Mars Global Reference Atmospheric Model for Mission Planning and Analysis

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An engineering model atmosphere for Mars has been developed with many of the same features and capabilities of the highly successful Global Reference Atmospheric Model (GRAM) program for Earth's atmosphere, including mean values for density, temperature, pressure, and wind components, and density perturbation magnitudes and random perturbation profiles for density variations along specified trajectories. This paper outlines the observational and modeling basis behind the development of the Mars-GRAM program, provides a general description of the operations of the Mars-GRAM program (available in FORTRAN-77 on IBM-PC compatible 360k diskettes), and presents some example applications for the Mars-GRAM model.

Nomenclature

F_{abs} = daily total, absorbed solar irradiance in the Mars-atmosphere system, Wm^{-2}
F_{exo} = exoatmospheric, daily total, solar irradiance at the position of Mars, Wm^{-2}
L_s = areocentric longitude of the position of Mars in its orbit about the sun, degrees
L_{s0} = value of L_s at the initiation of a global dust storm, degrees
P = correction term, for the polar night region, in temperature parameterizations, K
T_{avg} = daily average, near-surface, atmospheric temperature, K
T_{min} = daily minimum, near-surface, atmospheric temperature, K
T_{max} = daily maximum, near-surface, atmospheric temperature, K
α = planetary albedo for Mars, dimensionless

Introduction

A HIGHLY successful and well-utilized engineering model for the Earth's atmosphere, the Global Reference Atmospheric Model (GRAM), has been previously developed[1,2] and has undergone several improvement cycles.[3,4] GRAM applications include orbital mechanics and lifetime studies, vehicle design and performance criteria, attitude control analysis problems, analysis of effects of short-term density variation from geomagnetic storms, and aerobraking analyses (for missions requiring return from geosynchronous orbit to space-station rendezvous).

In addition to evaluating the mean density, temperature, pressure, and wind components at any height, latitude, longitude, and monthly period, GRAM also allows for the simulation of "random perturbation" profiles about the mean conditions. This feature permits the simulation of a large number of density profiles along a given trajectory through the atmosphere. With each profile generated from a different random number seed, each profile will be different in detail but consistent with the statistics appropriate for the given trajectory. Thus, the set of profiles so produced will have values which are more than 2 standard deviations above or below the mean value approximately 5% of the time (or with +3 standard deviations exceeded about 0.1% of the time).

With the planning activity for upcoming and proposed unmanned missions to Mars (e.g., Mars Observer, Mars Aeronomy Observer, Mars Rover, and Sample Return) as precursors to a possible future manned mission, interest has developed in having a similar type of engineering-oriented atmospheric model as GRAM for the atmosphere of Mars. This report discusses the development of such a new model, the Mars Global Reference Atmospheric Model (Mars-GRAM). The Mars-GRAM program has been developed primarily for use as a reference model atmosphere in a variety of engineering applications. Initial interest seems to be focused on analysis and planning for aerobraking or aerocapture maneuvers within the atmosphere of Mars (which requires knowledge of Martian atmospheric density to altitudes as low as 20 km). Mars-GRAM has also been employed recently for planning multisatellite, orbiter operations at Mars.[5] Another recent application is the generation of synthetic temperature profiles to be used in designing future Mars atmospheric sounder sensors and retrieval algorithms.[52] Other planned or potential applications for Mars-GRAM include design studies for Mars Lander/Rover systems and trajectory and thermal loads analyses for balloon measurement systems, such as those being considered on the Soviet Mars 1994 mission.

In the lower atmosphere of Mars (up to 75 km), the Mars-GRAM model is built around parameterizations of height, latitudinal, longitudinal, and seasonal variations of temperature determined from a survey of published measurements from the Mariner and Viking programs. Pressure and density are inferred from the temperature by making use of the hydrostatic and perfect gas law relationships. For the upper atmosphere (above about 120 km), the thermospheric model of Stewart[6] is used. A hydrostatic interpolation routine is used to insure a smooth transition from the lower portion of the model to the Stewart thermospheric model. Mars-GRAM includes parameterizations to simulate the effects of seasonal variation, diurnal variation, dust storm effects, effects due to the orbital position of Mars, effects of the large seasonal variation in surface atmospheric pressure because of differential condensation/sublimation of the CO_2 atmosphere in the polar caps, and effects of Martian atmospheric mountain wave perturbations on the magnitude of the expected density perturbations. The thermospheric model includes a parameterization for the effects of solar activity, measured by the 10.7-cm solar radio flux. Winds are computed by an areostrophic (thermal wind) approximation, with the inclusion of the effects of molecular viscosity, which, because of the low atmospheric densities, can

