	1.22	23	.99	57
54	.58	21	.84	23	1.28	22	.96	58
57	.64	18	.87	23	1.34	23	.93	60
60	.70	17	.90	25	1.40	23	.90	62
63	.70	20	.84	30	1.46	23	1.05	57
66	.70	36	.78	31	1.52	22	1.20	51
69	.70	47	.72	46	1.58	26	1.35	46
72	.70	50	.70	62	1.64	27	1.42	48
75	.70	57	.70	63	1.70	30	1.45	49
78	.70	59	.70	64	1.76	26	1.48	54
81	.68	63	.68	64	1.78	32	1.45	60
84	.62	71	.62	69	1.72	42	1.30	68
87	.56	75	.56	78	1.66	43	1.15	74
90	.50	78	.50	81	1.60	51	1.00	80

TABLE II.- Concluded

(d) Winter tape

Altitude, km	REACT density gradients, percent, at latitude -							
	10° N		30° N		50° N		70° N	
	Design value	Exceedance rate	Design value	Exceedance rate	Design value	Exceedance rate	Design value	Exceedance rate
30	0.40	9	0.40	11	1.60	0	2.60	0
33	.40	12	.46	11	1.66	0	2.72	0
36	.40	17	.52	17	1.72	1	2.84	2
39	.40	19	.58	13	1.78	1	2.96	4
42	.40	26	.66	10	1.92	1	2.92	7
45	.40	27	.75	10	2.10	1	2.80	9
48	.40	30	.84	9	2.28	1	2.68	14
51	.44	30	.92	9	2.45	1	2.56	17
54	.56	22	.98	10	2.60	1	2.44	16
57	.68	16	1.04	10	2.75	1	2.32	18
60	.80	12	1.10	9	2.90	1	2.20	20
63	.83	13	1.25	5	2.90	1	2.23	17
66	.86	27	1.40	5	2.90	1	2.26	16
69	.89	36	1.55	14	2.90	2	2.29	14
72	.94	36	1.64	15	2.86	5	2.28	17
75	1.00	43	1.70	14	2.80	7	2.25	19
78	1.06	39	1.76	23	2.74	8	2.22	25
81	1.07	46	1.75	29	2.61	14	2.15	34
84	.98	57	1.60	36	2.34	27	2.00	44
87	.89	62	1.45	47	2.07	36	1.85	52
90	.80	69	1.30	55	1.80	50	1.70	59

TABLE III.- NUMBER OF PROFILES IN DATA BASE FOR EACH LATITUDE-SEASON CATEGORY

Latitude band	Profiles in season -				Total
	Spring	Summer	Autumn	Winter	
15°	1928				1928
30°	495	468	516	504	1983
45°	184	193	154	147	678
60°	238	176	217	342	973
75°	101	128	91	122	442
					6004

TABLE IV.- NUMBER OF TEMPERATURE OBSERVATIONS AT EACH ALTITUDE IN THE 17 LATITUDE-SEASON CATEGORIES

Altitude, km	Number of temperature observations for season and latitude of -																
	Annual	Spring				Summer				Autumn				Winter			
	15°	30°	45°	60°	75°	30°	45°	60°	75°	30°	45°	60°	75°	30°	45°	60°	75°
0	1747	375	165	234	86	319	172	173	103	319	142	214	69	363	119	338	90
3	1759	457	170	234	88	436	174	173	107	454	141	214	74	475	122	338	94
6	1771	456	170	234	88	433	175	173	107	451	141	214	76	476	122	337	96
9	1781	457	170	234	90	435	173	173	108	452	142	214	77	477	122	337	101
12	1778	457	170	233	90	435	176	173	111	451	142	214	79	477	122	337	104
15	1782	456	170	231	90	436	176	173	110	451	142	211	80	477	122	334	104
18	1781	456	171	233	89	436	171	172	110	451	143	212	81	476	129	327	100
21	1772	452	173	233	90	428	175	173	111	450	142	209	81	474	129	324	100
24	1774	451	173	230	90	429	176	171	107	450	142	207	81	470	129	320	97
27	1768	445	172	227	90	427	174	171	108	451	142	205	78	466	132	315	95
30	1749	436	166	224	98	404	168	168	121	436	142	205	87	452	129	309	108
33	1690	419	158	221	99	395	155	166	118	423	140	200	85	427	118	300	105
36	1616	369	137	214	97	354	147	163	113	380	119	190	82	386	106	290	107
39	1569	353	133	210	87	329	136	152	111	350	114	188	78	364	102	281	102
42	1556	364	133	206	79	325	133	150	102	366	111	186	76	363	102	276	95
45	1560	365	133	203	74	330	133	147	96	371	108	187	69	365	102	273	84
48	1530	368	133	199	69	332	133	144	85	371	103	179	63	362	99	265	73
51	1476	365	126	192	64	324	132	144	79	366	94	177	57	353	95	260	67
54	1369	358	108	182	58	308	120	138	77	351	89	168	52	346	88	250	61
57	1284	321	92	155	50	295	96	120	69	328	76	152	49	326	74	229	53
60	986	286	80	126	44	238	76	108	62	284	53	129	44	273	52	180	45
63	486	183	51	80	40	129	38	81	53	181	21	91	37	154	28	99	39
66	136	90	17	42	33	59	17	46	46	88	12	41	28	58	18	33	36
69	64	47	13	25	28	28	16	13	41	48	8	12	24	25	15	15	33
72	67	20	11	8	23	11	14	0	37	31	7	1	21	24	15	3	28
75	69	14	10	0	22	12	15	0	34	27	7	1	21	24	13	0	26
78	67	14	10	0	19	12	13	0	24	28	6	0	18	23	11	0	21
81	65	14	9	0	14	12	13	0	17	27	6	0	16	23	6	0	17
84	66	13	6	0	0	11	13	0	1	27	6	0	4	20	6	0	2
87	59	13	6	0	0	9	12	0	0	22	5	0	2	13	4	0	1
90	56	11	2	0	0	10	10	0	0	21	5	0	0	11	1	0	0
93	40	1	0	0	0	0	5	0	0	5	3	0	0	2	0	0	0
96	26	1	0	0	0	0	3	0	0	3	3	0	0	1	0	0	0
99	25	0	0	0	0	0	3	0	0	2	3	0	0	2	0	0	0

