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A STATUS REPORT ON ATMOSPHERIC DENSITY MODELS AND OBSERVATIONS

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A STATUS REPORT ON ATMOSPHERIC DENSITY MODELS AND OBSERVATIONS

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SUMMARY

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The history of standard and model atmospheres reflects the political as well as the scientific thinking of the related eras, and follows a pattern of successively extending the upper-altitude limit of the atmospheric model in keeping with the successive increases in the altitude range of the human traveler or his machines and measuring equipment. The upward extensions of the atmospheric models have frequently been based on speculation or, at best, upon limited knowledge; and as improved information became available the need for revisions of these models became evident. Frequently, the refinements in measuring techniques which made possible the extension at the high-altitude end of the model also provided the basis for improvements and modification of the intermediate-altitude regions which were then defined in a quasi-legal manner to represent a best average model.

The vast amount of satellite drag-acceleration data acquired from the measured orbits of artificial earth satellites above 200-km altitude over the past nine years has led to the recognition that at high altitudes, at least, the atmosphere varies greatly with time; that is, from day to night as well as from periods of high solar activity to periods of low solar activity. Several models reflecting these variations have been developed, and these indicate a shift in thinking away from the concept of a single average model to that of the multiple model showing variability. During this same nine-year period the number of observations of atmospheric properties below 120-km altitude has also increased considerably, though not nearly at the same rate as those above 200 km. Models showing seasonal and latitudinal variations below 120 km have been prepared — some on the basis of rather limited data. These models suggest an isopycnic region at about 90 km with a density about 14 percent greater than that of the 1962 United States Standard Atmosphere at that altitude. These models also suggest seasonal variability to be minimum at tropical latitudes and to increase to maximum at sub-polar latitudes. No diurnal variation has yet been suggested at altitudes below 120 km.

A re-examination by the writer of seasonal and latitudinal variations of atmospheric density on the basis of 209 density-altitude profiles between 30 and 200 km (not including data gathered in the Meteorological Rocket Network) is currently under way. These data include the results from seven different measuring techniques employed at eleven different land sites and seven different sea sites. Preliminary results indicate that the mean summer and mean winter density-altitude profiles for 30°N latitude exhibits a crossing of isopycnic layer near 90-km altitude. A similar situation exists for mean-summer and

mean-winter density-altitude profiles for 38°N as well as for the pair of profiles for 58°N, but each occurs at a considerably different value of density. The 38° data and the 58° data each exhibit an additional isopycnic level about 2 scale heights above the near-90-km isopycnic level. The existence of this additional isopycnic level is in keeping with the predictions of a simple theory.

The mean of all data shows the standard-atmosphere densities to be too low between 83 km and some altitude above 120 km with the discrepancy being in excess of 40 percent in the vicinity of 95 km. Percentage departure-versus-altitude profiles of the set of recently adopted United States Supplementary Atmospheres appear to be increasingly in conflict with the data for measuring altitudes above 90 or 95 km, particularly for 38°N winter and for 58°N winter and summer. More data in the 100 to 200 km region are urgently needed.

Author

INTRODUCTION

As early as the middle of the last century pressure-altitude tables based on an isothermal atmosphere were used along with aneroid barometers as a means of determining the height of mountains [1].* That the temperature was observed to decrease with decreasing pressure led Radau [2] to develop pressure-altitude tables based on a temperature decrement of 0.08°C per mm Hg of pressure decrement. During the early part of the 20th century, tables based on this relationship were in general use throughout Europe, where the non-liquid barometers including airplane altimeters were generally calibrated in accordance with the Radau model.

Atmospheric studies at various meteorological observatories [3, 4] indicated that above 3000 meter altitude, the observed temperature-altitude profile was in considerable disagreement with that based on the Radau model, and some form of new standard atmosphere was needed especially for altimetry and performance testing in the newly developed aircraft industry. For these reasons, Toussaint [5] proposed a simple defining temperature-altitude profile consisting of two linear segments, one having a gradient of -0.0065°C/m from 0 to 11,000 meters altitude and a second having a gradient of zero degrees per meter from 11,000 to 20,000 meters altitude. Tousaint showed that this profile closely followed the observed average temperature-altitude profile over Italy. Grimault [6] examining this and other data confirmed the desirability of Toussaint's model, which on 15 April 1920 had been adopted as a French standard atmosphere and which in 1924 was to become the basis of the standard atmosphere for the International Commission for Air Navigation ICAN [7], an organization to which most European Nations belonged.

Political isolation kept the United States from joining the ICAN organization, while misinformation stemming from a lack of knowledge concerning Toussaint's French-language document caused the United States to adopt its own slightly different standard atmosphere.

*Numbers in [ ] represent reference numbers.

Diehl [8] following the suggestions of Gregg [9] recommended the adoption of the Toussaint negative temperature-altitude gradient of $-0.0065^{\circ}C/m$ but only to an altitude of 10,769 meters, at which altitude Diehl introduced a new isothermal layer $1.5^{\circ}C$ warmer than the ICAN value, presumably without knowing of Toussaint's recommendations for this altitude region. Amplifications were made to this atmosphere by Brombacher [10, 11] and in 1947, Warfield [12] prepared an extention of this standard to 120 km.

About this time, a new urge for international cooperation through the United Nations led to the formation of the International Civil Aviation Organization (ICAO), as a replacement for ICAN, with the United States now a prominent member. This organization adopted the Toussaint model from sea level to 20 km as a difinition of the ICAO standard atmosphere [13], and the United States was forced to begin the revision of its entire system of standard atmospheres above 10.769 km altitude. Apparently as a face-saving gesture for the United States, the ICAO organization agreed to relinquish the sea-level value of gravity acceleration (9.8062 meters sec^{-2}) used by ICAN [14] in favor of 9.80665 meters sec^{-2}, which many United States scientists considered as a standard value for 45 degrees north latitude.

In 1954, a quasi-official committee for the extension of the United States Standard Atmosphere (COESA) was formed, and on the basis of committee-approved studies of limited atmospheric data, Minzner and Ripley [15] prepared the 1956 ARDC Model Atmosphere, with tables extending to 500 km altitude. This model, with minor modifications, became the 1958 United States Standard Atmosphere [16] with tables extending to 300 km altitude.

The density data derived from the observed drag acceleration of the first few artificial earth satellites indicated a need for revising the 1958 United States Standard Atmosphere at least at high altitudes. As a result, the writer prepared the 1959 ARDC Model Atmosphere [17] which was to have been adopted as a revised United States Standard Atmosphere.

Because of internal political pressure placed upon it by some of its own members, COESA in 1955 had adopted a scientifically unsound temperature-altitude profile between 20 and 32 km, and in 1960 ICAO refused to accept this profile when it considered an upward extension of its atmosphere. In order to retain agreement between the ICAO standard atmosphere and the United States Standard Atmosphere above 20 km, COESA was forced to define a new United States Standard Atmosphere upward from 20 km altitude. The considerably increased quantity of data available at that time led Cole [18], and Champion and Minzner [19] to develop an improved model atmosphere to 700 km altitude. This model became the United States Standard Atmosphere, 1962 [20].

At the time of the adoption of this standard it appeared that the atmosphere above 200 km was not static, but varied considerably from day to night, and in accordance with other variables. Even in the region from 90 to 2000 km, the temperature was seen to vary considerably from the value adopted for the United States Standard as illustrated in Figure 1, which was taken from Champion and Minzner [19]. It was recognized by all concerned that while this

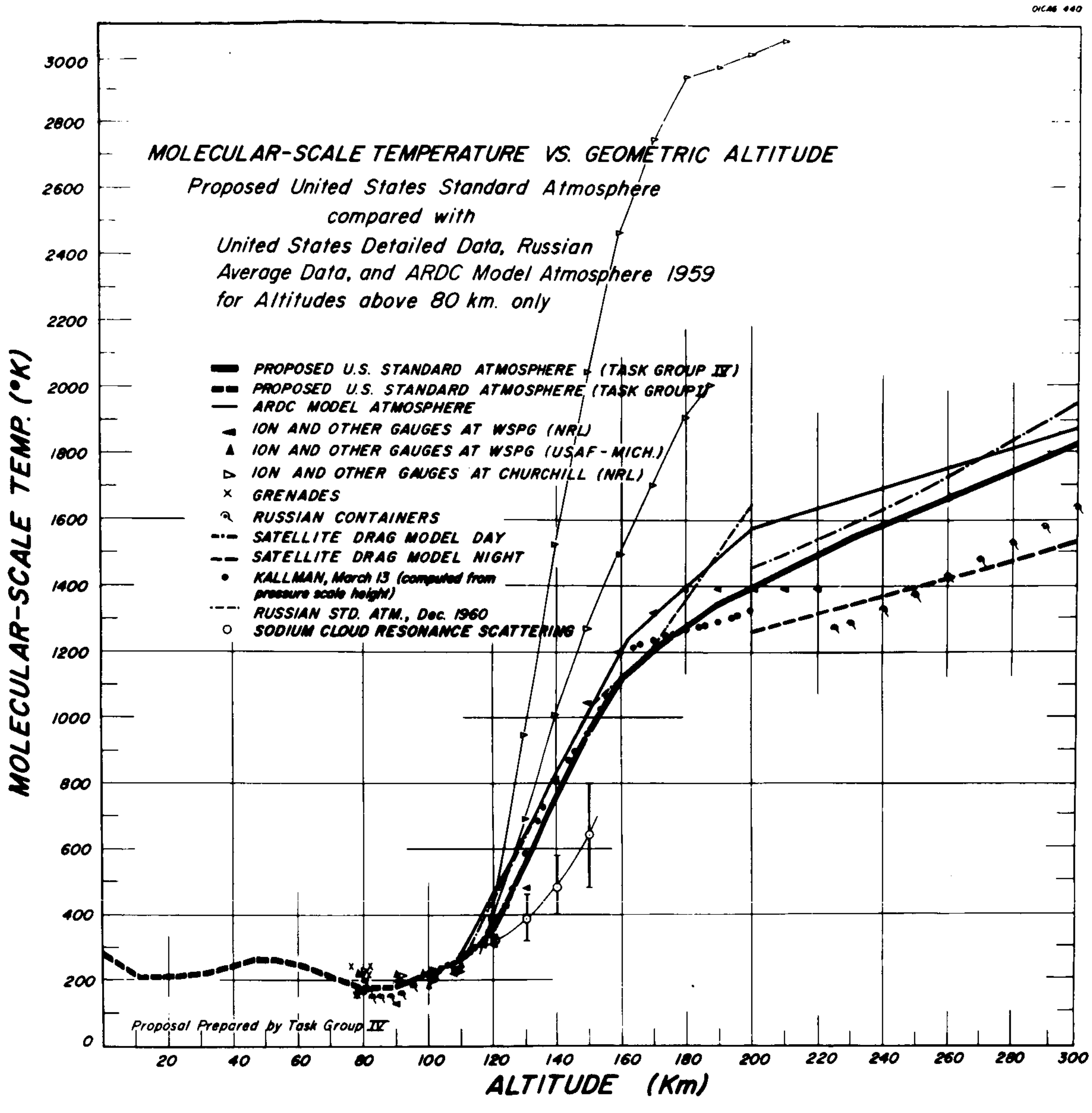

Figure 1. Temperature-altitude profile. The 1962 U.S. Standard Atmosphere compared with measured temperatures and temperatures associated with other computed models.

new standard atmosphere could serve as a quasi-legal reference atmosphere, it did not even suggest the degree of atmospheric variability which concurrent atmospheric studies were indicating.

