A Global Reference Atmospheric Model for Surface to Orbital Altitudes

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ABSTRACT

An empirical atmospheric model has been developed which generates values for pressure, density, temperature and winds from surface levels to orbital altitudes. The output parameters consist of components for: 1) latitude, longitude, and altitude dependent monthly means; 2) quasibiennial oscillations; and 3) random perturbations to partially simulate the variability due to synoptic, diurnal, planetary wave and gravity wave variations. The monthly mean models consist of: (i) NASA's four dimensional worldwide model, developed by Environmental Research and Technology, for height, latitude, and longitude dependent monthly means from the surface to 25 km; and (ii) a newly developed latitude-longitude dependent model which is an extension of the Groves latitude dependent model for the region between 25 and 90 km. The Jacchia 1970 model is used above 90 km and is faired with the modified Groves values between 90 and 115 km. Quasi-biennial and random variation perturbations are computed from parameters determined from various empirical studies, and are added to the monthly mean values. This model has been developed as a computer program which can be used to generate altitude profiles of atmospheric variables for any month at any desired location, or to evaluate atmospheric parameters along any simulated trajectory through the atmosphere. Various applications of the model are discussed, and results are presented which show that good simulation of the thermodynamic and circulation characteristics of the atmosphere can be achieved with the model.

1. Introduction

In response to needs for an engineering oriented global reference atmospheric model, a computer model has been developed at Georgia Tech which gives pressure, temperature, density and wind variables and their structure as a function of the three spatial coordinates—latitude, longitude, altitude—and time (monthly, plus statistically consistent perturbations about the monthly mean). The altitude range is from sea level to about 700 km.

The new computer program combines the previously developed Jacchia (1970) model for above 115 km, the four-dimensional (4-D) model of Spiegler and Fowler (1972) for below 25 km, and a newly developed latitude-longitude dependent model, which is an extension of the Groves (1971) model for the region between 30 and 90 km. Between 90 and 115 km a smooth transition between the modified Groves values and the Jacchia values is accomplished by a fairing technique (a combination of Groves and Jacchia values which insures smooth transition from Groves below 90 km to Jacchia above 115 km). Between 25 and 30 km an interpolation scheme is used between the 4-D results and the modified Groves values. Interpolation is also used to fill in between the discrete height, latitude and longitude intervals of data values on the input data tapes. On the 0 to 25 km tapes the resolution is 1 km in height and roughly $5°\times5°$ in latitude and longitude. For the modified Groves section the resolution is 5 km in height, 10° latitude for zonal mean, and 20° latitude by 30° longitude for the modification to the zonal means.

In addition to monthly mean values of pressure, density, temperature and winds, two types of perturbations are evaluated: quasi-biennial and random. The quasi-biennial oscillations in pressure, density, temperature and winds, empirically determined to be represented by an 870-day period sinusoidal variation, have amplitudes and phases which vary with height and latitude. An analytical technique based on a Markov chain process is used to ensure proper horizontal and vertical correlations of the random perturbations.

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2. Description of the model

a. The Jacchia section (above 90 km)

The Jacchia (1970) model for the thermosphere and exosphere was originally implemented to compute atmospheric density at satellite altitudes. The Jacchia model is made up of a set of analytical equations which can be evaluated at any desired height, latitude, longitude and time. The Jacchia model evaluates temperature and density variations due to solar and geomagnetic activity, diurnal and semi-annual variations, and seasonal and latitudinal variations.

b. The 0–25 km section

The 0–25 km atmospheric model, developed by Environmental Research and Technology (Spiegler and Fowler, 1972) was designed to extract from data tapes and interpolate on latitude and longitude, mean monthly and daily variance profiles of pressure, density and temperature at 1 km intervals from the surface to a height of 25 km for any location on the globe. The data tapes contain empirically determined atmospheric parameter profiles at a large array of locations. The Northern Hemisphere grid array is equivalent to the National Meteorological Center (NMC) grid network. Grids spaced at 5° intervals of latitude and longitude are used in the equatorial and Southern Hemisphere regions.

c. The modified Groves section (25–90 km)