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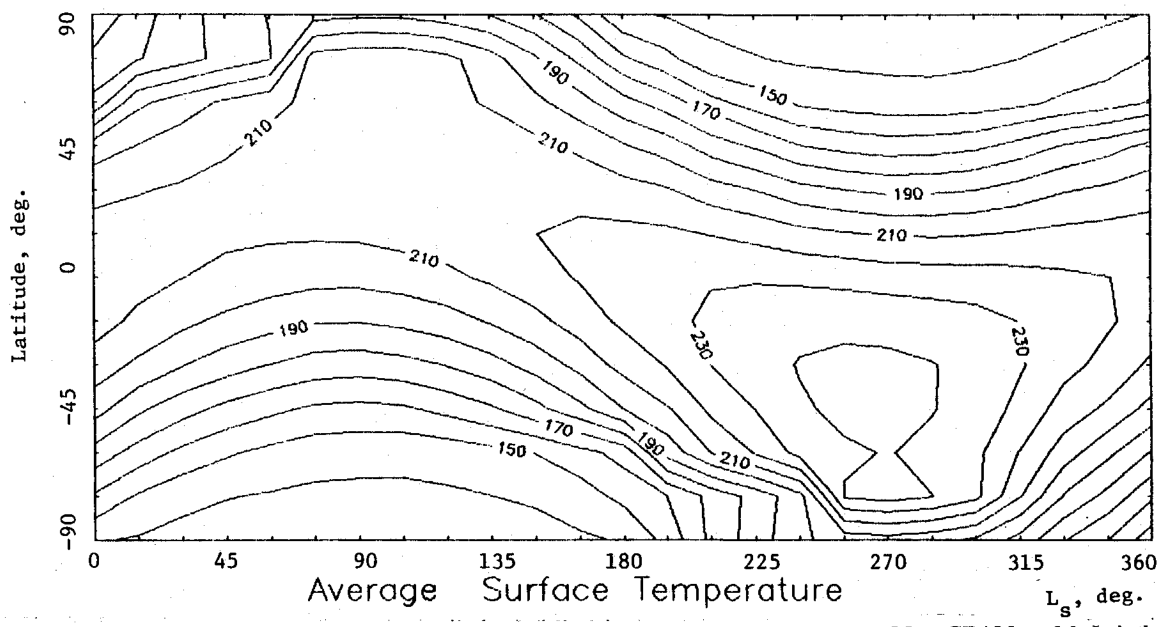

Fig. 1 Seasonal and latitudinal variation of daily average, near-surface, air temperature, computed by the Mars-GRAM model; L_s is the areocentric longitude of the sun.

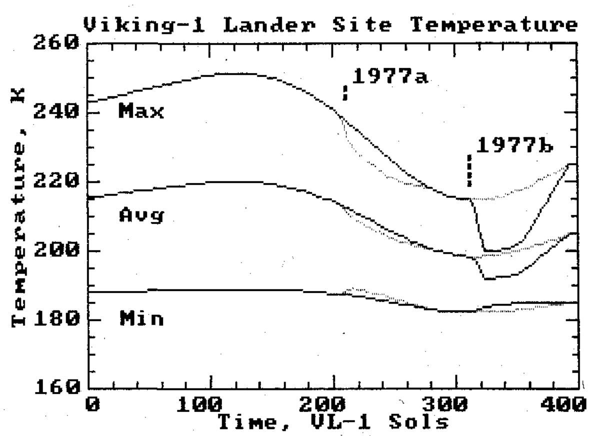

Fig. 2a Seasonal variation of the daily maximum, mean, and minimum, near-surface, air temperature at the Viking Lander 1 site computed by Mars-GRAM.

