P2.4 EARTH GLOBAL REFERENCE ATMOSPHERIC MODEL 2007 (EARTH-GRAM07) APPLICATIONS FOR THE NASA CONSTELLATION PROGRAM

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Engineering models of the atmosphere are used extensively by the aerospace community for design issues related to vehicle ascent and descent. The Earth Global Reference Atmosphere Model version 2007 (Earth-GRAM07) is the latest in this series and includes a number of new features. Like previous versions, Earth-GRAM07 provides both mean values and perturbations for density, temperature, pressure, and winds, as well as monthly- and geographically-varying trace constituent concentrations. From 0 km to 27 km, thermodynamics and winds are based on the National Oceanic and Atmospheric Administration Global Upper Air Climatic Atlas (GUACA) climatology. For altitudes between 20 km and 120 km, the model uses data from the Middle Atmosphere Program (MAP). Above 120 km, Earth-GRAM07 now provides users with a choice of three thermosphere models: the Marshall Engineering Thermosphere (MET-2007) model; the Jacchia-Bowman 2006 thermosphere model (JB2006); and the Naval Research Labs Mass Spectrometer, Incoherent Scatter Radar Extended Model (NRL MSIS E-00) with the associated Harmonic Wind Model (HWM-93). In place of these datasets, Earth-GRAM07 has the option of using the new 2006 revised Range Reference Atmosphere (RRA) data, the earlier (1983) RRA data, or the user may also provide their own data as an auxiliary profile. Refinements of the perturbation model are also discussed which include wind shears more similar to those observed at the Kennedy Space Center than the previous version Earth-GRAM99.

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1. OVERVIEW OF EARTH-GRAM

Reference or Standard atmospheric models have long been used for design and mission planning of various aerospace systems. The NASA/MSFC Global Reference Atmospheric Model (GRAM) was developed in response to the need for a design reference atmosphere that provides complete global geographical variability, and complete altitude coverage (surface to orbital altitudes) as well as seasonal and monthly variability of the thermodynamic variables and wind components. Another unique feature of GRAM is that, in addition to providing the geographical, height, and monthly variation of the mean atmospheric state, it includes the ability to simulate spatial and temporal perturbations in these atmospheric parameters (e.g. fluctuations due to turbulence and other atmospheric perturbation phenomena). For a summary comparing features of GRAM to characteristics and features of other Reference or Standard atmospheric models, see AIAA (1997).

The original GRAM (Justus *et al.,* 1974) has undergone a series of improvements over the years (Justus *et al.,* 1980, 1988, 1991, 1995, 1999). This paper describes recent additions and improvements to GRAM. Like earlier versions, EARTH-GRAM07 is a compilation of empirically-based models that represent different altitude ranges (and the geographical and temporal variations within these altitude ranges). In addition to using the Global Upper Air Climatic Atlas (GUACA) CD-ROM data of Ruth *et al.* (1993) for the lower altitude region (0 to 27 km), EARTH-GRAM07 alternately allows optional use of an ASCII-formatted Global Gridded Upper Air Statistics (GGUAS) data base for this height region.

The GUACA (or GGUAS) data cover the altitude region from 0 to 27 km (in the form of data at the surface and at constant pressure levels from 1000 mb to 10 mb). The middle atmospheric region (20 to 120 km) data set is compiled from Middle Atmosphere Program (MAP) data (Labitzke *et al.*, 1985) and other sources referenced in the GRAM-90 and GRAM-95 reports (Justus *et al.*, 1991, 1995). For the highest altitude region (above 90 km), the user now has the choice of three thermosphere models: the revised Marshall Engineering Thermosphere (MET-2007) model, the Naval Research Labs Mass Spectrometer, Incoherent Scatter Radar Extended Model (NRL MSIS E-00) with the associated Harmonic Wind Model (HWM-93), or the Jacchia-Bowman 2006 thermosphere model (JB2006).

Smooth transition between the altitude regions is provided by fairing techniques. Unlike interpolation (used to "fill in" values across a gap in data), fairing is a process that provides a smooth transition from one set of data to another in regions which overlap (e.g., 20 to 27 km for GUACA/GGUAS and MAP data, and 90 to 120 km for MAP data and the thermosphere models). Figure 1. provides a graphical summary of the data sources and height regions.