The starting point for the middle atmosphere (25–110 km) is the latitude dependent model of Groves (1971). This empirical model combines many observations from a wide range of longitudes. Observational results over approximately six years were used to compute zonal averages (i.e., averages over longitude), which are presented versus latitude and month. Latitude coverage of the Groves model is from the equator to 70° or in some cases 80°. In order to overcome the difficulty of the lack of Groves values at 80° and 90° an interpolation scheme was used which was based on an assumed parabolic variation of the zonal mean values across the poles. Southern Hemisphere data were utilized in developing the Groves model as Northern Hemisphere data with a 6-month change of date. Inter-hemispheric differences are recognized (see, e.g. Labitzke, 1974; Belmont *et al.*, 1975). However, lack of Southern Hemispheric data in the 30–90 km height range forced this assumption to be retained. The 0–25 km height range (where most of the topographic influence will be felt) is handled by separate Northern and Southern Hemisphere data in that section of the program. When the Southern Hemisphere data base in the 30–90 km height range becomes adequate, this atmospheric region can also be treated separately in the atmospheric model program. The Groves model data has only height and latitude variation for each month. Since longitude variation was required, the Groves model data had to be modified to incorporate this additional variation. Unfortunately, the Groves region (25–110 km) is data-sparse, and most of the available data have already been used by Groves in the development of his model. A scheme for using 10, 2 and 0.4 mb map data and extrapolating up to 90 km was devised for purposes of evaluating longitude dependent relative deviations from the Groves data. These deviations, called *stationary perturbations*, were evaluated at longitudes 10°, 40°, 70°, . . . 340° for latitudes 10°, 30°, 50°, 70°, 90°. The stationary perturbations at heights of 30, 40 and 52 km were evaluated from data read from 10, 2 and 0.4 mb upper air charts. Presently these results are averages from the 1966 and 1967 10 mb charts (NOAA, 1969b) and the 1966, 1967 and 1968 2 and 0.4 mb charts (NOAA, 1969a, 1970, 1971). The only other currently available charts [for 1964 and 1965 and more recently for 1972 and 1973 (NASA-SP-3091)] are now being read to improve the modeling of the stationary perturbations. Lack of 2 and 0.4 mb chart data over portions of the eastern hemisphere meant that these charts had to be subjectively extrapolated to fill the data gap. Comparisons of model results with Russian meteor winds at 90 km indicate, however, that no serious error resulted from this procedure. In order to introduce longitude variability at heights above 52 km, the extrapolation technique of Graves *et al.* (1973) was used to project the 52 km interpolated chart data up to 90 km. The five extrapolation height levels are 60, 68, 76, 84 and 90 km. Graves has shown this technique to give reasonable extrapolations to 90 km, and the simulations with the model (presented later in this paper) confirm the validity of the method. The Graves extrapolation method between 52 and 90 km is used in the model only to generate the longitude dependent stationary perturbations about the zonal means, with the zonal means still being taken from the Groves model. The 50–110 km region of the atmosphere is the most data-sparse, especially in the Southern Hemisphere and the eastern half of the Northern Hemisphere. Hence it is this region which can be improved most when the data base improves in this height range.

d. Winds in the model

Conceptually, an independent wind model, such as the east-west wind model of Groves (1971), could be added to the pressure, density and temperature model. However, the approach taken in the model was to compute a mean wind from the geostrophic wind equations (which rely on horizontal pressure gradients). The eastward (i.e., blowing toward the east) wind component u and northward component v can be evaluated from the geostrophic wind equations

$$u = -(1/\rho f)\partial p/\partial y, \tag{1}$$

$$v = (1/\rho f)\partial p/\partial x, \tag{2}$$

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where ρ is the density, f the Coriolis parameter ($2\Omega \sin\phi$), and $\partial p/\partial x$ and $\partial p/\partial y$ are the eastward and northward components of the horizontal pressure gradient. For evaluation in the model, the pressure gradient terms must be approximated by finite differences. Specific models for the random and quasi-biennial components of the wind are also added to the mean wind, as discussed later.

e. The random variations

In addition to the monthly means, two types of perturbation are considered in the model: random variations and quasi-biennial oscillations, discussed in the following section. The random variations are considered to have a Gaussian distribution about the monthly mean with a standard deviation σ determined from empirically observed atmospheric variability. Tables of the random pressure, density, temperature and wind components are input to the program from a data tape.