RECENT HIGH ALTITUDE MULTI-VALUED MODELS

Studies by Jacchia [21], Priester [22], as well as by King-Hele [23], all indicated the considerable variability in satellite drag and, thus, in density at altitudes in excess of 200 km. It was demonstrated that these high-altitude variations of density are directly related to solar radiation and thus show a strong diurnal effect as well as an effect related to long-term variations in solar activity. In addition, it was discovered that there are 27-day variations, semi-annual variations, and variations associated with geomagnetic activity.

Considering the various aspects of the problem of material distribution in the atmosphere, including the time-dependent energy balance, Harris and Priester [24 to 26] developed a set of expressions for computing number-density distribution of various atmospheric gas species on the basis of euv radiation absorption by molecular nitrogen and heat loss in the form of infrared reradiation from an atomic oxygen transition. In these expressions, vertical heat transport from thermal conduction as well as energy transport from mechanical expansion and contraction of the atmosphere was considered, and realistic density-altitude profiles at satellite altitudes were determined, but only when an unexplainable second heat source was introduced into the calculations. In spite of this theoretical limitation, the process represented a tremendous step forward in atmospheric model generation.

Using this process, Harris and Priester [26] prepared a set of tables for the Committee on Space Research (COSPAR) as an international reference atmosphere. These tables contain ten models, one for each of ten values of solar activity between the extremes observed over the decreasing half of the most recent 11-year solar cycle. For each model there are twelve tables, each successive one representing the conditions at successive 2-hour intervals throughout the day; thereby there are 120 different sets or pages of tabulated data. In order to compare the results of these tables with actual density observations, it is necessary to normalize the observed values for the 27-day variation, the semi-annual variations, and variations due to geomagnetic activity.

Using empirical temperature-altitude profiles of exponential form, Jacchia [27] recently integrated the diffusion equation to reproduce density-altitude profiles derived from satellite drag over the years. He computed thirty of these models, one for each of thirty different exospheric temperatures. Appropriate equations relate variations in exospheric temperature to solar and geomagnetic activity as well as to time of day and day of the year. Thus, for a given set of conditions, of day of year, time of day, solar activity, and geomagnetic activity the appropriate exospheric temperature may be determined, and the appropriate model selected. Both the Jacchia and the Harris and Priester models are limited by a similar fixed set of boundary conditions at 120 km, and while the Jacchia models have no flexibility in the variation of temperature between the two end-point values, they are smaller and more convenient and perhaps have a validity comparable to the more extensive Harris and Priester tables.

RECENT LOW ALTITUDES MULTI-VALUED MODELS AND RELATED TRANSITION MODELS

Cole and Kantor Models

At low altitudes, between 30 and 90 km, statistical studies of a large amount of atmospheric data below 70 km, and a considerably reduced amount above 70 km, led Cole and Kantor [28] to a set of models which show seasonal variations at several latitudes in accordance with Figure 2. These models were adopted by COESA to be published as a supplement to the 1962 United States Standard Atmosphere, but with the advent of models showing diurnal and solar-related variations at altitudes above 120 km, it was decided that some system of transition models should be developed for the region between 90 and 120 km. Consequently, COESA appointed a task group to study the problem and to make recommendations for connecting the Cole-Kantor models to the Jacchia models.

The name "Transition Model" is fortuitous, since it is doubly applicable. While the original concept was to signify a transition between two sets of established models, it also applies in that the altitude region of concern is a transition region where basic changes in atmospheric structure are known to occur. The nature of these changes, however, is certainly not thoroughly understood, and the time dependence of these variations is only beginning to be studied. Unfortunately, the number of observations in this altitude region is very small with the total number at any one altitude for all times and all locations decreasing from about 50 at 90 km down to about 20 at 120 km. Between 120 and 200 km, the number of observations per altitude level decreases rapidly with increasing altitude so that at many levels the number of points has dropped to one or zero. Thus, at best, the results of studies to determine correlations between 120 and 200 km would not be very reliable.

The task group was charged by COESA to define transition models in accordance with certain limiting conditions. As a minimum condition the task group could develop a set of seven models corresponding respectively to the seven season- and latitude-dependent models of Cole and Kantor, to which the transition models must be respectively continuous, somewhere within their 90-km isothermal layers. Simultaneously these seven transition models must satisfy the single set of 120-km boundary conditions of the non-seasonal, non-latitude Jacchia models.

In contrast to this minimum-condition situation the task group could work within more expanded conditions and study the limited atmospheric data for the transition region. They could seek out dependence on any or all of season, latitude, solar flux, and magnetic activity between 90 and 120 km, and between 120 and 200 km, the base of the region of the large body of satellite-derived density data upon which the Jacchia models depend.

The writer has developed a set of transition models under the minimum conditions specified above, and is currently involved in a program of study suggested by the more expanded conditions. Champion [29] has also developed

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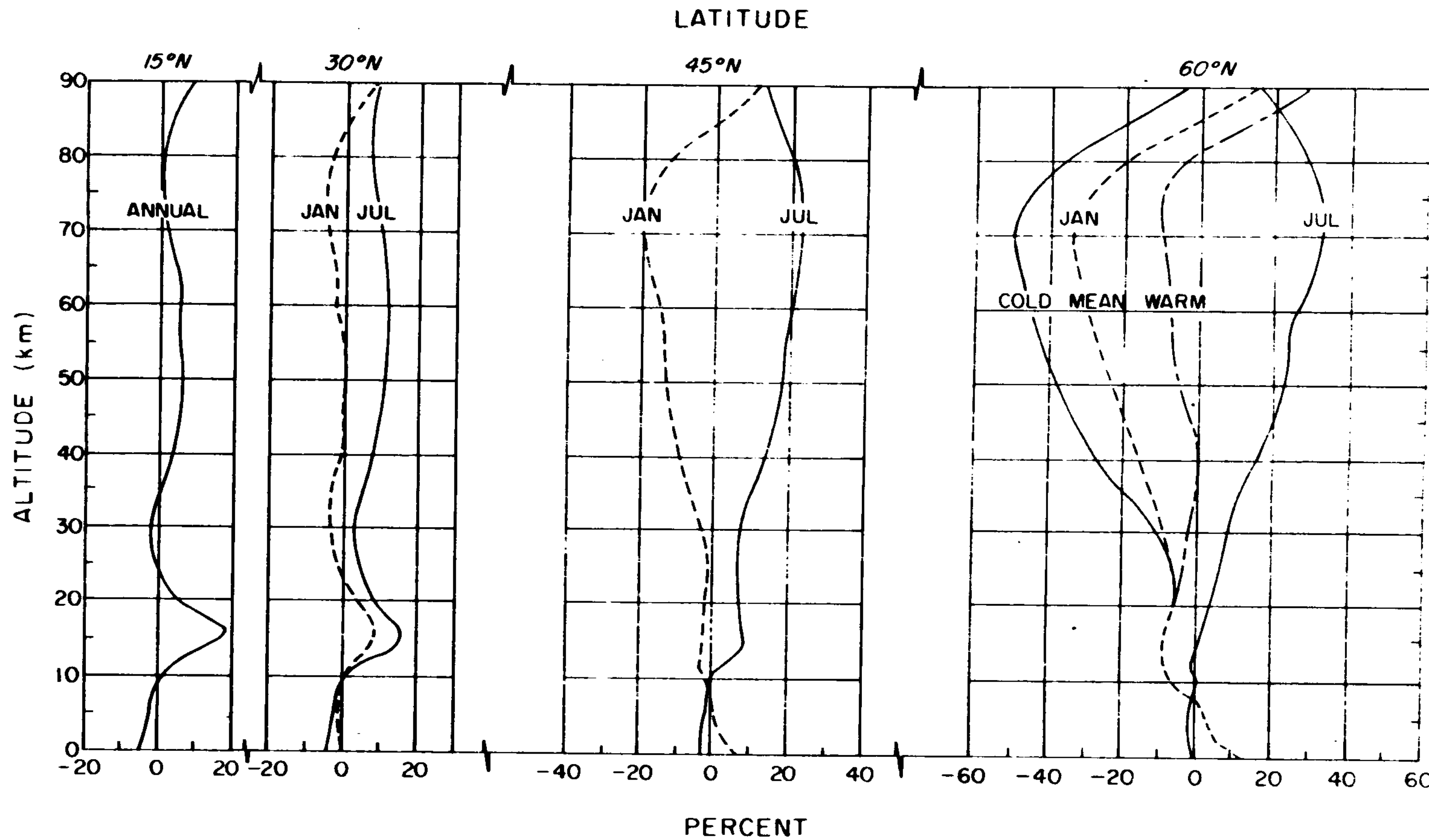


Figure 2. Percentage departure of density-altitude profiles of supplemental atmosphere from those of the U. S. Standard Atmosphere [28].

a set of models under the more expanded conditions, and his results are compared with those of the writer this report.

Minimum-Condition Transition Models

In keeping with the minimum conditions specified by COESA, the author prepared a set of seven transition models [30]. Each was defined by a single value of L the gradient of molecular scale temperature T_M (linear with respect to geopotential h) between some geopotential altitude h_x, within the 90-km isothermal layer of each of the Cole and Kantor models, and h_a, where h_a represents each of the various geopotential equivalents of 120 geometric kilometers for these models. Since these models are for latitudes 15°, 30°, 45°, and 60° the corresponding geopotential altitudes h_a are for 117.495, 117.611, 117.776, and 117.929 geopotential kilometers, respectively. All of these transition models conform with the single Jacchia 120-geometric-km value of molecular scale temperature (T_M) and of density ρ_a, and each independently conforms respectively with the value of molecular scale temperature $(T_M)_b$ and of density ρ_b at the base of the 90-km isothermal layer of the related Cole and Kantor model. The particular value of h_x, and implicitly the related temperature-altitude gradient, for each transition model was obtained by a digital machine solution for h_x in the following equation, for each of the seven Cole-Kantor models:

$$\rho_x = \left[\rho_a \frac{(T_M)_a}{(T_M)_b}\right]^{\left(1 + Q\frac{h_a - h_x}{(T_M)_a - (T_M)_b}\right)} = \rho_b \exp\left[-\frac{Q(h_z - h_b)}{(T_M)_b}\right]$$

where Q is a constant equal to 0.0341632°K per geopotential meter. The exponential member on the right-hand side of the equation relates the values of density and temperature at h_x (that is, ρ_x and $(T_M)_x$ at h_x) to values of density and temperature at h_b (that is, ρ_b and $(T_M)_b$ at h_b) where h_b is the base of the 90-km isothermal layer of a particular Cole and Kantor model. The power member in the center of the equation relates ρ_x and $(T_M)_b$ at h_x to Jacchia's ρ_a and $(T_M)_a$ at h_a the geopotential equivalent of 120 geometric km for the latitude in question.