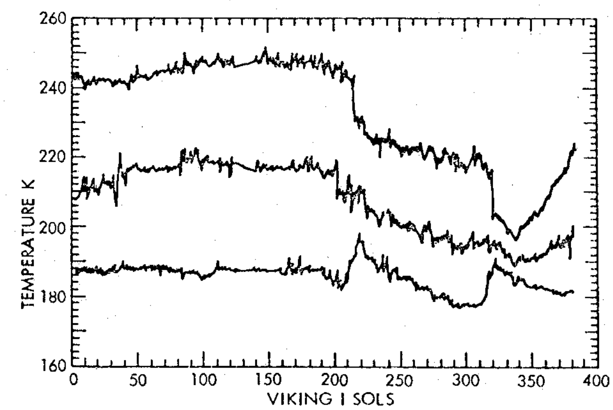

Fig. 2b Seasonal variation of the daily maximum, mean, and minimum, near-surface, air temperature at the Viking Lander 1 site as reported by Ryan and Henry.[17]

be very important at high altitudes. The mountain wave perturbation model also includes a new damping approximation due to the effects of molecular viscosity. A complete description of the mountain wave perturbation model is given by Justus and Chimonas.[7] Plans are under way to add additional perturbations by the use of the Zurek wave perturbation model.[8]

Mars Global Reference Atmospheric Model

Mars-GRAM is based on parameterizations to approximate, as realistically as possible, the temperature, pressure, density, and winds of the Martian atmosphere and their latitudinal, longitudinal, diurnal, seasonal, and altitude variation from the surface through thermospheric altitudes. Parameterizations are also included for the effects of global-scale dust storms on the variations of the thermodynamic and wind properties of the Martian atmosphere. Recently, Kaplan, compiler of the definitive report "Environment of Mars, 1988,"[9] has decided to propose Mars-GRAM as the reference model atmosphere for use by engineers on upcoming equipment design contracts for NASA's Mars Rover and Sample Return Mission.[53]

The near-surface air temperature on Mars is parameterized in the Mars-GRAM program by computing an approximate value for the geographically and seasonally dependent daily total absorbed radiation flux, F_{abs}. The daily average, maximum and minimum near-surface air temperatures are then calculated from a simple regression relationship assumed between the daily absorbed flux and the temperature parameters. The absorbed flux estimates include the variations in insolation due to the orbital position of Mars, the latitudinal variation of surface albedo,[10] and seasonally dependent parameterizations for the polar caps[11-15] and polar hood clouds.[16] The absorbed solar flux is computed by

$$F_{abs} = (1 - \alpha) F_{exo} \tag{1}$$

The regression relations for daily minimum, daily maximum, and daily average, near-surface, atmospheric temperature T_{min}, T_{max}, and T_{avg}, respectively, are given by

$$\begin{aligned} T_{min} &= 139 + 0.596 F_{abs} - 0.00176 F_{abs}^2 - 8P \\ T_{max} &= 143 + 0.601 F_{abs} + 0.00078 F_{abs}^2 - 9P \\ T_{avg} &= (T_{min} + T_{max})/2 \end{aligned} \tag{2}$$

where P is a latitude-dependent correction term, applicable only in the polar night region. The regression coefficients for Eq. (2) were derived from the observed variations of near-sur-

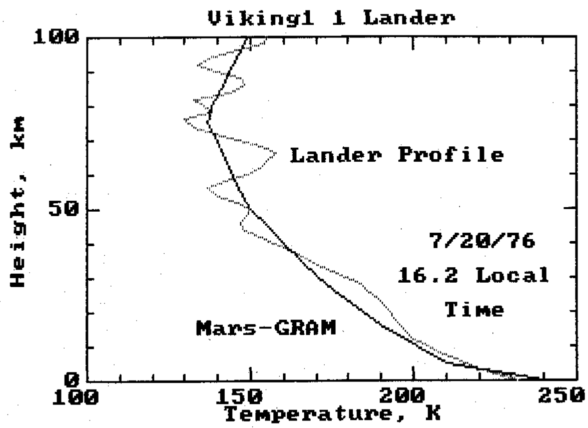

Fig. 3 Vertical temperature profile simulated by Mars-GRAM for date, time, and position of Viking 1 Lander site (solid line) and measured Viking 1 Lander profile (dotted line).