In the altitude range below 25 km the random σ's are taken directly from the data tapes as the square root of the tabulated variance values. For the region above 25 km, random σ's were evaluated (Justus and Woodrum, 1975) from Meteorological Rocket Network (MRN) and NASA grenade and pitot tube data summaries (Theon *et al.*, 1972), which covered 25 to 90 km. Above 90 km random σ's were estimated from previous study results (Justus and Woodrum, 1973) on atmospheric variation statistics. The random perturbation magnitudes in the thermodynamic variables were adjusted to make them consistent with constraints required by the perfect gas law (Buell, 1970) and the hydrostatic equation (Buell, 1972b). Vertical correlation scales for the random perturbations were evaluated (Justus and Woodrum, 1975) by Buell's (1972b) depth-of-pressure-systems equation and from vertical structure function analysis (cf. Justus and Woodrum, 1973). Use of the Buell depth-of-pressure-systems vertical scale for the random perturbations implies that profiles of pressure and density generated by the random perturbation model will have realistic vertical compensation, e.g., positive perturbations at some heights, negative at others. Horizontal correlation scales were evaluated from results of Buell (1972a) at the 500 mb (6 km) level, and from horizontal structure function analysis in the 25–130 km height range (Justus and Woodrum, 1973).

f. The correlated random perturbation model

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

The random perturbation model used is an extension of one originally developed for simulation of turbulence (Justus, 1971; Justus and Hicks, 1971). The perturbations generated by the model are not only correlated with each other over successive times, but also a time series of such perturbations can be Fourier transformed and has a spectrum which agrees with that expected from the correlation function which describes the correlation between successive positions.

g. Quasi-biennial variations

In addition to the maximum near 25 km in the tropics, it was shown from periodogram analysis by Justus and Woodrum (1973) that quasi-biennial oscillations of the wind, pressure, density and temperature were significant in the height range 45–60 km. In many instances the amplitudes of the quasi-biennial oscillations were comparable to the annual and semiannual oscillations (e.g., near 45 km at low latitudes). Other publications have indicated the same (e.g. Belmont and Dartt, 1973; Cole, 1967; Rahmatullah, 1968). Consequently, in modeling the winds and thermodynamic variables of the atmosphere, the quasi-biennial oscillations should definitely be considered.

In the present work, the amplitudes and phases of the quasi-biennial oscillations were found by first performing harmonic analyses on MRN data from three sites. These results were combined with the previous results of Cole (1967), Rahmatullah (1968), Groves (1973), Shah and Godson (1966), Reed (1965) and Angell and Korshover (1962, 1963, 1964, 1965), and interpolated values of the quasi-biennial parameters were evaluated at the necessary latitudes throughout the height range 15 to 90 km. It was assumed in the above analysis that the quasi-biennial variations have no longitude dependence and are symmetric about the equator.

3. Sample results

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

Fig. 1 shows a ground plot of a "Mission 3" re-entry and return trajectory. Mission 3 has a 104° orbital inclination with launch from and return to Vandenburg AFB. The height and time along the trajectory ground plot are also shown in Fig. 1. Fig. 2 shows computed density, in percent deviation from the U. S. Standard Atmosphere, for a typical January run to simulate conditions along the return trajectory of Mission 3. The solid line and shaded area in Fig. 2 show the

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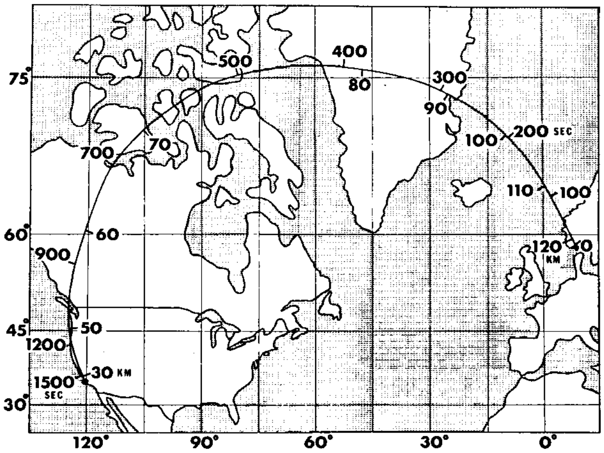

FIG. 1. Ground plot of the re-entry and return trajectory for Mission 3, a 104° inclination polar orbit launched from and returning to Vandenburg AFB. The altitude (km) is plotted on the inner side of the orbital plot and the time (s), measured from time of de-orbit, on the outer side.

monthly mean and ± 2 standard deviations of the random density perturbations. The data points with error bars at 80 km height show observed mean and ± 2 standard deviations at 80 km above Point Barrow, Alaska (Theon *et al.*, 1972), which is located at 71°N, 157°W some 5° south and 109° west of the 80 km height point on the trajectory. This polar orbit trajectory is the situation for which the model is most valuable, because of the large variations from nominal (1962 U. S. Standard) values which can be encountered.