TABLE V.- NUMBER OF DENSITY OBSERVATIONS AT EACH ALTITUDE

IN THE 17 LATITUDE-SEASON CATEGORIES

Altitude, km	Number of density observations for season and latitude of -																
	Annual	Spring				Summer				Autumn				Winter			
	15°	30°	45°	60°	75°	30°	45°	60°	75°	30°	45°	60°	75°	30°	45°	60°	75°
0	1744	372	163	232	86	304	172	168	102	316	142	212	68	360	119	335	88
3	1748	452	169	233	86	431	173	173	105	449	140	214	71	473	122	338	91
6	1753	451	170	233	87	429	174	173	105	449	141	212	72	475	122	337	90
9	1755	449	167	233	87	429	173	173	103	445	140	213	74	472	122	337	95
12	1734	453	170	233	87	424	170	173	106	445	142	214	75	476	122	333	100
15	1766	453	169	231	87	431	166	173	107	447	141	211	75	475	122	332	102
18	1762	453	168	232	87	432	2	169	107	449	143	209	77	474	129	326	98
21	1748	447	170	232	88	424	173	170	107	445	141	203	78	471	128	320	95
24	1727	447	166	227	86	423	174	166	105	435	142	200	79	466	127	313	89
27	1710	438	168	220	87	417	170	165	107	435	140	198	76	459	128	304	86
30	1680	421	157	216	96	390	166	162	118	415	142	196	84	445	127	289	99
33	1580	400	154	204	96	381	151	158	114	404	138	185	80	418	112	272	93
36	1487	335	135	186	91	325	139	149	109	351	117	165	76	367	101	241	89
39	1426	312	131	171	79	292	133	131	103	309	112	153	71	342	98	230	82
42	1411	322	131	169	71	285	131	127	92	327	109	150	70	338	99	222	73
45	1409	326	132	163	66	289	129	124	86	332	106	148	63	340	98	222	62
48	1377	328	131	158	61	290	130	123	77	331	101	141	56	336	96	215	52
51	1328	327	123	152	56	289	129	120	70	329	92	139	51	329	93	211	49
54	1257	324	106	145	50	272	117	112	68	313	87	129	47	322	86	202	43
57	1141	292	91	121	43	259	93	98	63	294	74	118	44	303	72	185	41
60	870	261	80	94	37	202	75	85	59	253	51	101	40	254	52	144	35
63	423	168	51	60	36	110	38	66	52	160	20	72	34	137	28	83	29
66	121	85	17	36	31	51	17	40	46	80	11	34	26	55	18	30	28
69	60	45	12	22	28	25	16	11	40	46	8	10	23	24	15	15	28
72	60	18	10	8	23	11	14	0	37	31	7	1	21	22	15	3	26
75	66	13	10	0	22	11	15	0	34	27	7	1	21	23	13	0	25
78	62	13	10	0	19	10	13	0	24	26	6	0	18	23	11	0	21
81	60	13	9	0	14	11	13	0	17	25	6	0	16	22	6	0	17
84	61	12	6	0	0	11	13	0	1	26	6	0	4	19	6	0	2
87	54	12	6	0	0	9	10	0	0	22	5	0	1	13	4	0	1
90	51	10	2	0	0	10	9	0	0	21	5	0	0	11	1	0	0
93	39	1	0	0	0	0	5	0	0	5	3	0	0	2	0	0	0
96	26	1	0	0	0	0	3	0	0	3	3	0	0	1	0	0	0
99	24	0	0	0	0	0	3	0	0	2	3	0	0	2	0	0	0