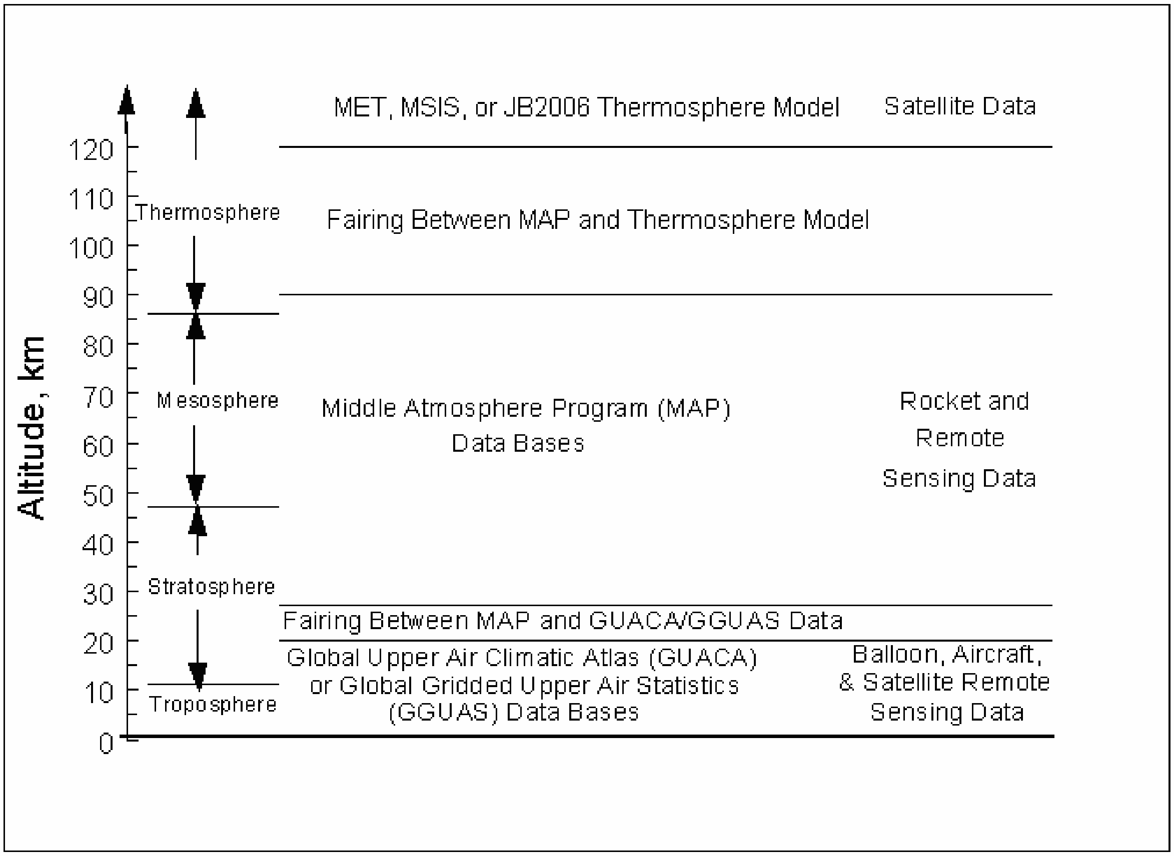

Figure 1. *Schematic summary of the atmospheric regions in the EARTH-GRAM07 program, sources for the models, and data on which the mean monthly EARTH-GRAM07 values are based.*

Beginning with GRAM-95, the model provides estimates of atmospheric species concentrations for water vapor (H_2O), ozone (O_3), nitrous oxide (N_2O), carbon monoxide (CO), methane (CH_4), carbon dioxide (CO_2), nitrogen (N_2), molecular oxygen (O_2), atomic oxygen (O), argon (Ar), Helium (He), and Hydrogen (H). The MET (Jacchia) model provides the species concentrations for N_2, O_2, O, A, He, and H above 90 km. Air Force Geophysics Laboratory (AFGL) atmospheric constituent profiles (Anderson *et al.*, 1986) are also used extensively for the constituents to 120-km altitude.

The GUACA data set provides water vapor data from the surface to the 300-mb pressure level. The NASA Langley Research Center (LaRC) water vapor climatology (McCormick and Chou, 1994) includes H_2O values from 6.5- to 40.5-km altitude. Middle Atmosphere Program (MAP) data (Keating, 1989) include H_2O data from 100-mb to the 0.01-mb pressure level.

2. NEW FEATURES IN EARTH-GRAM07

2.1 *Revised Atmospheric Perturbation Model*

Atmospheric variability on less than monthly time scales is produced by several types of physical phenomena. Planetary scale Rossby waves have periods of several days, and, at longer wavelengths, may produce quasi-stationary wave patterns. Baroclinic instability of the Rossby waves produces the familiar patterns of fronts, cyclones and anti-cyclones of tropospheric weather. Atmospheric tides, produced primarily by solar heating of water vapor in the troposphere and ozone in the stratosphere, have planetary-scale wavelengths and predominately diurnal and semi-diurnal periods. Time-of day variations due to atmospheric tides tend to amplify with altitude.

The upper atmosphere section of GRAM treats the major aspects of time-of-day variations. Surface heating produces convective circulations that can lead to thunderstorms. Instability or other mechanisms can produce organized lines of thunderstorms and groups of thunderstorms called a mesoscale convective complex. Atmospheric gravity waves may be produced by orographic flow effects or may be triggered by thunderstorms, tropical storms, or other disturbances. Like tides, gravity waves tend to amplify with height, but, since they are more irregular in their nature, cannot be modeled explicitly. Atmospheric turbulence occurs at relatively small scales and can be triggered by surface heating, orographic effects, or instability processes produced by gravity waves, tides, or jet stream shears associated with the Rossby waves.