Figs. 3–6 illustrate example applications of the model program and show the accuracy with which it is capable of reproducing actual atmospheric processes. Figs. 3a and 3b show quasi-meridional temperature cross sec-

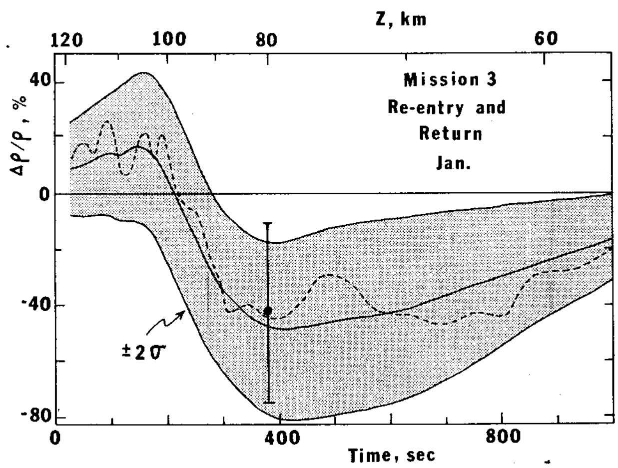

FIG. 2. Density along a January Mission 3 rentry and return trajectory. Density deviations are with respect to the 1962 U. S. Standard Atmosphere. The solid line and shaded area shows the January monthly mean and ± 2 standard deviations of the random density perturbation. The dashed line shows a typical density profile of mean plus random component.

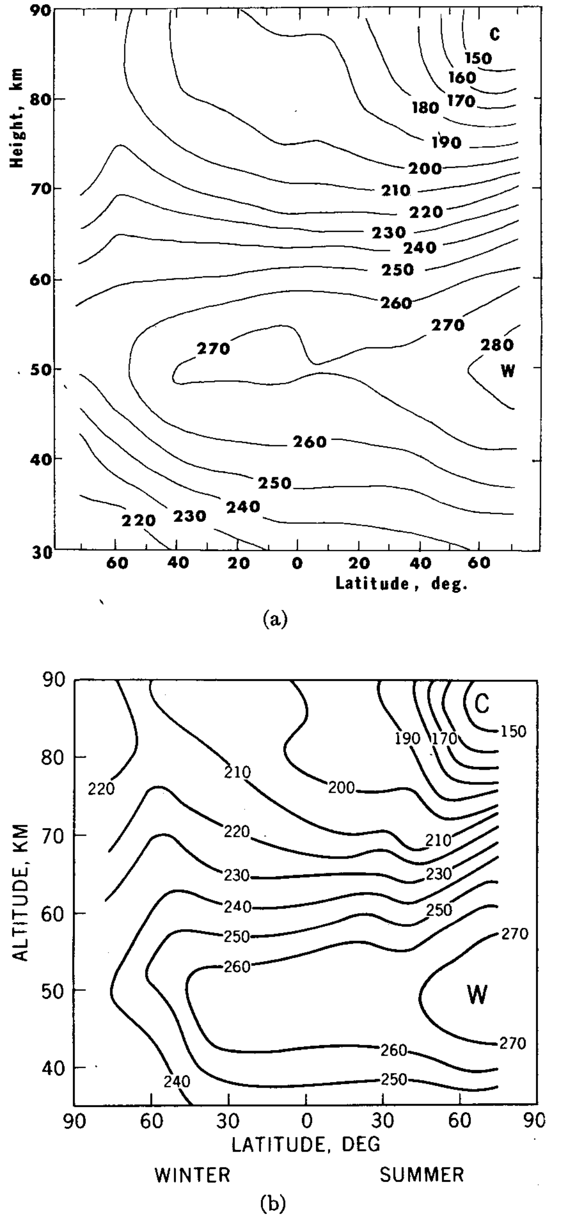

FIG. 3. Quasi-meridional cross section of temperature (K) for mean winter conditions at Point Barrow, Fort Churchill, Wallops Island, and Natal-Ascension: (a) computed by the model, and (b) observed by Theon *et al.* (1972).