face temperature at the Viking-1 and Viking-2 lander sites[17]; the polar adjustment factors were derived from data presented by Kieffer.[18]

The resultant, seasonally and latitudinally dependent, daily average temperature T_{avg} from the regression relations Eq. (2), is shown in Fig. 1. The average as well as the corresponding maximum and minimum values agree well with the surface temperature maps of Kieffer,[19] with more realistic variations in the polar regions, as suggested by the observations of Ref. 18 (the source of data for the polar correction factor P). Seasonal variations of the daily maximum, minimum, and average temperature at the latitude of the Viking 1 lander, as evaluated by Mars-GRAM, is shown in Fig. 2a. This plot agrees nicely with the Viking 1 observational data reported by Ref. 17, shown for comparison in Fig. 2b. The agreement evidenced between Figs. 2a and 2b is to be expected, since the temperature regressions were based primarily on these Viking data. The agreement with the surface temperature maps of Kieffer (not shown here) illustrates that these temperature regressions are more generally applicable than just for the Viking lander sites.

Parameterizations for the seasonal, latitudinal, diurnal and dust-storm influence on surface pressure were taken from data of Hess et al.[20-26] Model information on the latitudinal variations of surface pressure was incorporated from Haberle et al.[27] The Mars-GRAM simulations for daily average surface pressure vs time at the Viking 1 and Viking 2 Lander sites compare favorably with observations of Refs. 22 and 26. Parameterizations for the seasonal, latitudinal, and diurnal variation of pressure on the reference ellipsoid level were developed from the Viking 1 and Viking 2 data and the model of Ref. 27. Pressures are adjusted from the values on the reference ellipsoid to values at the local terrain height by integration of the hypsometric equation.[28] The effects of dust storms on daily mean pressure and on the amplitude of the diurnal variation in pressure are included in the parameterizations.

Mars-GRAM parameterizations for the geographical, seasonal, and altitude dependence of nondust storm, daily average temperatures above the surface come from a combination of observational and model values. The observational data include Mariner 9 Infrared Spectroscopy Experiment (IRIS) data,[29] and Conrath data as reported by Leovy[30] and Magalhaes,[31] Viking Infrared Thermal Mapper (IRTM) data,[32] Mariner 9 radio occultation data,[33] and Viking 1 radio occultation data.[34-36] Model output used include results from Pollack.[37,27,8] Profiles for daily average temperature are computed in Mars-GRAM from seasonally and latitude-dependent parameterizations for temperature lapse rate in five height intervals: 0–5, 5–15, 15–30, 30–50, and 50–75 km. The vast bulk of the observational data for these parameterizations comes in the lowest three height intervals. The parameterized lapse rate values are adjusted slightly in order to insure agreement between the Mars-GRAM temperature at 25-km height with the observed latitudinal and seasonal variation of 25-km temperature, as given by Fig. 14 of Ref. 30.

The parameterizations in Mars-GRAM for temperature variations during dust-storm conditions were taken from observational data of Kliore et al.,[38] Jakosky and Martin,[39] Hanel et al.,[40] Conrath,[41] and Ref. 32. Model values for dust-storm effects were taken from Refs. 27 and 8.

Data for the Mars-GRAM parameterizations of the height variation of the diurnal (longitudinal) variations of temperature about the daily mean value were taken from Viking IRTM

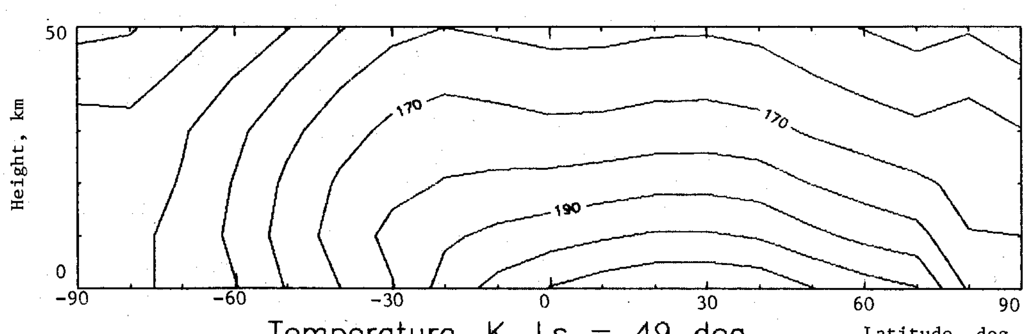

Fig. 4a Cross section of temperature (K) at 9 a.m. local time for L_s = 49 deg.