The temperature-altitude profiles for these several models and those of the contiguous portions of the Cole and Kantor models are shown in Figure 3. These single-segment models are unique in that they represent the condition of greatest possible altitude for the top of the 90-km isothermal layer and the least possible value of temperature gradient which might be employed in the top segment of any conceivable multiple-segment model meeting the boundary conditions, provided only that such multiple-segment models be limited to those having only monotonically increasing values of temperature gradients between the 90-km isothermal layer and 120-geometric-km level. The figure shows that the upper segment of two of the Cole and Kantor models were modified in the process of developing the transition models.

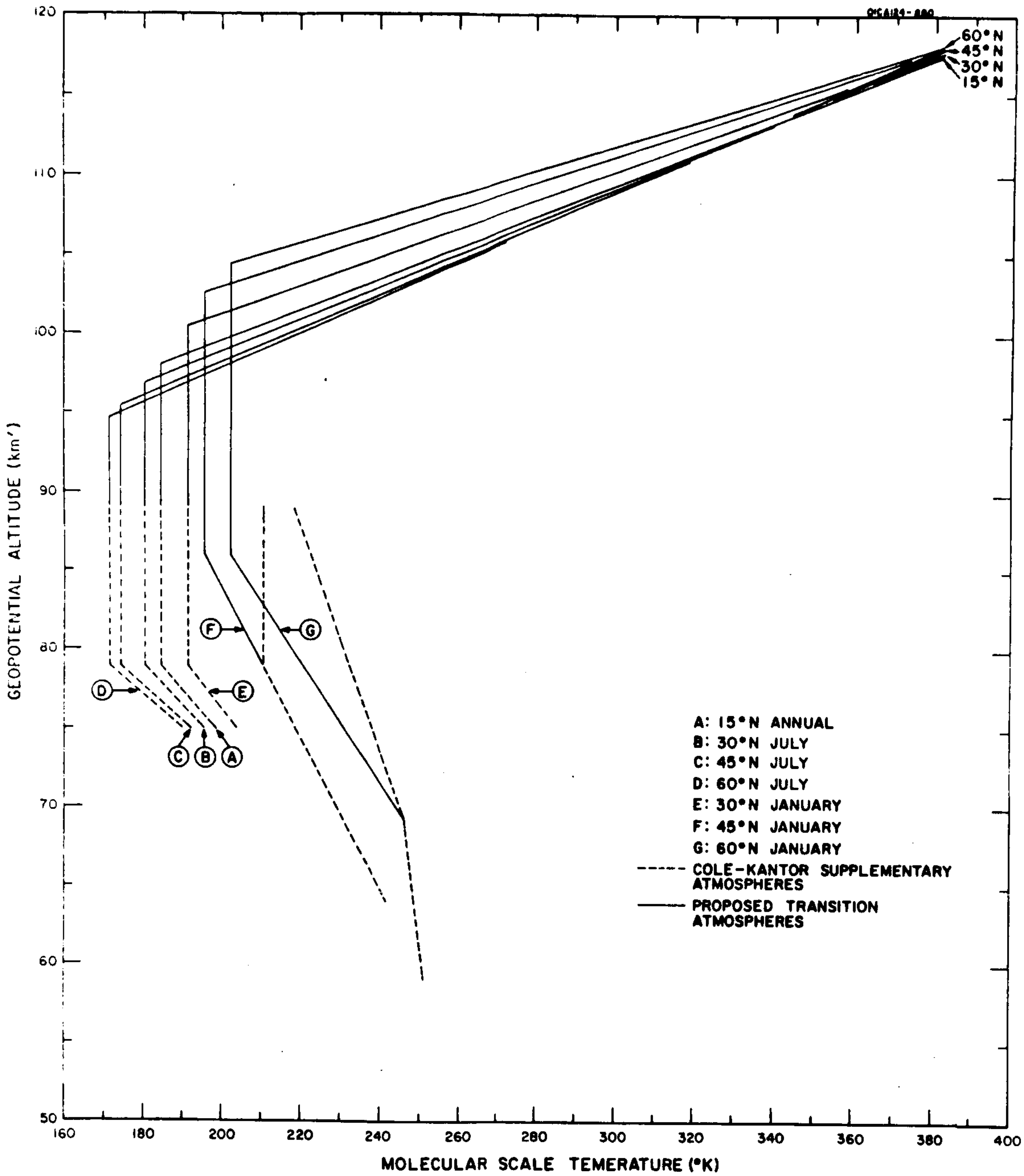


Figure 3. Temperature-altitude profiles defining seven proposed transition models connecting supplementary atmospheres to thermospheric models.

The several density-altitude profiles consistent with the temperature altitude profiles of Figure 3 depart from the density of the United States Standard in accordance with Figure 4. The sharpest break in the slope of each of these curves corresponds to the point where the gradient of the corresponding temperature-altitude profiles changes abruptly from zero to the large positive value. The less pronounced breaks in the slope of the curves at 88.7, 98.4, and 108.1 geopotential kilometers correspond to points of successive change in temperature gradient in the United States Standard; that is, from 0 to +3 to +5 to +10 degrees per kilometer. Any multi-segment transition model which satisfied the boundary conditions would not have the single very pronounced break in slope of the relative departure curve but would have additional lesser ones in accordance with the number and location of the temperature-gradient changes.

Realistic Transition Models by Champion

In an attempt to improve over the approach just discussed, Dr. Champion [29] undertook to examine the density variations above 90 km. He considered an earlier study of four winter and one summer density-altitude profiles all at Fort Churchill, Canada, in which Kantor and Cole [31] suggested a density-altitude variation for 45^{o} and 60^{o} north latitude in accordance with Figure 5, as deduced from geostrophic wind considerations. It is evident that the limited number of more directly observed density data are not in good agreement with the proposed models.

After studying this Kantor and Cole graph, and reviewing other data, particularly for lower latitudes, Champion prepared a similar though more extensive pattern of density deviation from the standard atmosphere as shown in Figure 6. In regard to this figure, Champion states, "it shows the best estimates that can be made at this time of the mean density deviations from the standard as a function of latitude and season between 80 and 120 km".

It appears that only four of the eight curves of the composite of Champion's estimated seasonal and latitudinal density-deviation models are in close agreement with the incomplete density data which he presents. These are the 15^{o} annual, the 30^{o} - winter, the 45^{o} - summer and the 60^{o} - winter models. Only the first of these is based on a nearly complete set of data for the latitude in question. This profile stemming from data at 9.4^{o}N, is based on thirteen density-altitude measurements at Kwajalein. Champion carries this profile to 125-km altitude even though the greatest altitude of any of the particular density-altitude observations [32] is only 6 of the 13 profiles extending to that great an altitude. (For completeness Champion might also have considered Horvarth's three sets of data from Ascension [33]. This data ought to be included in the determination of the tropical mean atmosphere above 80 km).

As a basis for a 30^{o} atmosphere, Champion presents a graph showing a scatter of ten density-deviation profiles determined by his falling-sphere experiment from both summer and winter observations at Eglin and White Sands.

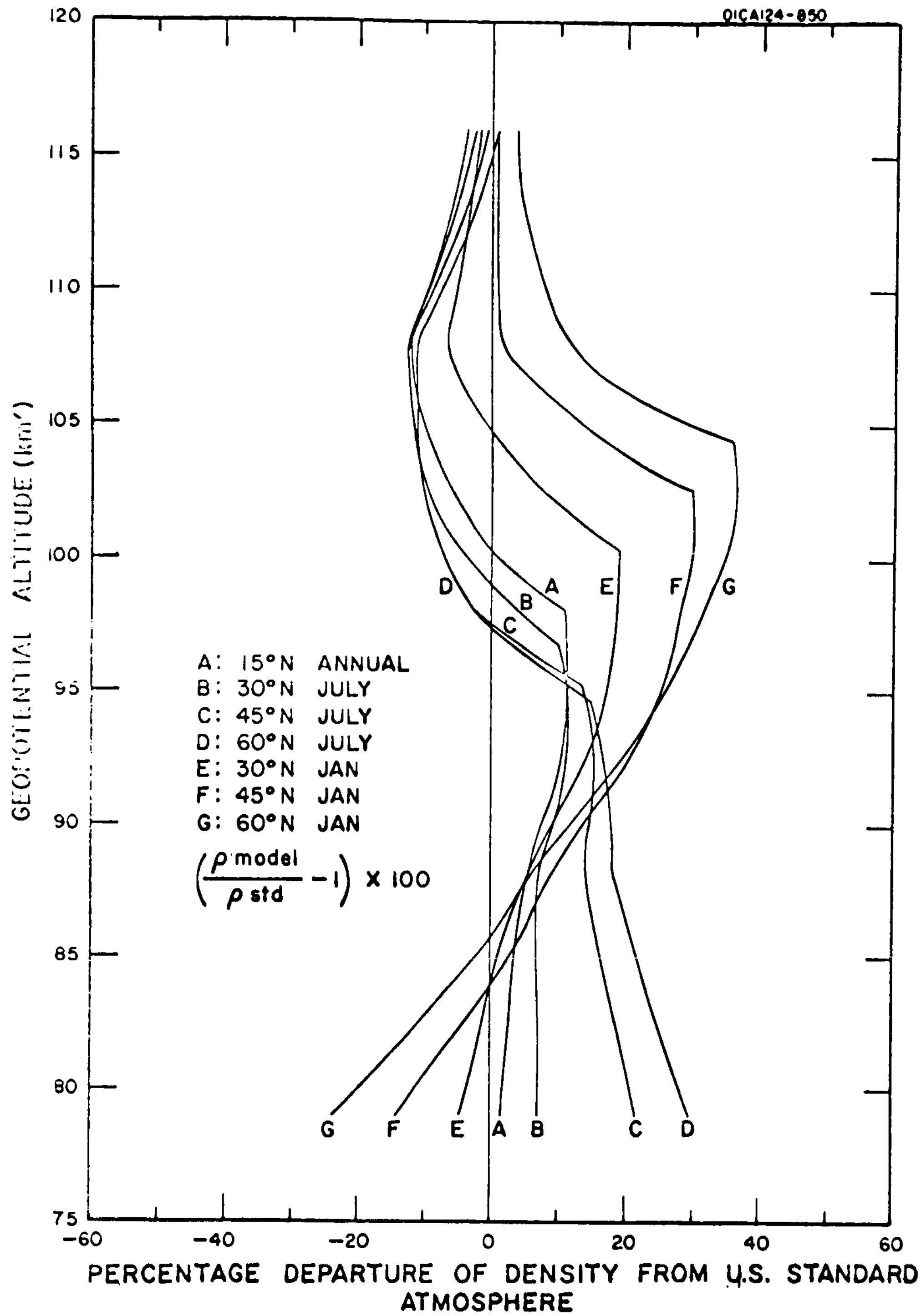


Figure 4. Percentage departure of the density-altitude profile of each of various transition models from that of the U. S. Standard Atmosphere.