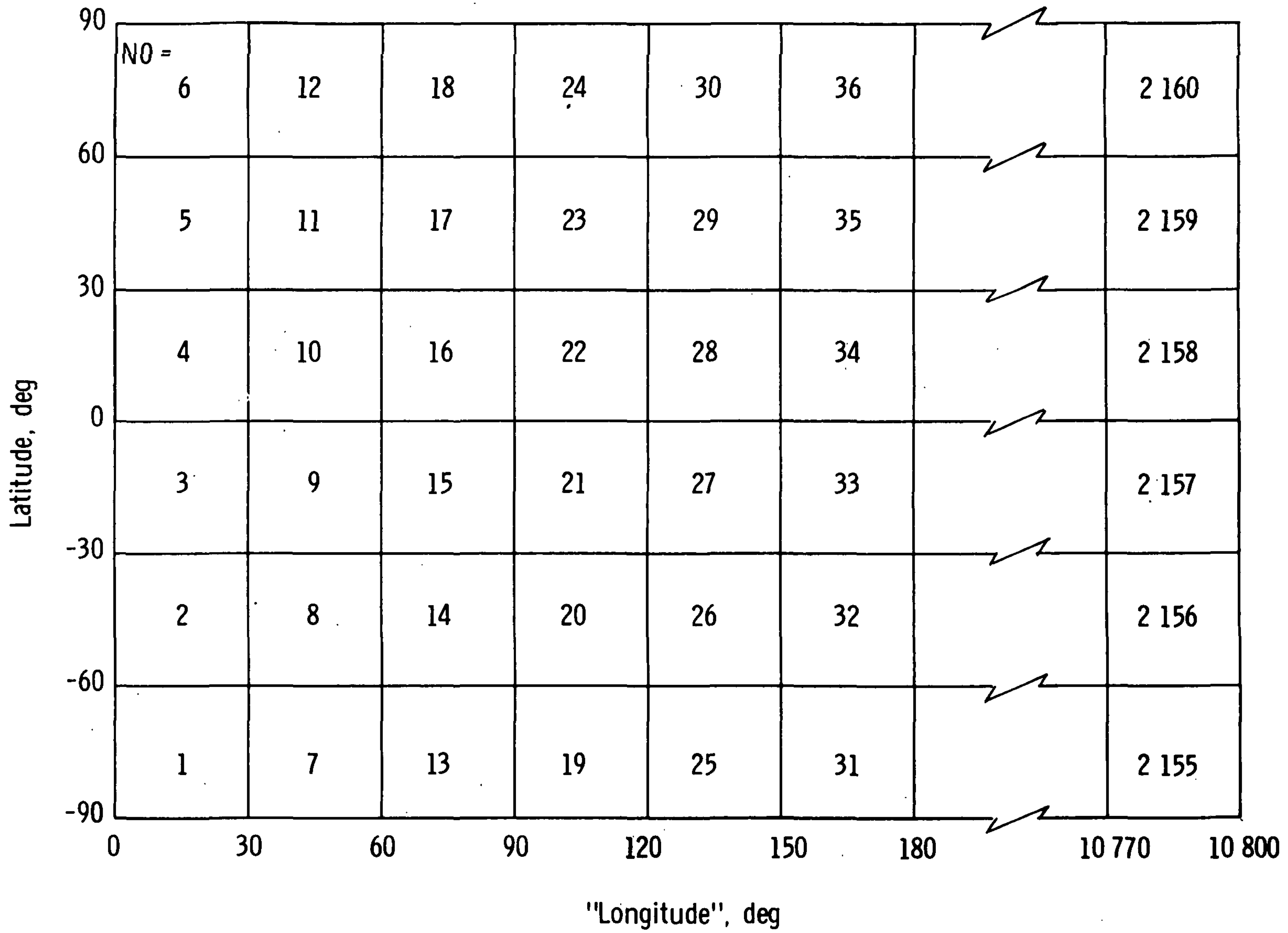


Figure 1.- Arrangement of blocks on TAPE10 as a function of latitude and "longitude."

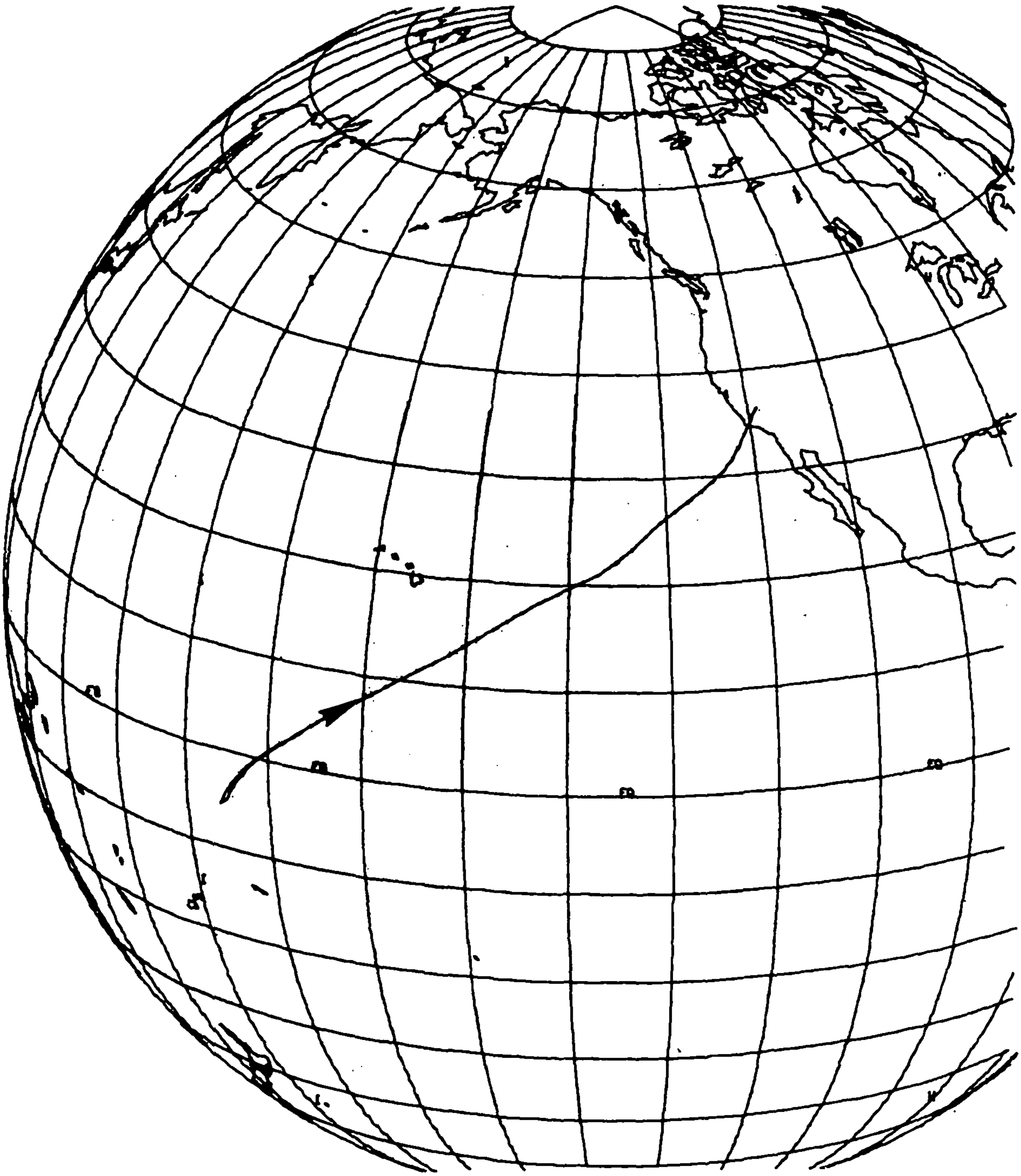


Figure 2.- Ground track of entry trajectory from 28.5° inclined orbit.