tions through Point Barrow (71°N, 157°W), Fort Churchill (59°N, 94°W), Wallops Island (38°N, 75°W), and Natal-Ascension (6°S, 35°W and 8°S, 14°W). Fig. 3a was evaluated by the model from January and July runs for these four locations. Fig. 3b was evaluated by Theon *et al.*, (1972) from average summer and winter grenade and pitot tube data. Fig. 4 shows time cross sections of monthly mean temperature (°K) for Wallops Island (38°N). Fig. 4a was computed from 12 monthly vertical profiles evaluated by the atmospheric model program, and Fig. 4b was constructed by Theon *et al.*

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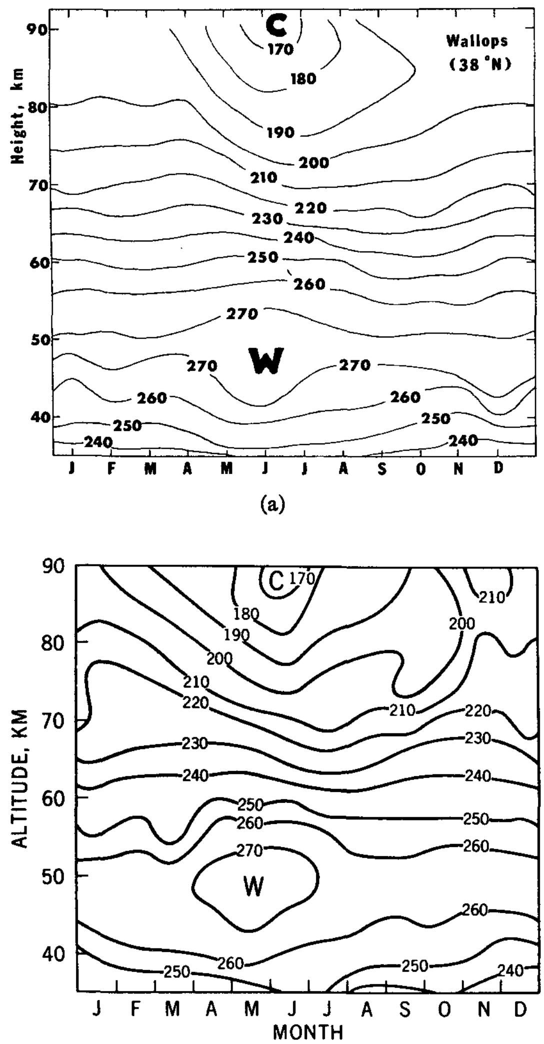
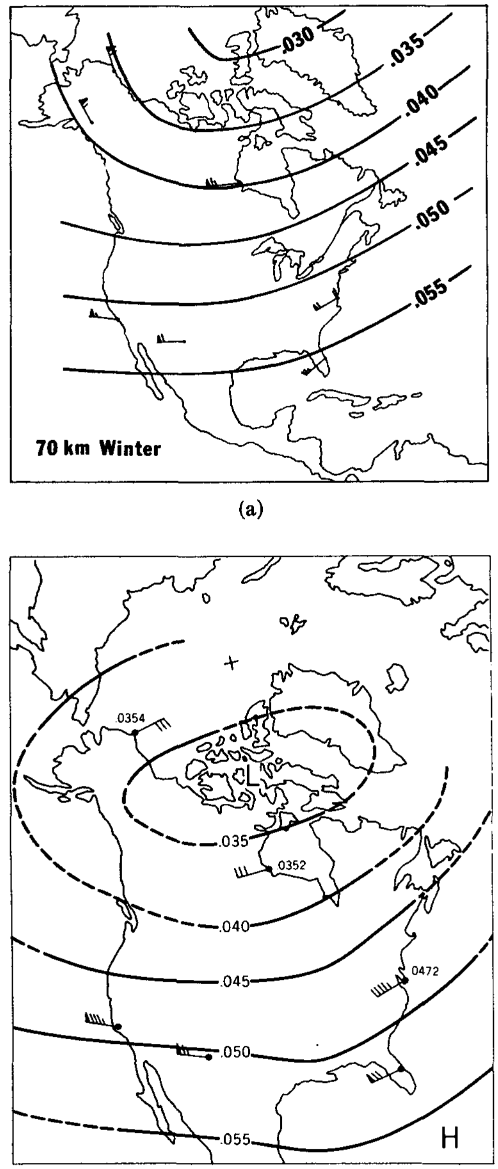
(1972) from monthly mean profiles based on 93 rocket grenade soundings. Fig. 5 shows the average winter (December, January, February) circulation at 70 km. Fig. 5a was evaluated by averaging model calculated monthly means of pressure and winds, for the three winter months, and Fig. 5b was constructed by Theon *et al.* (1972) from 70 km observed winds and pressures at the locations indicated, and calculation of isobar orientation and spacing by the geostrophic wind equation. The good correspondence between Figs. 4a and 4b and between Figs. 5a and 5b indicates that no serious errors were introduced by the use of the Groves extrapolation of stationary perturbations in the 52–90 km height region. Fig. 6 shows similar winter circulation maps for 90 km in the eastern hemisphere. Fig. 6a was evaluated from the global reference atmospheric model, and Fig. 6b represents average observed winds at 90 km by the meteor wind method (Lysenko *et al.*, 1969). The nine lettered dots in Fig. 6b are meteor observation sites and arrows from these dots represent direction and speed of the diurnally and monthly averaged wind (scale of arrows not given by Lysenko). Arrows from non-lettered dots are hypothetical circulation patterns proposed by Lysenko for the period of observation (December 1965–January 1966). The comparisons in Figs. 3–6 indicate that the agreement between observed and model-computed atmospheric height, latitudinal, longitudinal and seasonal