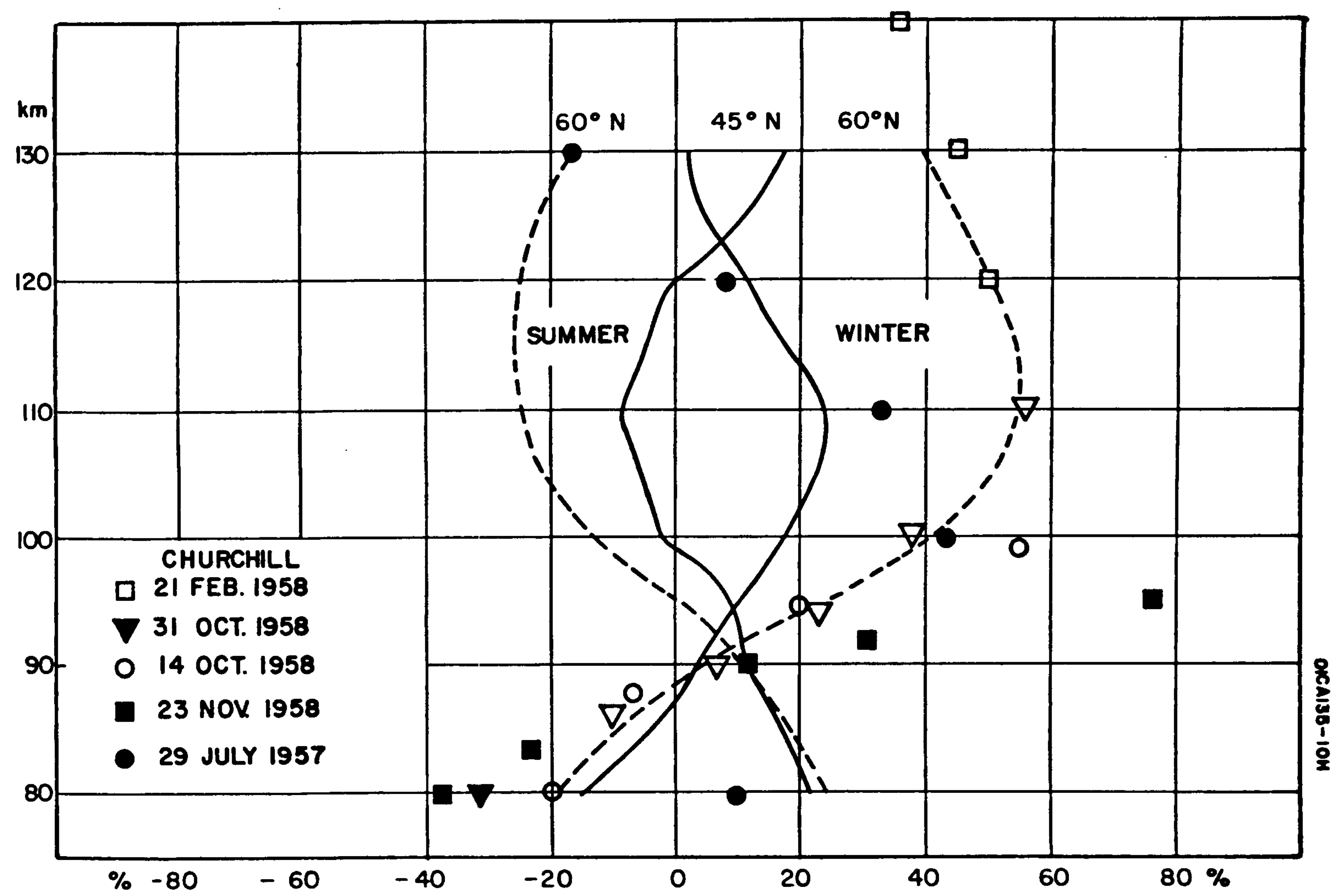


Figure 5. Percentage departure from the density-altitude profile of the U.S. Standard Atmosphere 1962, of those density-altitude profiles for summer and winter at 45°N and 60°N latitude deduced by Kantor and Cole from geostrophic wind considerations.

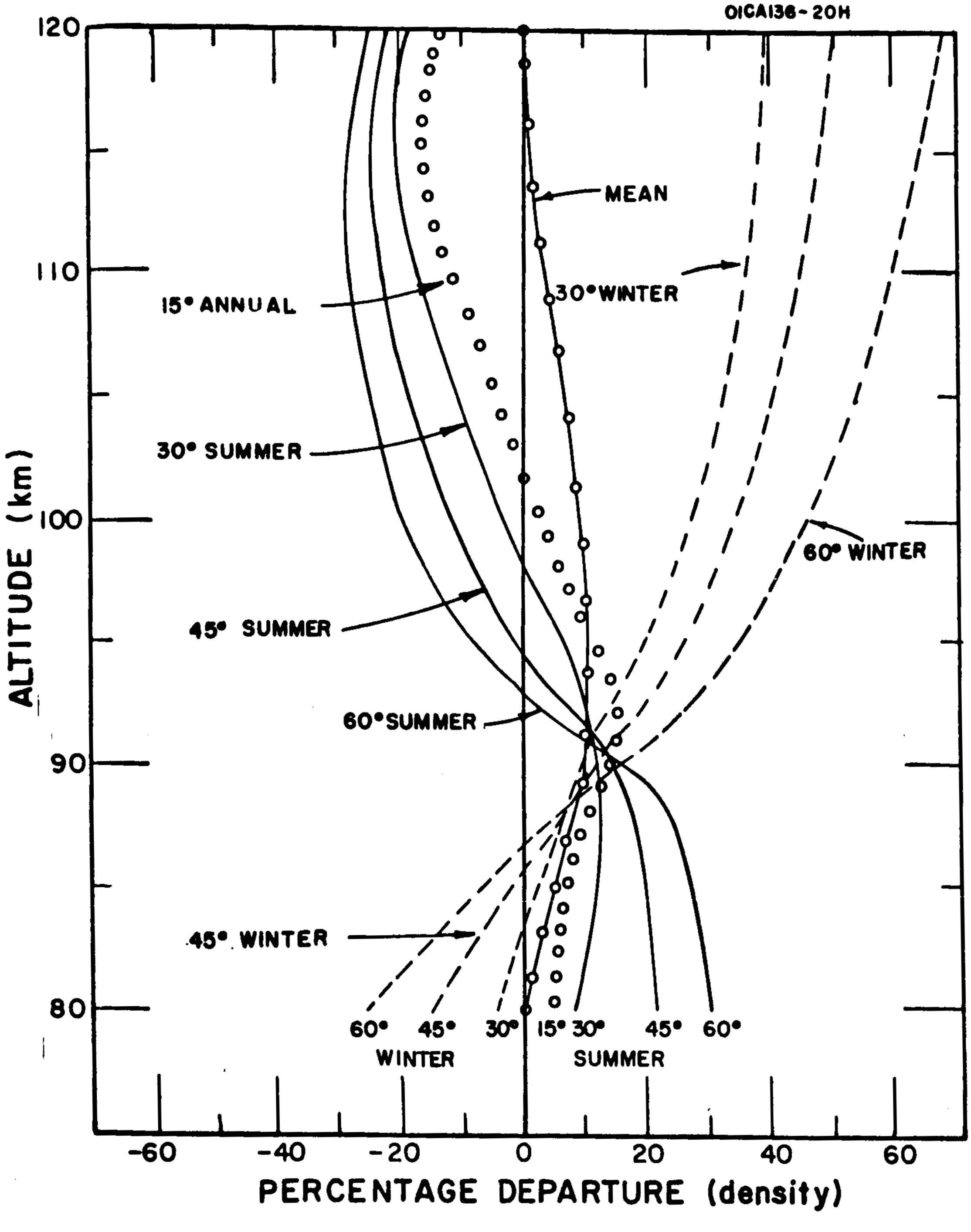


Figure 6. Percentage departure of each of Champion's estimated mean winter and summer density-altitude profiles for various latitudes from that of the 1962 U. S. Standard Atmosphere (from Champion 1965).

This graph indicates no apparent distinction between summer and winter values, and Champion shows no evidence of having computed mean summer or mean winter values from these data. Champion's 30° winter profile shown in Figure 6, appears to follow the general trend of the data which he cites, but his 30° summer profile in the same figure is not at all suggested by his falling sphere data. He cites no other data to support has 30° summer profile.

Champion's 45° summer mean atmosphere from 80 to 110 km is determined from two density-altitude profiles measured at 38°N latitude when a total of 19, 9, 3, and 3 summer data points are available respectively for altitudes 80, 90, 100, and 110 km at the same latitude. Above 100 km, Champion's curve represents the available data quite well. He presents no data to support his 45° winter model, unless the earlier Kantor and Cole estimate for 45° winter as reproduced by Champion and again by the writer in Figure 5 can be considered to be supporting data. No density observations are shown in this figure to support either of the Kantor and Cole models for 45° North, but below 110 km the summer model has been found to be reasonably supported by density data not shown on that figure. The winter 45° model, however, departs significantly from other available data above 90 km. Hence, Champion's 45° winter model is similarly limited.

Champion's summer and winter models for 60° North are taken almost identically from the Kantor and Cole models shown in Figure 5 without any additional supporting data. It is interesting, therefore, to compare the Kantor and Cole models with the density data cited by them. Two of the observations presented by Kantor and Cole, those for 14 October 1958 and for 31 October 1958 at Fort Churchill, support the suggested 60°N winter profile to 100 and 110 km, respectively. The data for 23 November 1958, however, depart rapidly from the suggested model for increasing altitudes above 90 km, and at 103 km (the greatest altitude of reported data for this date) the density reaches about +190 percent of the United States Standard Atmosphere. Hence, this part of this particular observation hardly supports the suggested model. The data for 21 February 1958 which are available in 5 km increments from 115 to 215 km do not appear to be accurately plotted in Kantor and Cole's graph. The writers calculations show departures according to the following:

Altitude	Percentage Departure
115	- 2.7
120	+ 64.2
125	+127.0
130	+ 71.2
135	+ 62.5
140	+ 47.4

These values support neither the Kantor and Cole models nor the Champion - suggested model. An average of the data from the four winter flights cited by Kantor and Cole would support their 60° winter model only to about 95 km, and hence similarly support the corresponding Champion model to only the same low altitude. When additional observations are considered the Champion 60° winter model appears to be less applicable even below 95 km.

The data for the single summer observation at Fort Churchill cited by Kantor and Cole is accurately plotted, but the suggested summer model for 60°N hardly fits this observation which, to the writers knowledge, is the only summer subartic density data for the altitude region between 100 and 130 km. No data exists between 89 and 100 km, and only one summer-time observation exists for 88 km. Kantor and Cole's suggested summer-time model for 60°N is certainly not supported by the density data they present, nor by any other density data known to the writer, and the Champion model is thus similarly unsupported.

In Figure 6, Champion shows what is alleged to be a density-deviation profile for the mean of all data, but apparently it is not a calculated one. An average deviation curve carefully calculated from these data at 90 km and above would differ markedly from the mean Champion curve.

In summary Champion's eight density-altitude profiles may be categorized as follows:

(1) His 15° model closely follows an accurately calculated average of nearly all the available tropical data which extends to an altitude of 120 km.

(2) His models for 30°N winter, 45°N summer, and 60°N winter appear to fit the cited data reasonably well to altitudes of 105 or 110 km, at which altitude the data either end or depart significantly from the model as in the case of the data for 60°N winter. Champion apparently did not accurately calculate averages of data in the preparation of these models.