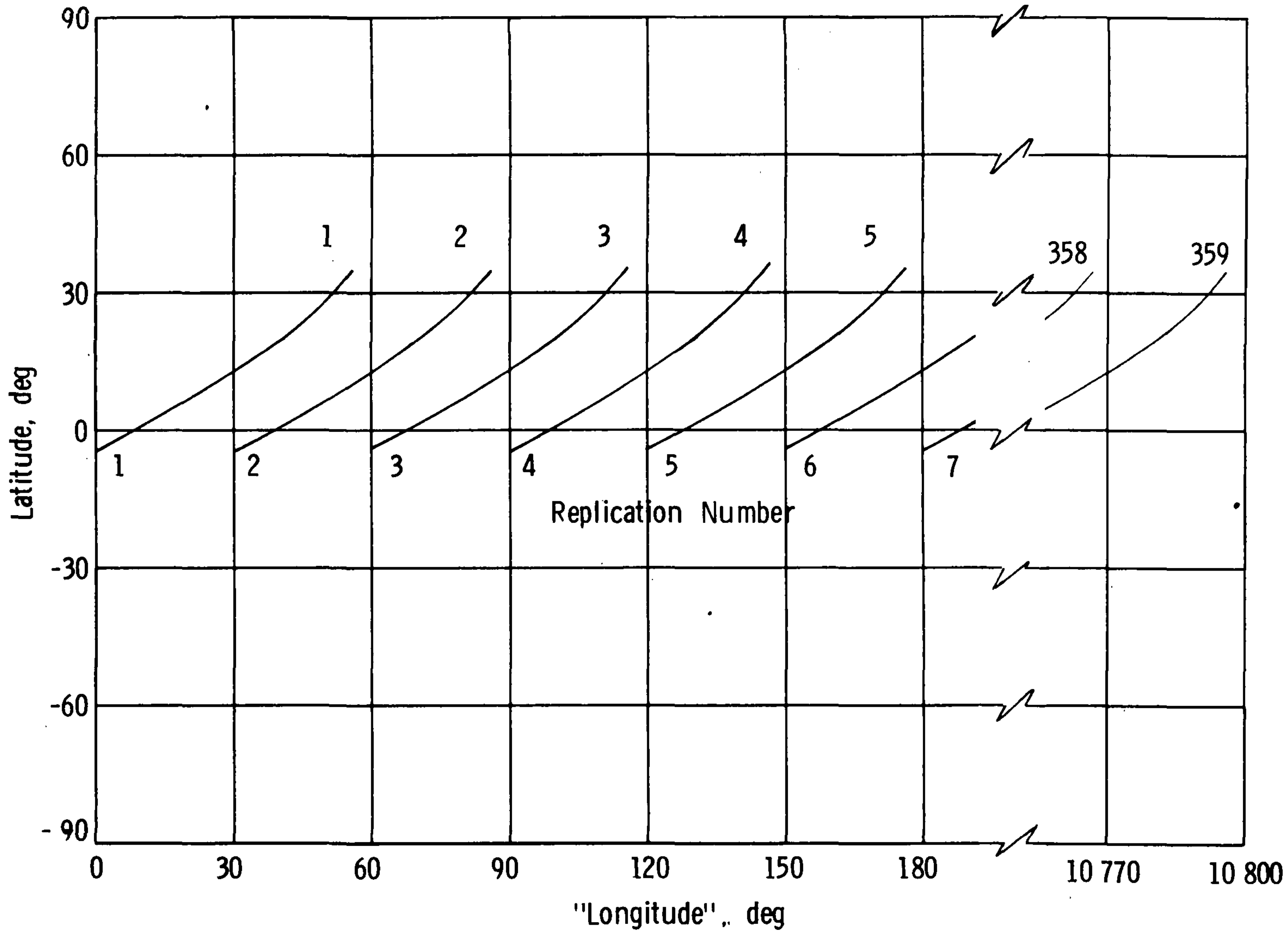


Figure 3.- Independent replicates of trajectory shown in figure 2 relative to blocks on TAPE10.

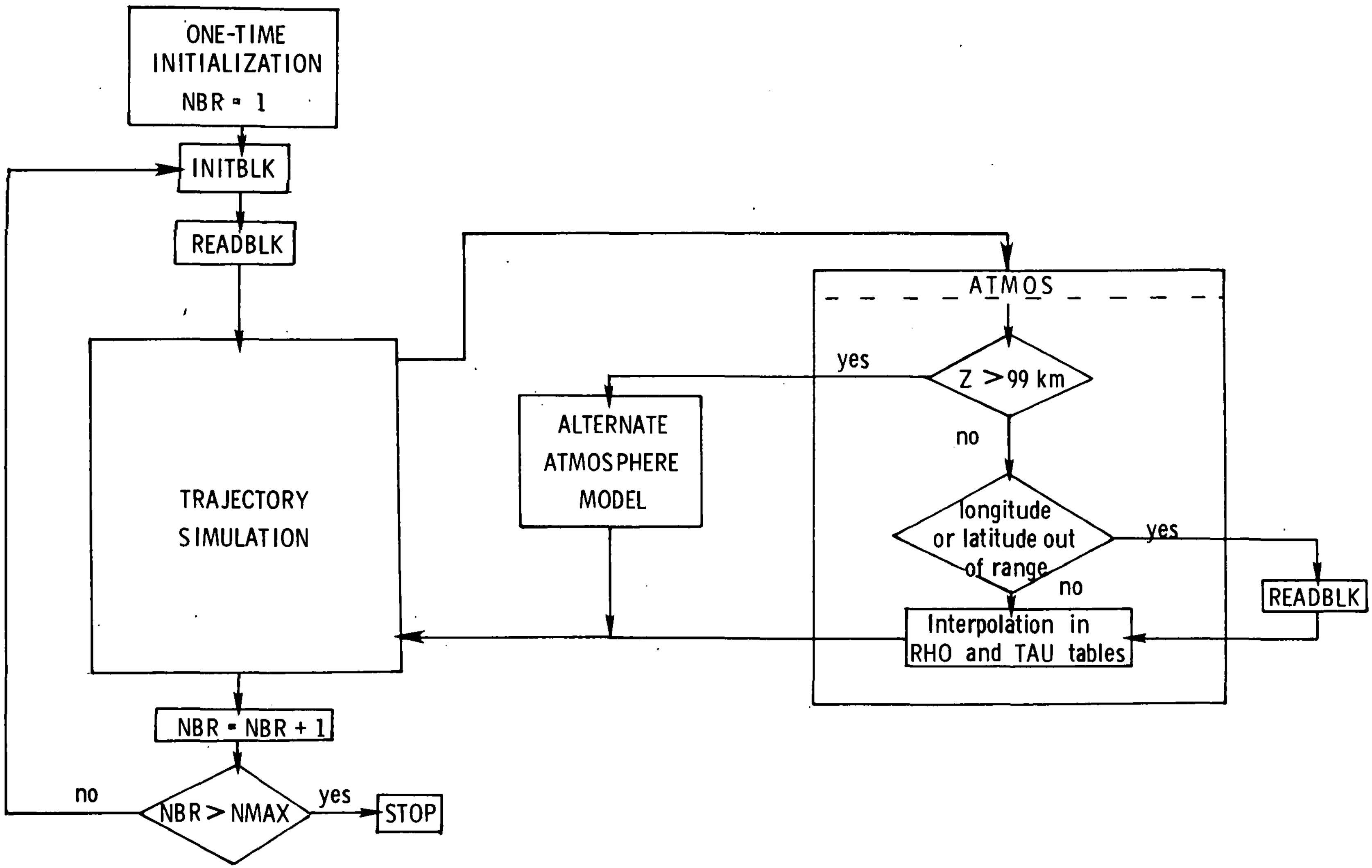


Figure 4.- Flow chart for typical trajectory computer program using subroutines INITBLK, READBLK, and ATMOS.