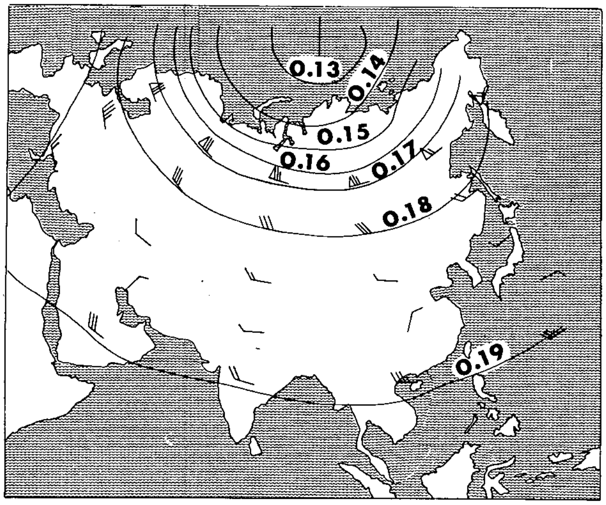
(a) (b)

FIG. 4. Time cross section of monthly mean temperature (K) for Wallops Island (38°N) constructed from 12 monthly profiles: (a) evaluated by the model, and (b) observed by Theon *et al.* (1972).

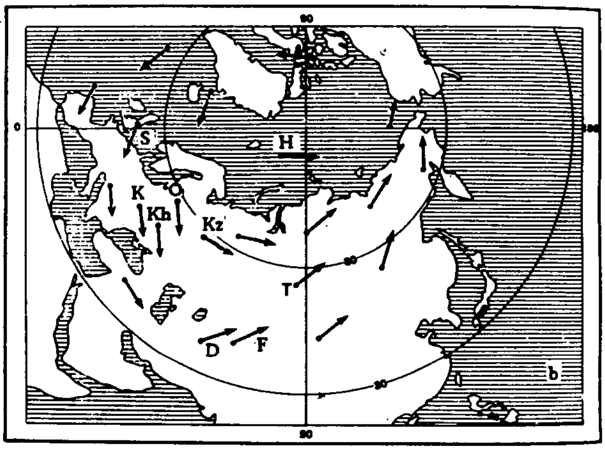


(a) (b)

FIG. 5. Mean winter circulation at 70 km showing isobars (mb) and winds (m s^{-1}): (a) for the model [3-month (December, January, February) average] and (b) observed by Theon *et al.* (1972).



(a)



(b)

FIG. 6. Mean winter circulation showing isobars (N m^{-2}) at 90 km over Eurasia and the Arctic (a) as evaluated by the model, and (b) observed by Lysenko *et al.* (1969) from meteor wind measurements.

variations are quite good. The good correspondence between Figs. 6a and 6b indicates that no serious errors were introduced by the subjective extrapolations used to fill in the data gaps between 50 and 90 km above Eurasia.

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