(3) His models for 30°N summer, 45°N winter, and 60°N summer are either unsupported by data as in the case of 45°N winter or do not fit the cited data, and are probably unreliable even at altitudes as low as 85 to 90 km.

In spite of there limitations, Champion has "idealized" the density-deviation profiles of Figure 6 to the form shown in Figure 7. Here the three summer profiles and the tropical annual profile are seen to pass through a common point at 120 km, where the density is 1.939×10^{-8} kg m^{-3} or about 20.40 percent less than that of the U.S. Standard Atmosphere. Similarly, the three winter profiles are seen to pass through a different common point at 120 km, this one having a density of 3.586×10^{-8} or about 47.2 percent greater than that of the U.S. Standard Atmosphere. In addition, all density-deviation profiles including the so-called mean have been forced to pass approximately through a common point at about 91 km where the density is about 15 percent greater than that of the standard.

The mean model matches the common density (2.461E-08 kg m^{-3}) and the common temperature (355°K) of the eleven Jacchia models [27] at 120 km, and connects with the density and temperature of the existing United States Standard Atmosphere at some altitude below 80 km. A temperature-altitude profile matching these two boundary values and simultaneously generating the required density-altitude profile defines the mean model.

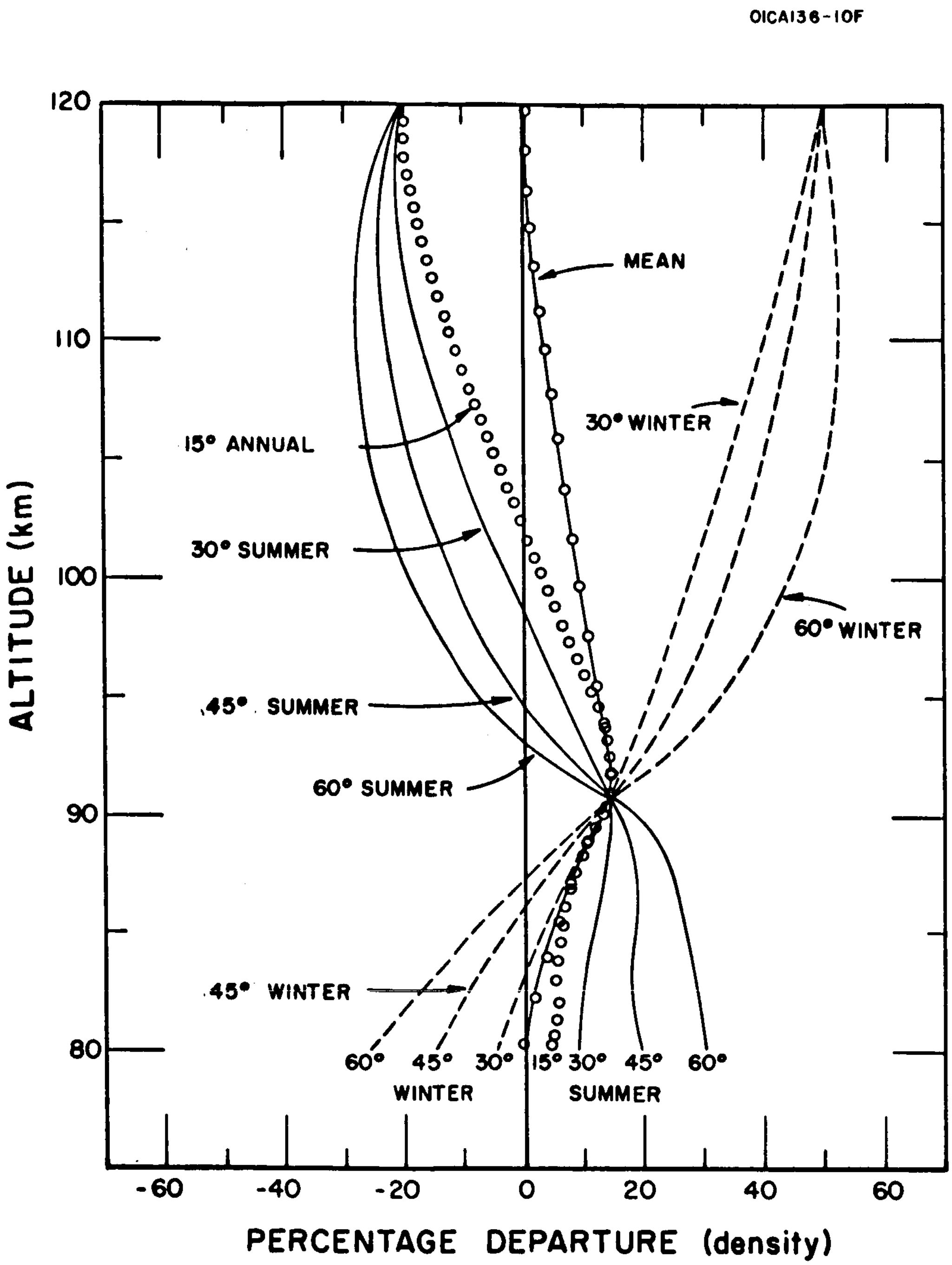


Figure 7. Percentage departure of the density-altitude profiles of each of the sets of U. S. Supplementary Atmospheres (as prepared by Champion) from that of the U. S. Standard Atmosphere 1962 (from Champion 1965).

The common 120-km winter density value and a temperature of 355.9°K have been used as the reference-level values of a set of winter Jacchia-type transition models which Champion has generated to merge with the existing Jacchia models between the altitudesof 200 to 250 km. Similarly a set of summer Jacchia-type transition models have been generated to connect the common summer density value and a common temperature of 410.9°K at 120 km with the Jacchia models in the altitude region from 200 to 250 km. That is, each Jacchia model which is now single valued for all altitudes will branch in the vicinity of 200 to 250 km so that at altitudes below this region there will be a summer and winter set of values as well as the previously existing set of "mean" values. As of the moment this system of models in spite of its limitations is in the process of becoming the system of United States Supplementary Atmospheres from which time-dependent density variations are to be determined for many engineering and design considerations over the coming years.

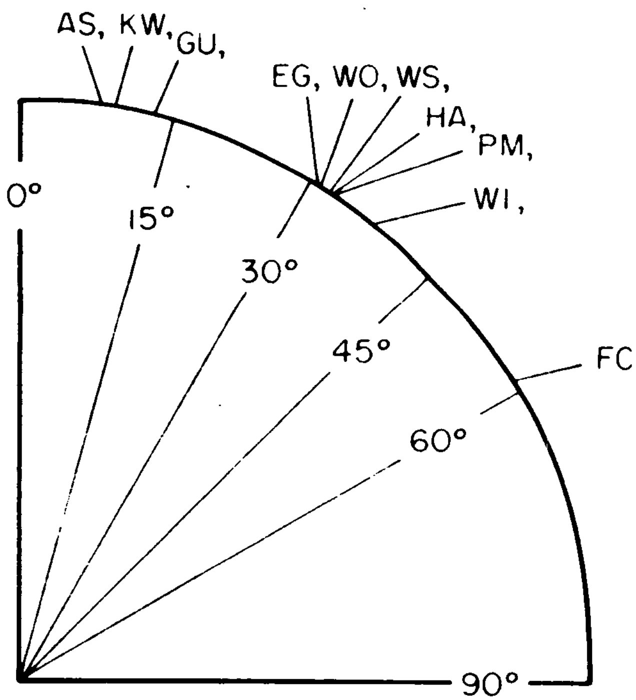
CURRENT STUDY

The writer has for some time been involved in gathering all available density-altitude data for use in a thorough statistical study. At present, excluding density data from the meteorological rocket network, which data usually are limited to altitudes below 60 km, the data collection includes 208 density-altitude profiles varying from 167 density-altitude points per profile to a single point per profile. Only three profiles are in the latter category. In cases of data from the falling-sphere technique, when both an up and down trajectory are often given, each trajectory is separately counted. These up and down trajectories usually have only a small region of overlap so that when these paired profiles are combined, there are 180 profiles available for study. Some of these extended only over limited altitude regions, and many less than 180 data points are available at any one altitude. In the present study, the greatest number of points at any one altitude is 120 at 62 km altitude. Six sets of Champion's recent observations, two at White Sands and four at Eglin, were not available for the writers study; data from both sites contribute to the thirty degree atmospheres.

A preliminary set of calculations have been made to yield results for this paper, and the results which follow are tentative since not all available data have been used, and not all the possible checking and averaging procedures have been employed.

Many of the density-altitude data have been made available by the original investigator in the form of a series of points for successive integral multiples of 1 km. In other cases, the data points are separated by 1 km, or about 1 km, but are not given for integral multiples of 1 km. These and other less uniformly distributed data points have been adjusted to the nearest integral multiple of 1 km by a semilogarithmic interpolation, so that for each original data point at some non-integral altitude, there is a new density-altitude point adjusted in altitude by 0.5 km or less, with an appropriately adjusted density. Thus, all data points are comparable at the appropriate integral-kilometer values of altitude. The data were obtained from 10 fixed land sites and seven variable shipboard sites and were sorted according to site and latitude of observation. The fixed land sites are shown in relative latitude position in Figure 8 on one quadrant of a circle such that north and south latitudes are combined. This figure graphically verifies the validity of grouping data from various sites for common atmospheres. Data from Ascension, Kwajalein, and Guam are logically grouped together to determine an annual tropical atmosphere. Data from Eglin, White Sands, Holloman, Point Mugu, and Woomera, with winter and summer phases reversed in the latter, determine winter and summer subtropical atmospheres, or 32^{o} atmospheres. Data from Fort Churchill determine summer and winter subarctic atmospheres, or 58^{o} atmospheres. The only extensive data for use in determining a midlatitude atmosphere or a 45^{o} atmosphere is from Wallops Island, and this is just inside of the 15^{o} band centered on 45^{o}. It is questionable whether these data are really typical of a mean 45^{o} atmosphere.

After sorting the tropical data according to site, the data at each kilometer altitude were averaged, and the percentage departure from the standard



AS	ASCENSION IS.	7.98°S
KW	KWAJALEIN IS.	9.4°N
GU	GUAM	13.62°N
EG	EGLIN RANGE	30.40°N
WO	WOOMERA	31.11°S
WS	WHITE SANDS	32.40°N
HA	HOLLAMAN	32.88°N
PM	POINT MUGU	33.25°N
WI	WALLOPS IS.	37.83°N
FC	FORT CHURCHILL	58.73°N

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Figure 8. Latitudinal distribution of launch sites of high altitude rockets whose instrumentation yielded the data used in this study.

was determined for the mean atmosphere of each of the three tropical sites. The mean atmospheres for each of these three tropical sites were also averaged into a single tropical atmosphere, and the percentage departure of this atmosphere from the standard was then determined, along with the 95-percent confidence limits. A machine-print-out graph of these results is shown in Figure 9. The percentage departure of the annual tropical atmosphere of Figure 9 is similar to that computed by Champion, since only a small additional percentage of data was employed in the writer's version.