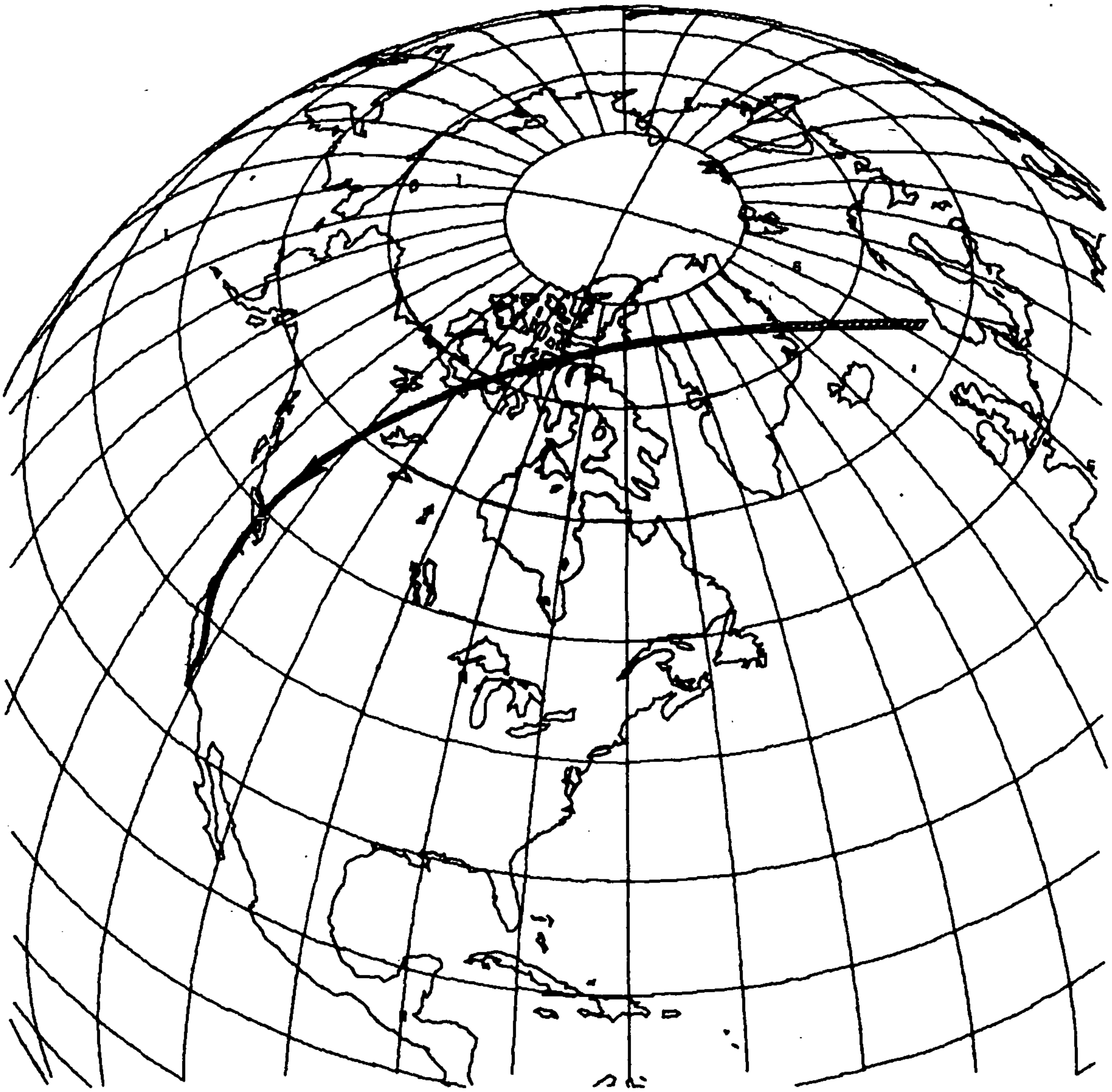


Figure 5.- Ground track of entry trajectory from 104° inclined orbit.