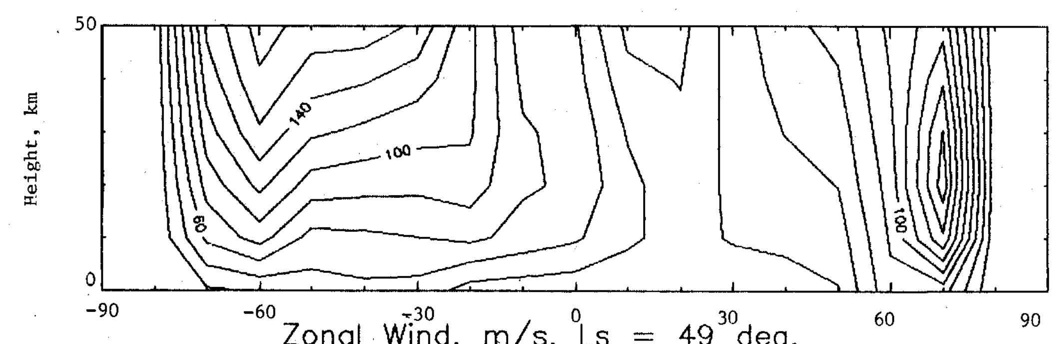

Fig. 4b Cross section of zonal wind (m/s) at 9 a.m. local time for L_s = 49 deg.

observations of Ref. 32, Mariner 9 IRIS data of Ref. 40, and model results from Zurek, as reported in Ref. 8. Diurnal temperature variations are significantly larger during dust storm periods than during nondust storm conditions.

An example of the altitude dependence of temperature during nondust storm conditions is provided by Fig. 3, which compares Mars-GRAM simulations for the date, time, and location of the Viking 1 Lander site with temperature observations from the Viking Lander 1 entry profile.[42]

In Figs. 4 and 5, the model height-latitude cross sections of temperature and zonal wind are compared for Mars-GRAM simulation results for $L_s = 49$ deg (mid-spring season) and for Mariner 9 results from $L_s = 43$–54 deg (Ref. 30, from data provided by Conrath). Winds in the shaded area of Fig. 5 have negative values (i.e., from the east), but the near-equatorial boundary for this zone of easterlies is uncertain. The magnitude and location of the jet in the southern hemisphere is fairly well simulated by the Mars-GRAM results. The strong jet near 25 km and 70°N, shown in the Mars-GRAM results of Fig. 4b, is not consistent with the Conrath observations, however. Although this disagreement may indicate a problem with the Mars-GRAM temperature parameterizations near this latitude and time of year, there are no direct wind observations with which to compare.

Both the Mars-GRAM winds and those (as depicted in Fig. 5) derived from the Mariner temperature profiles are based on the thermal wind relations. The thermal wind relations imply that the vertical gradient in the zonal wind, across a given altitude layer, is proportional to the meridional gradient in layer-average temperature. The meridional gradient of near-surface air temperature is rightfully expected to be large at this latitude and time of year, which corresponds to the position of the retreating polar cap edge (see Fig. 1). Therefore, the problem, if any, with the Mars-GRAM wind values near 25 km and latitude 70°N in Fig. 4b, must be in the meridional gradient of the temperature lapse rates. From the Viking radio occultation observations, Ref. 35 reports strong, surface-based temperature inversions near the retreating polar cap edge.