The data from the five subtropical sites within the limits of 30 to 34° were combined and then separated into winter and summer by means of an arbitrary division according to month, such that the 4th through the 9th month was considered to be summer, while the 10th through the 3rd month was considered to be winter. To save time at this point, mean winter and summer atmospheres as well as their percentage departures from the standard were computed for the entire subtropical group without separately examining the mean atmospheres for individual sites, although separate site atmospheres should be computed later. Similarly, winter and summer atmospheres and percentage departures were computed for Wallops Island and Fort Churchill. Graphs of the percentage departure of each of these six models were prepared but are not shown separately here. Finally, a total mean atmosphere with percentage departure was prepared from all the data. The graph of the percentage departure of this mean atmosphere is presented as Figure 10. This graph differs markedly from that estimated by Champion for altitudes above 85 km. The numbers at the right-hand margin of the figure are the number of data points contributing to the average at the related altitudes. Similar numbers of data points are involved at each integral multiple of 1 km.

The percentage departure profiles are generally quite serrated particularly when the number of data points at any particular altitude becomes small. Even for the total mean atmosphere, which involves nearly 100 points at any altitude level, the serration is quite marked. In order that the serrations may be reduced, a 3-km or 5-km machine-averaging process should be applied to the percentage deviation data before it is plotted in any reprocessing of the data. Time did not permit a recalculation for this paper. Hence, in this instance a kind of graphical eyeball smoothing was employed in all but the upper portions of the curves for 30° winter, 38° summer, and 58° winter for which curves a desk calculator was employed for averaging.

A composite of the eight graphs of the percentage deviations from the standard for the eight previously discussed cases are presented in Figure 11 in what at first appears to be a confusing picture. Below 80 km, the pattern is in general agreement with the Cole-Kantor profiles of Figure 2 except for the 58° summer and winter profiles, which have less departure from the standard than those shown by Cole and Kantor [28]. Between 80 and 90 km, however, all of the models except that for midlatitudes appear to fall increasingly below and to the right of the corresponding Cole-Kantor models, particularly in the cases of the summer atmospheres. Since the Champion models in this altitude region are essentially identical to the Cole-Kantor models, the same comments concerning apparent discrepencies apply.

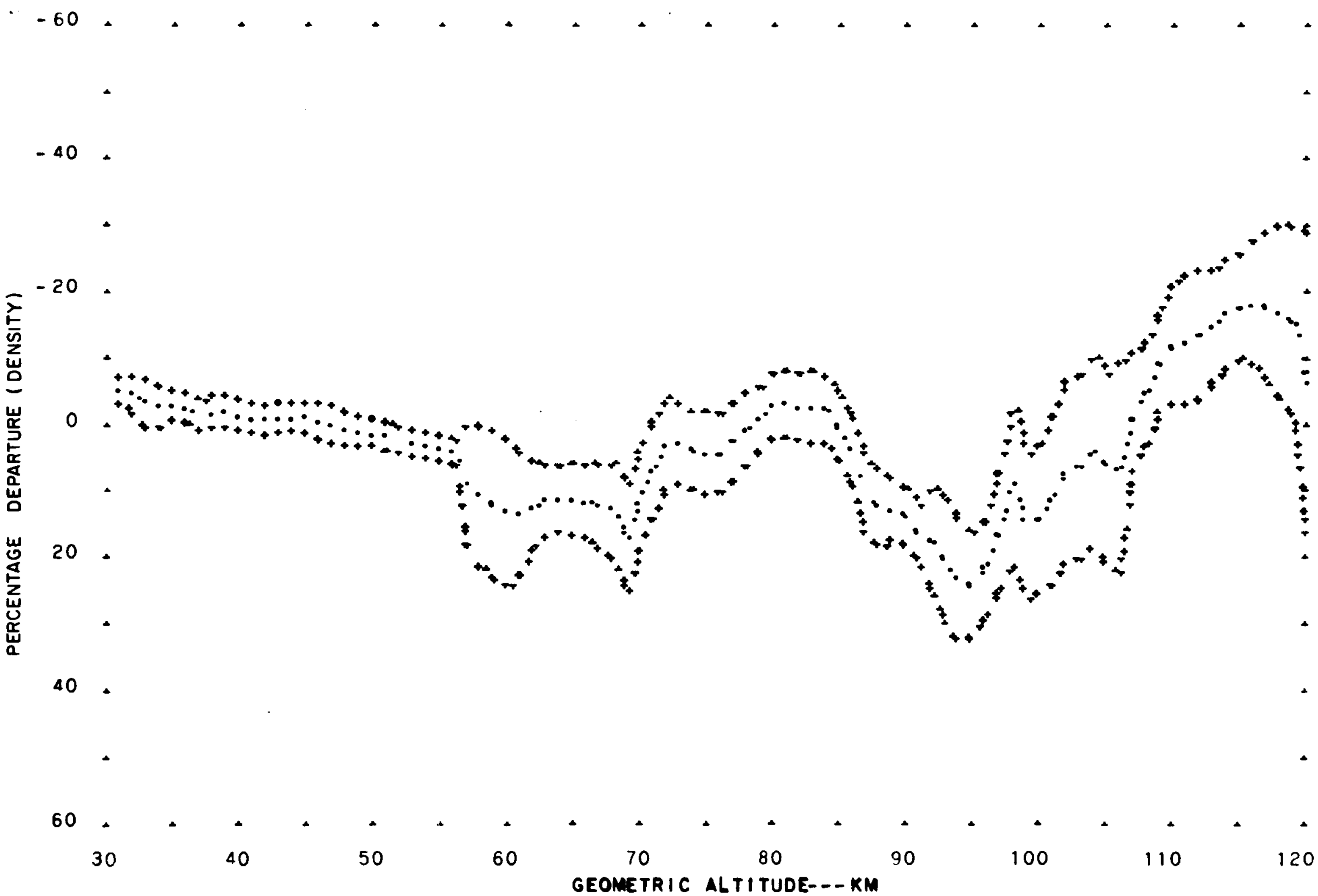

Figure 9. Percentage departure of the mean annual tropical density-altitude profile from that of the 1962 U. S. Standard Atmosphere.

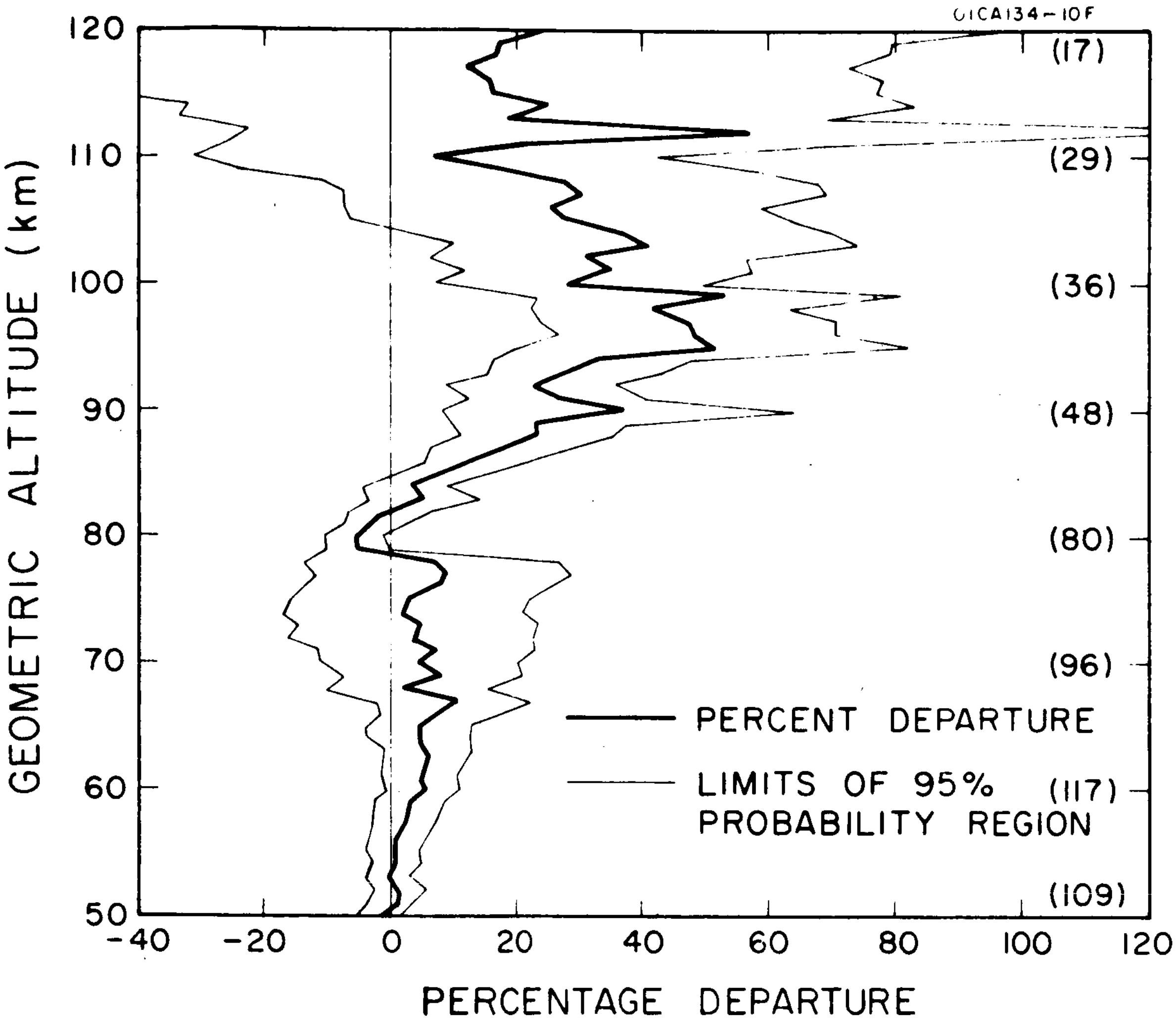

Figure 10. Percentage departure of the total mean density-altitude profiles for all seasons and latitudes from that of the 1962 U. S. Standard Atmosphere.