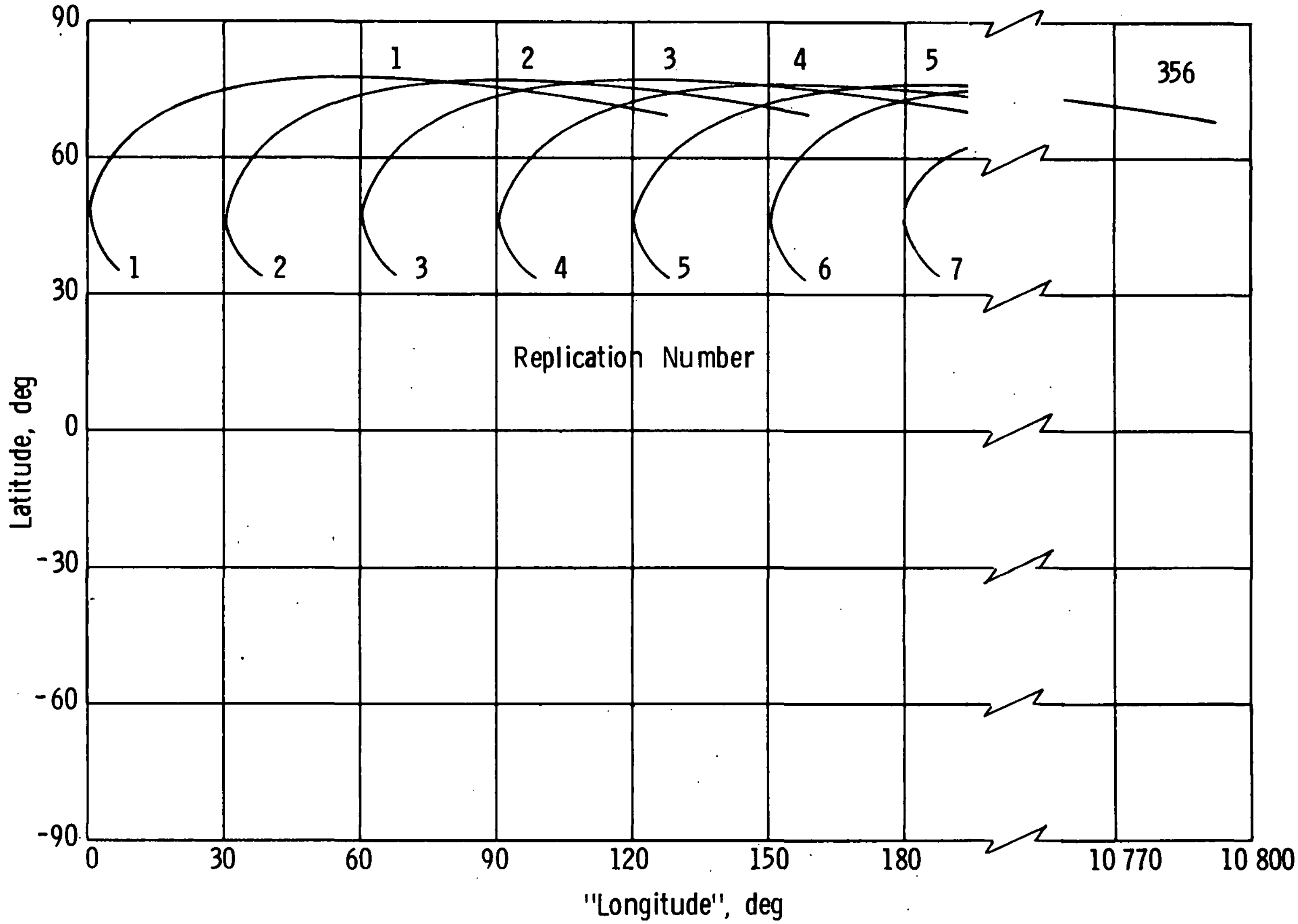
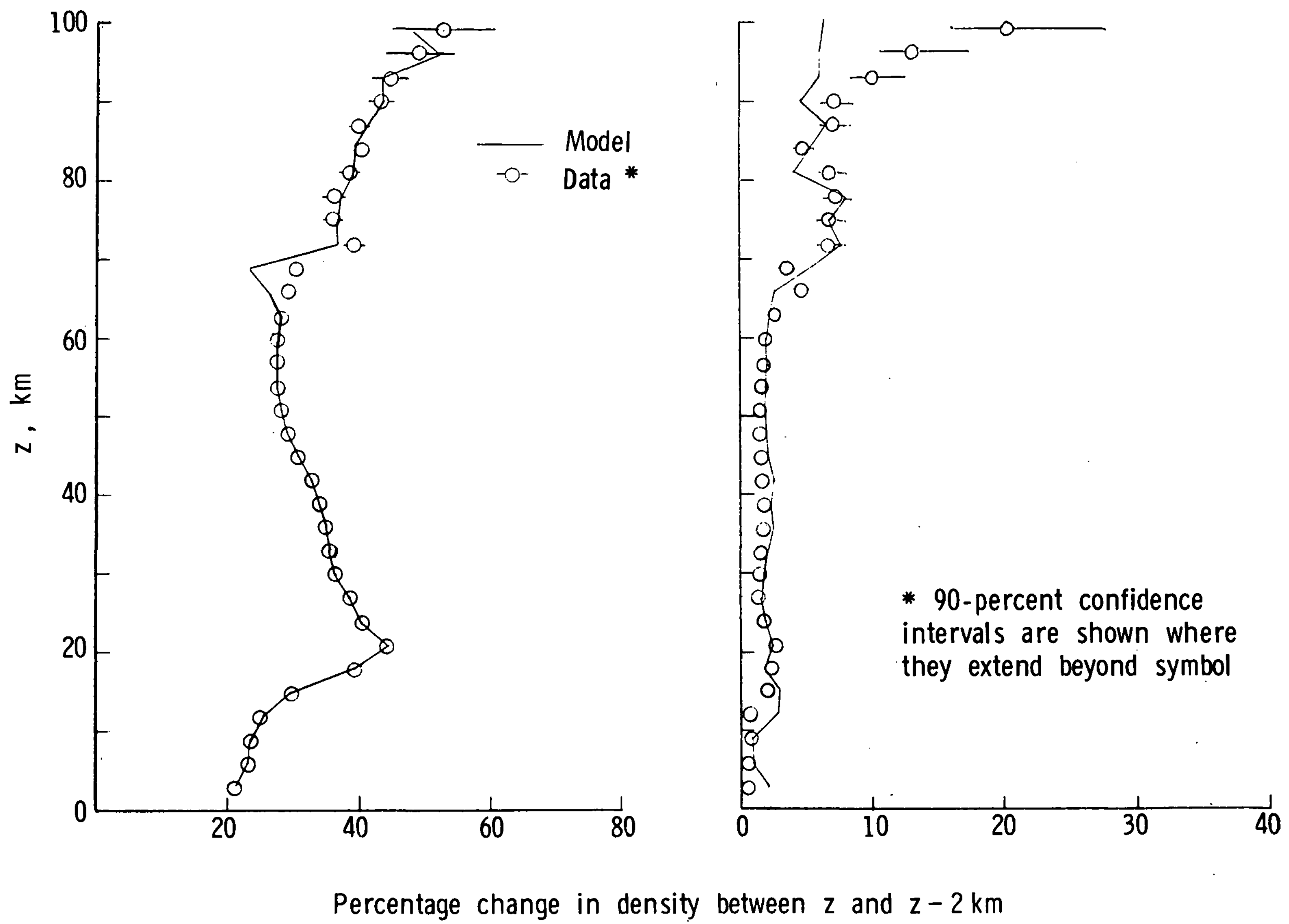