These inversions could have the effect of lessening the gradient in the layer-mean temperature. However, the presence of these inversions in springtime, at high northern latitudes, is not confirmed by the radio occultation data obtained during the Mariner extended mission period.[33] In his Fig. 10, Ref. 31, Magalhaes reports strong meridional gradients in 0–15 km layer-mean temperature at both high northern and high southern latitudes. These observations (which came from Mariner 9 data of Conrath) would be consistent with both northern and southern hemisphere jets earlier in the Martian year (L_s = 346 deg). The Magalhaes figure shows no indications, however, of any surface-based temperature inversions at either the advancing (southern hemisphere) or retreating (northern hemisphere) polar cap edge. Therefore, a complete resolution of

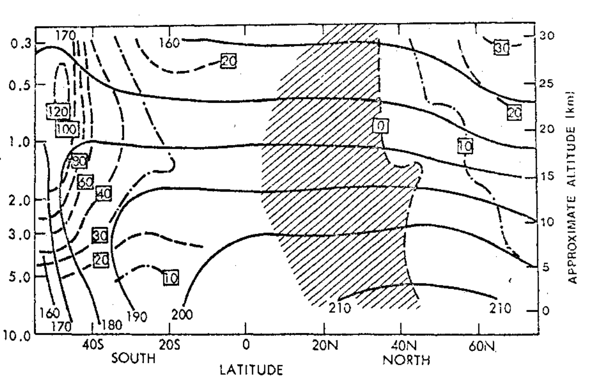

Fig. 5 Cross section of zonally averaged temperature (K) and areostrophic zonal wind (m s^{-1}) based on Mariner 9 IRIS data between L_2 = 43 and L_s = 54 (approximately early May in analogous terrestrial season), Leovy.[30]

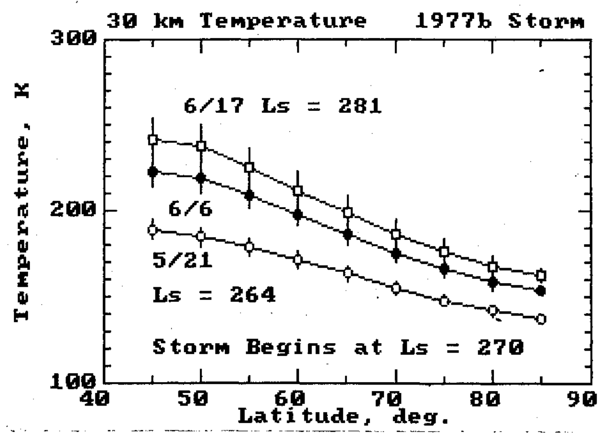

Fig. 6 Progression of simulated dust-storm effect on daily average, maximum, and minimum temperature near 30 km, vs latitude and L_s value (degrees) for the 1977b storm.

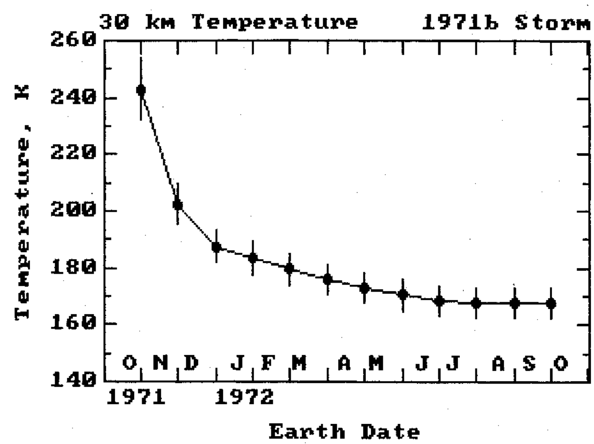

Fig. 7 Progression of simulated dust-storm effect on daily average, maximum and minimum temperature at 30 km altitude and latitude 25°S, vs time for the 1971b storm.

the question of the reliability of Mars-GRAM winds, such as in Fig. 4b, must await new data from future Mars missions or analysis of additional Viking and/or Mariner data not yet employed. An effort is currently under way to build a more complete, computer-readable data set of radio occultation results.[54] The potential for obtaining additional data, not yet used in the development of Mars-GRAM, from the Planetary Data System,[43] is also being considered.