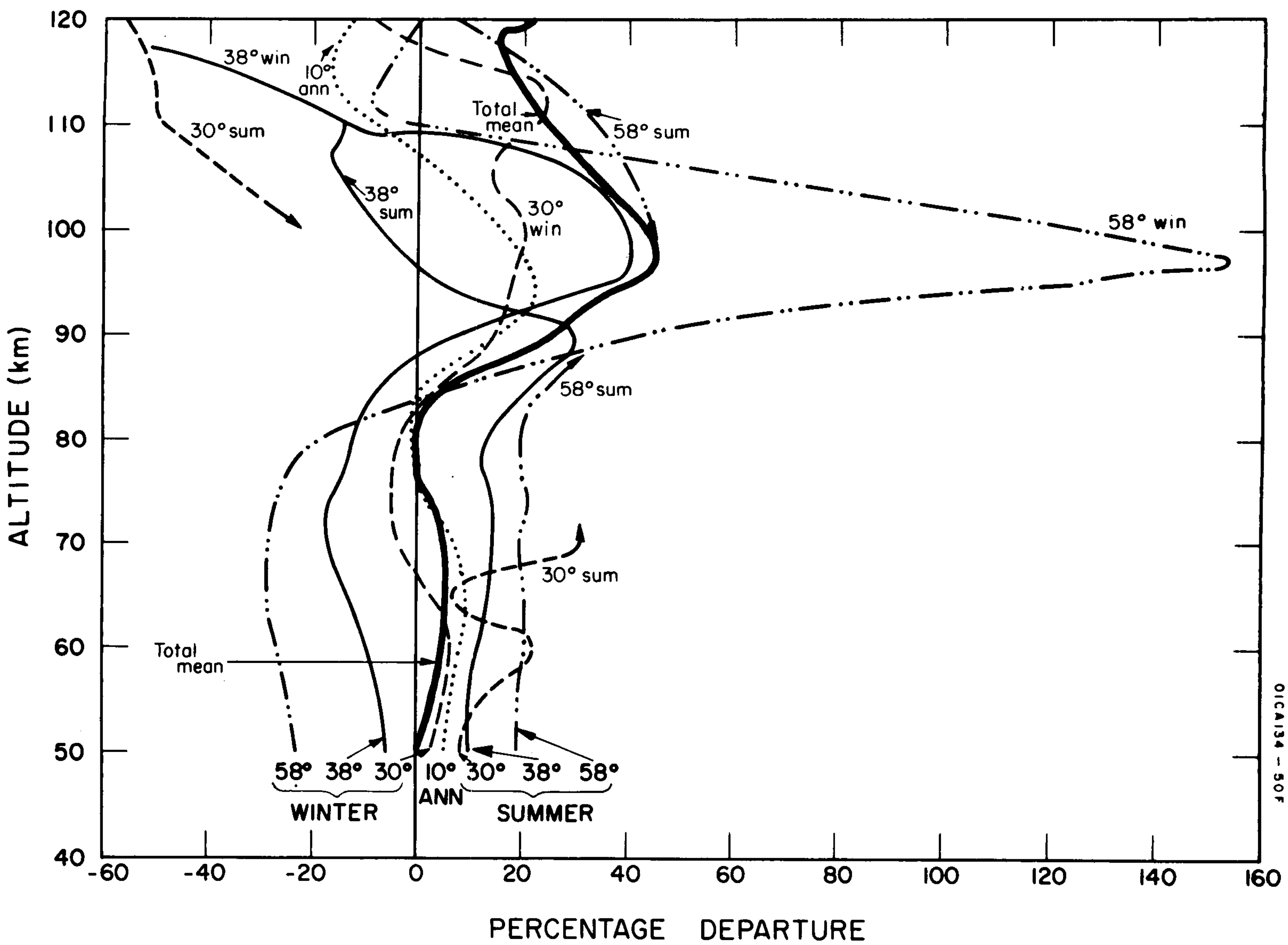

Figure 11. Percentage departure of the density-altitude profile for each of eight season-latitude combinations from that of the 1962 U. S. Standard Atmosphere.

Above 90 km, only two of Champion's models shown in Figure 6; i.e., 15^{o} annual and 45^{o} summer are supported by any of these curves over any extended region. The 45^{o} winter model of Champion is supported by the 38^{o} curve only up to about 92 km when the slopes of the two diverge rapidly. Champion's 30^{o} summer and 30^{o} winter models agree with the corresponding curves of the writer's graph only insofar as they are on the same side of the zero deviation axis. In both cases, the writer's computed curves depart considerably from the Champion estimates, particularly in the case of the 58^{o} winter curve which is about one hundred percent higher than Champion's at 100 km.

The nearly + 40^{o} slope from the horizontal of all curves of Figure 11 between 80 and 90 km indicates that the mean atmosphere is having a rapid percentage increase in density to the standard in this region. At altitudes from 95 km to about 115 km, the slope of all but one of the profiles becomes nearly -40^{o} from the horizontal; it is, thereby, indicated that in this region there is a rapid percentage decrease in the density of the mean atmosphere relative to the standard. These situations have already been apparent from Figure 10, and it is suggested that, at least between 80 km and 115 km, the standard atmosphere is not a good reference of comparison to use in studying seasonal and latitudinal variations. When the percentage departures of the several atmospheres are taken relative to the total mean atmosphere, the composite profile appears as in Figure 12. (The transformation from Figure 11 to Figure 12 was accomplished graphically for this presentation.) The mean slopes of all but one of the profiles between 80 and 90 km are now nearly vertical while above 95 km many of the profiles still appear to be tilted relative to the vertical. Cyclic patterns as may exist above 90 km appear to be more evident in this figure, however, than in Figure 11.

A distinct isopynic region appears to exist at 92 km for three density-departure profiles, i.e. 38^{o} summer, 38^{o} winter, and tropical annual. The density at this point is 20 percent greater than that of the U. S. Standard and 10 percent less than the total mean atmosphere. Above 92 km, the 38^{o} summer and 38^{o} winter profiles depart from each other more or less symmetrically about the tropical annual profile to a maximum separation of about 50 percent of the standard-atmosphere density near 100 km, above which the separation diminishes until the two models intersect again at 110 km. The tropical annual profile is very close to this second intersection point. Above 110 km, the location of the 38^{o} summer profile is unknown. This pattern of crossing and recrossing of the 38^{o} summer and winter profiles is in keeping with the Kantor-Cole estimated 45^{o} density-deviation profile shown in Figure 4 as determined from geostrophic wind considerations. In that case, however, the estimated recrossing occurred at about 123 km instead of at 110 km as indicated by the density data.

Minzner [30] has shown that this recrossing at about 110 km is not without some theoretical justification. It may be shown that above an isothermal layer, the density-altitude profile corresponding to various constant positive and negative temperature gradients follows a pattern shown schematically in Figure 13. When a temperature-altitude profile is such that as altitude is increased an isothermal region changes to one with a small constant positive temperature-altitude gradient at altitude h_b, the density-altitude

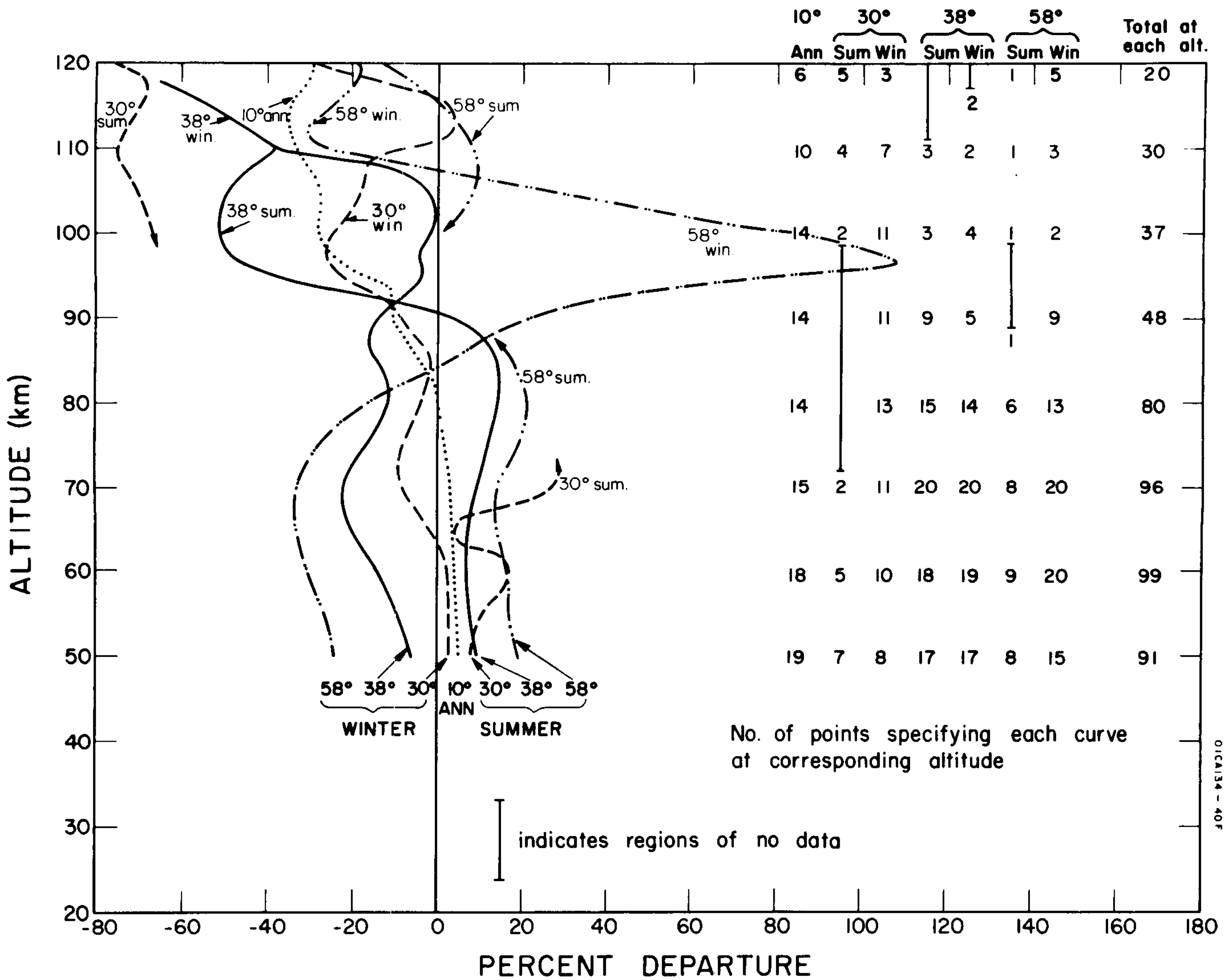

Figure 12. Percentage departure of density-altitude profiles for each of seven seasonal-latitude combinations from the mean density-altitude profile for all seasons and latitudes from the mean of available data.