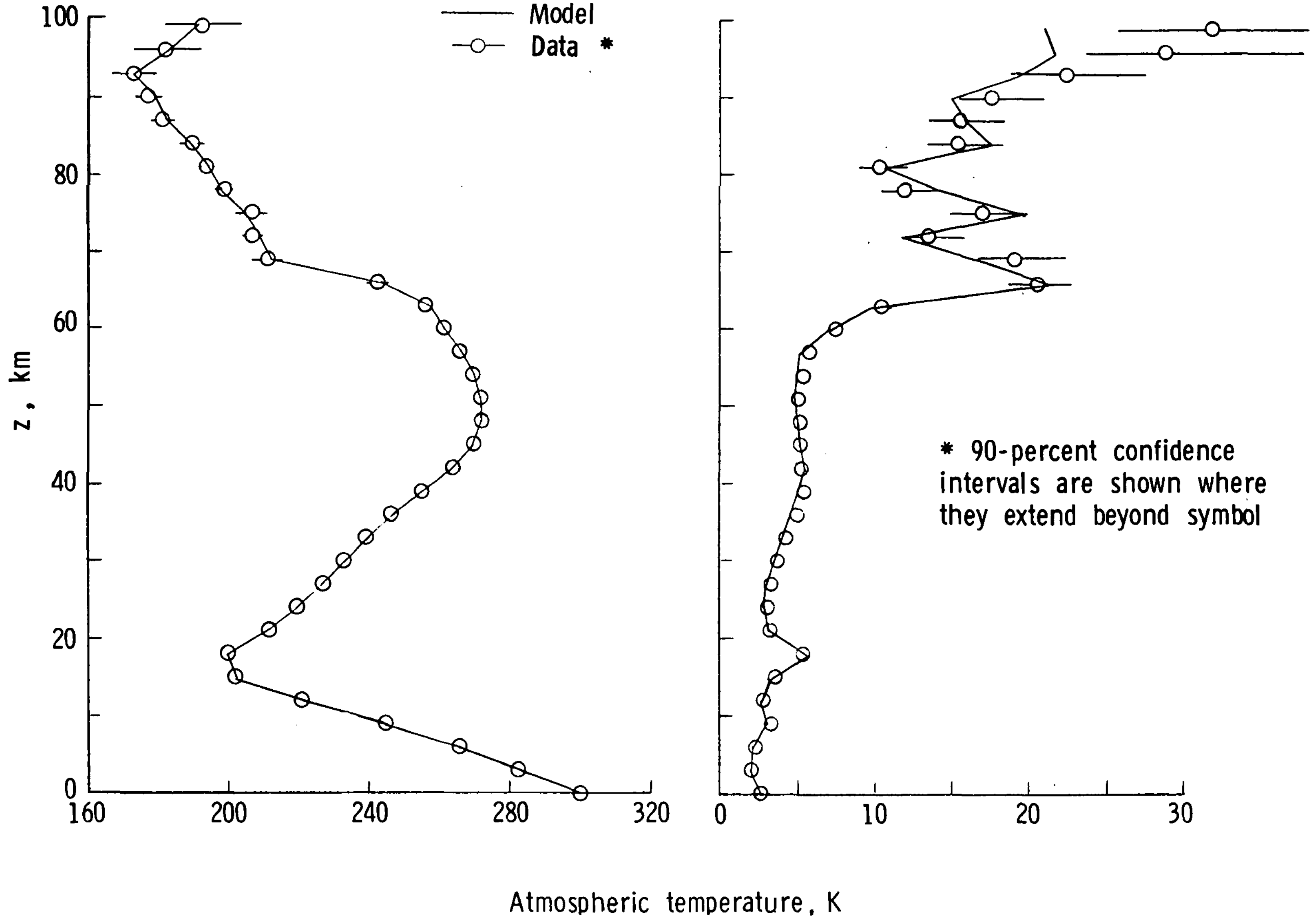
Figure 6.- Independent replicates of trajectory shown in figure 5 relative to blocks on TAPE10.



(a) Mean.

(b) Standard deviation.

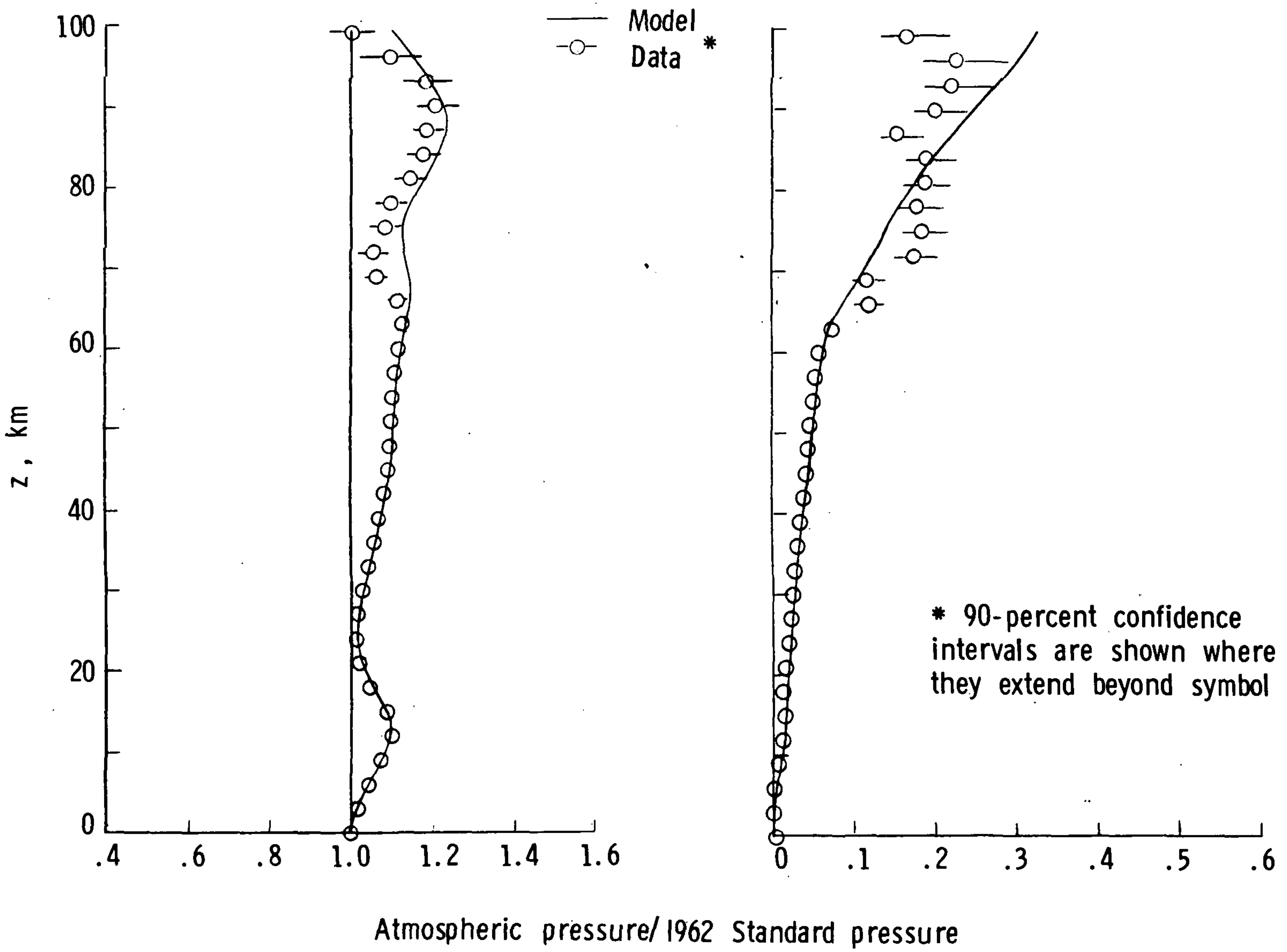
Figure 7.- Comparison of model and data means and standard deviations of vertical density gradients in the 15° latitude zone.