Examples of the Mars-GRAM capabilities to simulate the spatial and temporal variation of global dust-storm effects on temperature are provided by Figs. 6 and 7. These figures show both daily average, 30-km temperature, and the range of diurnal variation in temperature during the development (Fig. 6) and decay (Fig. 7) of global dust storms. The buildup of all dust storms is assumed to be linear with L_s angle, from zero at L_{s0}, the L_s value for which the storm starts, to full magnitude at L_{s0} + 6 deg. The storm is assumed to remain at full magnitude between L_{s0} + 6 deg and L_{s0} + 24 deg, then to decay linearly with L_s, back to zero at L_{s0} + 48 deg. The full magnitude of the dust storms can be selected from an arbitrary intensity scale ranging up to a maximum value of 3.0. Figure 6, similar in format to Fig. 5 of Ref. 32, shows the simulated development of dust-storm effects on temperature at 30-km altitude for a simulation of the 1977b global dust storm, which was observed by the Viking IRTM. The simulations in Fig. 6 were based on an assumed intensity of 3.0. Comparison with the data of Martin et al. indicates that better correspondence would be achieved by attributing an intensity of about 2 to the 1977b storm. Figure 7, similar in format to Fig. 1 of Ref. 41, is for a simulation of the decay of the 1971b global dust storm, which was observed by Mariner 9. The simulation in Fig. 7 also assumed an intensity of 3.0, although the model would compare better with the 1971b storm observations if an intensity of about 2 were assumed. The 1977b global dust storm produced a visible optical depth of about 3 at the Viking-1 lander site.[10] If an intensity value of 2 is assumed to best represent this storm, then the (arbitrary) Mars-GRAM intensity scale may be taken as approximately equal to 2/3 the visible optical depth produced by the storm.

The newly developed parameterizations for Mars-GRAM provide a simulation capability to altitudes reaching the base of the thermosphere. For simulations of the seasonal, geographical, and solar-activity dependence of thermospheric conditions, the Mars-GRAM uses an adaptation of the thermospheric model of Stewart[44–46] (see also Ref. 6 and the revised Stewart program code given in Ref. 8).

The Stewart model thermosphere incorporates results from a number of data and model sources, e.g., the Mars Reference Atmosphere,[47] occultation data and mass spectrometer data from Mariner and from Viking orbiters,[48–51] Ref. 34, Ref. 38, and data from the Viking lander atmospheric entry trajectories.[42] The model includes parameterizations to simulate the effects of solar activity, seasonal variation, diurnal variation magnitude, dust storm effects, and effects due to the orbital position of Mars.

Conclusions

The Mars-GRAM has numerous applications as a "poor man's global circulation model." That is, it can produce some (but not all) of the kinds of output usually produced by a global circulation model, but with considerably less manpower and computer resources required. For example, the computation of all of the data necessary to describe the complete seasonal variations at the surface and all altitudes takes at most a few minutes on an IBM Personal Computer (with 8087 coprocessor and can be accomplished even faster on more recent vintage personal computers). Comparable data would take many hours of computation on a mainframe using a three-dimensional global circulation model for Mars. The diurnal (longitudinal) variability incorporated into the Mars-GRAM program is not even available in a two-dimensional version of a Mars global circulation model.

In addition to the engineering applications envisioned for Mars-GRAM (e.g., aerocapture mission profile studies, Mars Rover Sample Return mission planning and design, etc.), the Mars-GRAM has a number of potential scientific applications. One of these is its ability to provide realistic, geographically, and seasonally dependent fields of temperature and density for atmospheric chemistry studies, and background (mean) temperature and wind fields for studies of the atmospheric propagation of tides and other wave disturbances (e.g., gravity waves, mountain lee waves, etc.). Another application would be in providing realistic "first guess" profiles for the inversion processing for temperature retrievals from temperature sounders on upcoming Mars missions.

Of course, being a parameterization model, rather than a first principles one such as a global circulation model, Mars-GRAM is only as good as the parameterizations built into it. Also, Mars-GRAM would not be reliable for testing the sensitivity to variation of parameter values beyond those on which the parameterizations are based (e.g., it cannot estimate reliably the effects which might be produced by a dust storm of twice the optical depth previously observed). However, with continued analysis of additional observational data from the Viking and Mariner programs, analysis of new results from global circulation models, and analysis with new data expected to be coming in from the Mars Observer program, Mars-GRAM should steadily improve in its realism and reliability in the future.

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