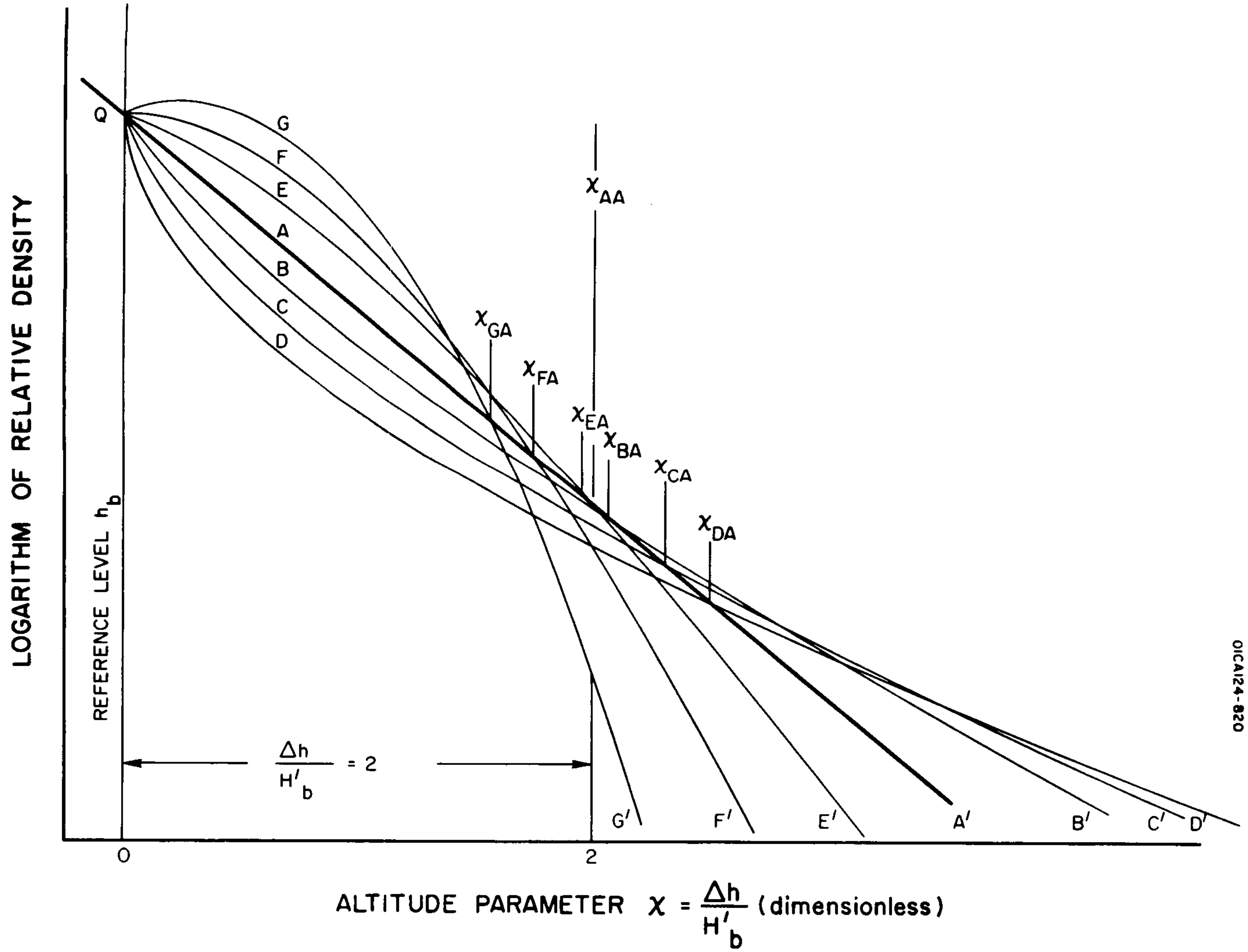

Figure 13. Normalized density altitude profile schematic representation of normalized density-altitude profiles for various constant positive and negative scale-height gradients.

profile, instead of continuing to fall off exponentially, as shown in the straight line A of Figure 13, follows the type of pattern of line B. In this case, curve B leaves line A at h_b and crosses the straight line A again at an altitude interval x_{BA} about the reference level h_b. This interval x_{BA} corresponds to an altitude interval slightly in excess of two scale heights. For successively more positive temperature-altitude gradients, the related density-altitude profiles follow successively the curves C and D, and the related recrossing points occur at successively greater scale-height intervals x_{CA} and x_{DA} above the reference level.

For successively increasing negative temperature-altitude gradients, the density-altitude profiles follow successively curves of the form of E, F, and G, with crossings of the exponential profile occurring at successively smaller scale height intervals x_{EA}, x_{FA}, and x_{GA} where x_{EA} corresponds to an altitude interval less than two scale heights above the reference level.

Minzner has calculated the size of the intervals x as a function of temperature-altitude gradient or as a function of scale-height gradient with results as given in the graph of Figure 14. Here, for realistic temperature-altitude gradients the crossing altitude is seen to be confined to a region between about 1.8 and 2.3 scale heights, as indicated by the heavy portion of the curve. Thus, density-altitude profiles which cross at one point near the top of the isothermal layer will tend to recross at an altitude of about 2 scale heights above the first crossing point. Since the scale height at 90 km altitude is about 5 km, a recrossing of the two 38° density-departure profiles at about 10 km above the top of the isothermal layer is seen to be predicted by this admittedly elementary theory.

From Figure 12, we see that the 58° summer and 58° winter profiles cross at about 87 km with the common density point about 30 percent greater than that of the U.S. Standard. This crossing point is the one which Cole reported in 1961 [34] as the "Second Isopycnic Level," the first occurring at about 11-km altitude. Tracing the 58° winter profile in Figure 12 to altitudes above 100 km one can see a recrossing of the 58° models, making a third isopycnic level at about 107 km. As in the case of the 38° models, the interval between these two successive crossings of the 58° models is also about 2 scale heights. The 58° summer percentage-departure profile is missing between 88 and 99 km in the figure because there is no data for this interval. Similarly there is a lack of data for the much more extended interval from 72 to 98 km in the 30° summer profile.

The second and third isopycnic levels for the 58° latitudes occur for conditions of relative density more than 30 percent greater than the standard atmosphere at the same altitude, or at about 10 percent greater than the total mean atmosphere. This is in contrast to the second and third isopycnic levels of the 38° models which have relative densities of 10 and 30 percent less than that of the total mean atmosphere at the same altitude.

The 30° atmospheres do not appear to follow the same pattern of having a third isopycnic level. If the two segments of the 30° summer profile are connected by some reasonable interpolation, which is realistic, this

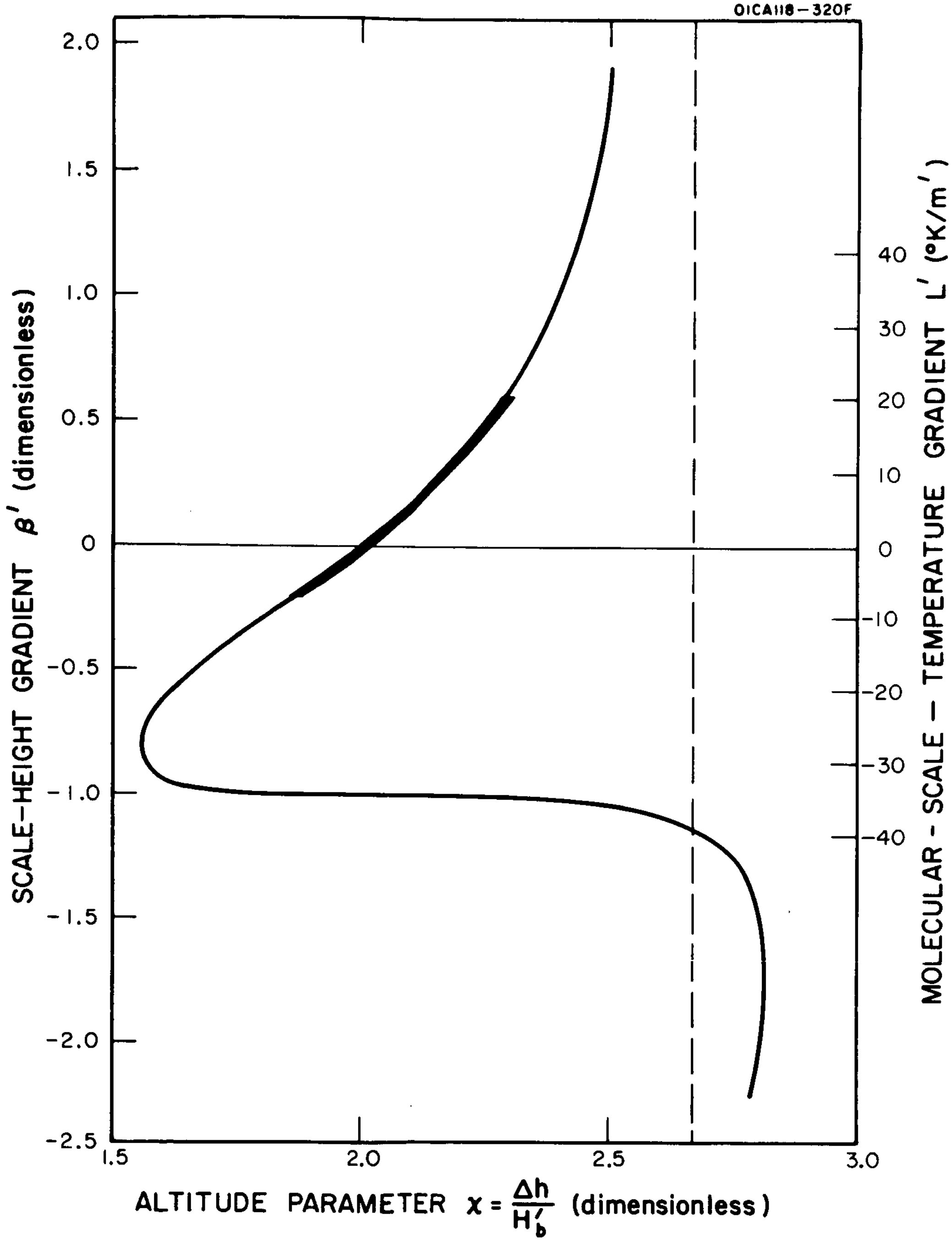

Figure 14. Crossing interval versus scale-height gradient. Value of the altitude interval x between successive crossings of an exponential density altitude profile with those determined by various related constant temperature-altitude gradients.

interpolation segment must cross the 30° winter model, probably near 90-km altitude. The data available to the writer, however, do not suggest a re-crossing of the 30° models at any altitude in the vicinity of 110 km.

Second and third isopycnic levels for 38° and 58° models do seem to be indicated by the limited data, but these do not seem to occur at the density of the total mean atmosphere for the altitudes in question. In other words, the annual mean atmosphere for 58° latitude does not appear to be the same as that for 38° latitude or the same as the total mean atmosphere. It does appear, however, that the 38° annual mean atmosphere would agree closely with the tropical mean atmosphere. Both of these atmospheres above 80 km were determined essentially from data collected between 1961 and 1964. The Churchill model, however, is dominated by data collected between 1957 and 1958, and may be influenced in some way by the high solar activity at that time. Almost no density observations were obtained at other latitudes during this period.

CONCLUSIONS

(1) Model atmospheres have been developed to a point where the variability of the earth's atmosphere is known within reasonable bounds for altitudes from sea level to 1000-km altitudes or more.

(2) The variability is least well known between 90 and 200 km.

(3) The results of the recent study reported herein provides general support to the Cole-Kantor supplementary atmosphere models below 80 km, except for the 58° summer model where the difference appears to be quite extensive. Above 80 km, the Cole-Kantor summer models appear to need revisions.

(4) Figures 11 and 12 demonstrate that neither the simplified transition models based on Minzner's [30] single linear temperature gradients between the Cole-Kantor models and the Jacchia models, nor the more eleaborate transition models suggested by Champion express the reality of observations particularly as they apply to the 58° winter and summer atmospheres, and to the 30° winter atmosphere.

(5) It is suggested that the best solution for supplementary atmospheres at present would be to develop internally consistent systems of pressure, temperature, and density for each latitude such that the densities are in essential agreement with the mean values determined from a more careful study of the type described herein.

(6) There should be a further analysis of available data to try to determine the influence of parameters other than latitude and season; for example, solar activity, and geomagnetic index. The limited number of existing data points particularly above 100 km makes the accuracy of such an analysis questionable however, with a much worse situation existing above 120 km.

(7) More vertical-probe atmospheric density measurements should be made particularly in the altitude region between 90 and 200 km where satellite-drag observations cannot contribute significantly.

(8) Some indirect method such as measuring scattering from a lazer beam in a polar orbiting satellite, where vertical profiles of density over the entire globe may be mapped in a 12-hour period, would be an excellent approach.

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