(a) Mean.

(b) Standard deviation.

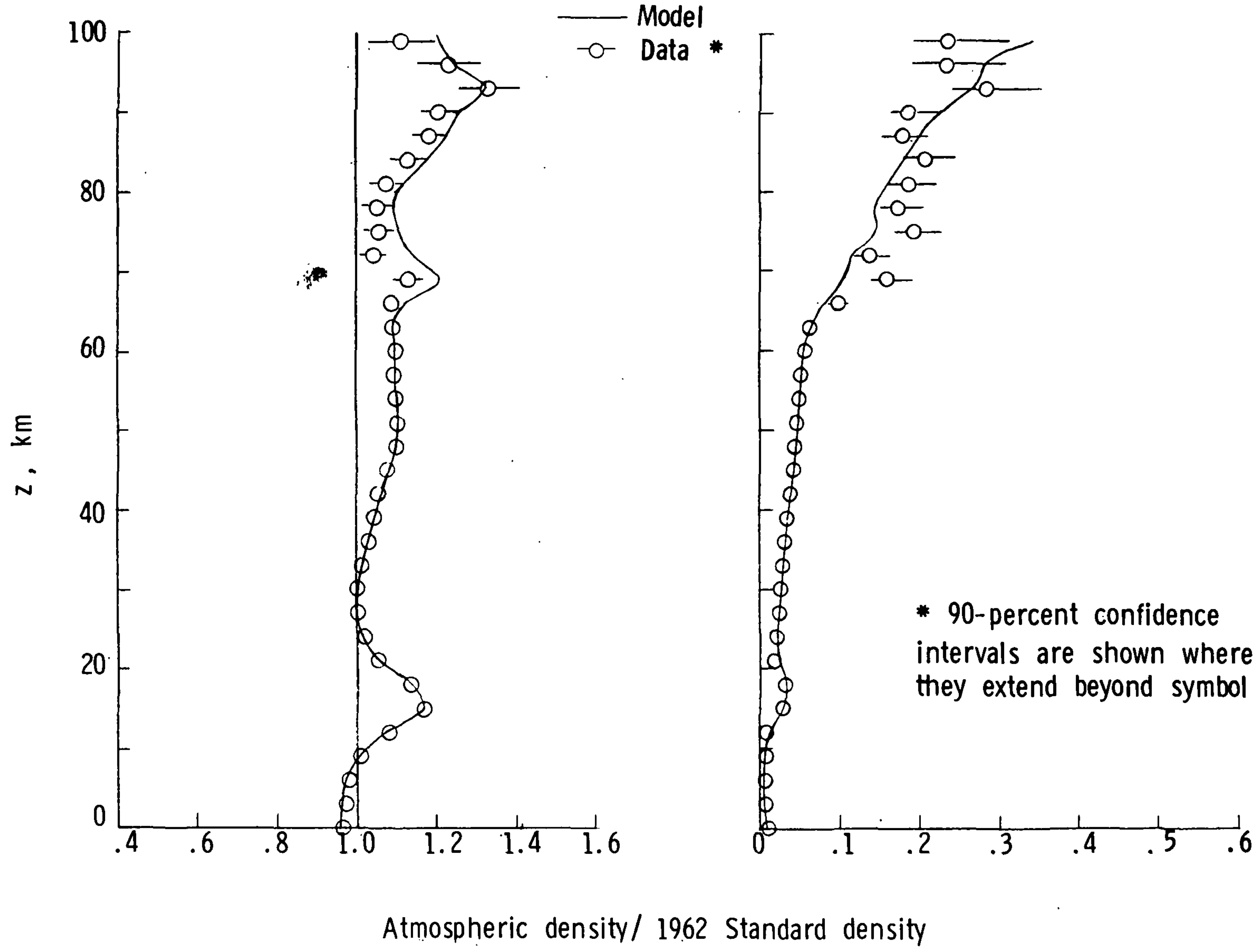
Figure 8.- Comparison of model and data means and standard deviations of atmospheric temperature in the 15° latitude zone.



(a) Mean.

(b) Standard deviation.

Figure 9.- Comparison of model and data means and standard deviations of atmospheric pressure in the 15° latitude zone.



(a) Mean.

(b) Standard deviation.

Figure 10.- Comparison of model and data means and standard deviations of atmospheric density in the 15° latitude zone.

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