In GRAM-90, all these processes were parameterized stochastically using a scale perturbation model. A smaller scale parameter was used to represent such small-scale processes as turbulence, mesoscale storms, and gravity waves while a larger scale parameter was used to represent such large-scale processes as Rossby waves, cyclones and anticyclones, and tides. Each of these two-scale parameters was used, in the sense of a spectral integral scale, to characterize a spectrum that spans a significant range of wave numbers. These scale parameters were assumed in GRAM-90 to be altitude and latitude dependent only.

In GRAM-95 a new, variable-scale, small-scale perturbation model was introduced. Through stochastic variation of the value of the small-scale parameter, this model incorporates many of the features of the atmospheric turbulence model of Justus *et al*. (1990). In particular, the effects of intermittency, the tendency of turbulence to appear in patches or layers, are incorporated. The modeling approach, described more fully in section 2.6 of Justus *et al*. (1995), results in a simpler implementation incorporating fewer simulation parameters than the original model.

In GRAM-99 the time-series simulations of the variable length scale was introduced and used to categorize the turbulence as normal (light-to-moderate) or disturbed (severe). The turbulence (wind, density, temperature, etc.) is in disturbed conditions whenever the length scale drops below a prescribed "minimum" value. The probability of being in disturbed conditions is taken from statistics in Justus *et al* (1990), and varies from 1 to 2.5 percent near the surface to about 0.15 percent near 25-km altitude to about 2 percent near 75-km and back to about 1 percent above 120-km altitude. The values for standard deviation of the length scales within the model were modified to get these appropriate probability values.

In Earth-GRAM07, several changes/additions have been made in the GRAM perturbation model. These include:

(1) A new feature to update atmospheric mean values without updating perturbation values. This option can be beneficial in trajectory codes that use fast calling frequencies. In cases for slow moving vehicles the spatial step may be so small that adjacent points are highly correlated and do not recover the appropriate statistics. In Earth-GRAM07, the mean values can be updated at one frequency while the perturbations are computed at a more appropriate interval. Another application is in trajectory codes that use Runge-Kutta (or other predictor-corrector) techniques that iterate before determining a final position. Earlier versions of GRAM would correlate each subsequent guess position instead of just the first and final positions. With this new feature, proper correlations can be obtained.

(2) Large-scale perturbations now have randomized amplitude, wavelengths, phase, and period. In the previous version of GRAM the large-scale was modeled with a cosine function of fixed amplitude. This limited the large-scale perturbations to square-root(2) (= 1.4) times the large-scale standard deviations. By using a randomized amplitude, excursions beyond this limit were realized. When this modification was combined with refinements in the small-scale perturbation model, the dispersions appear to be more Gaussian in distribution. Figure 2 shows the probability distribution of air density when patches of severe turbulence have been disabled (designated Patchy Off), but allowing for moderate turbulence. The GRAM output (shown as navy blue) is in good agreement with a Gaussian distribution (magenta). For this particular run, the maximum (minimum) deviation was 3.38 (-3.35) standard deviations.

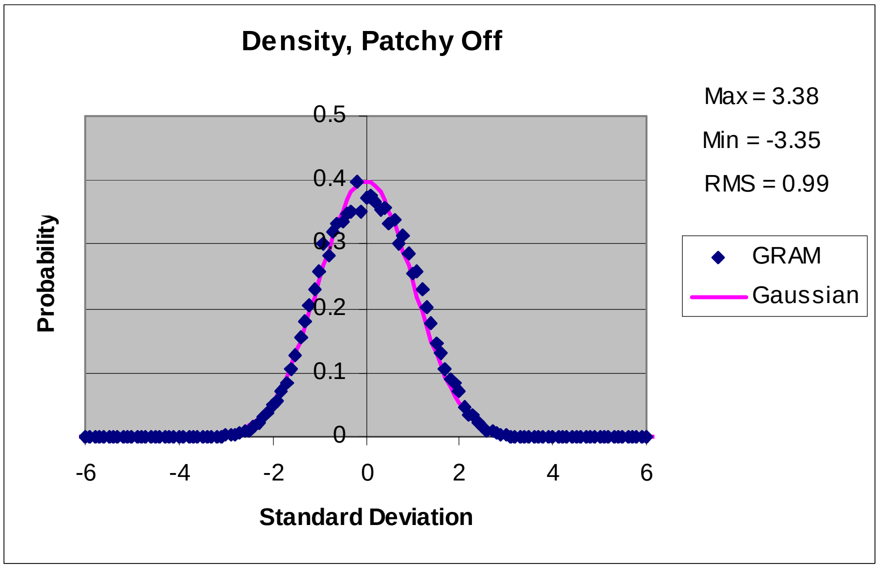

Figure 2. *Comparison of Earth-GRAM07 density dispersions with a Gaussian distribution.*

(3) The ability to simulate large-scale, partially-correlated perturbations as they progress over time for a few hours to a few days. Earth-GRAM07 comes with a driver program called *corrtraj* that simulates wind persistence. The program generates an initial wind profile as well as subsequent profiles at later times. The profiles are not only correlated vertically, but in time as well. This program could be useful, for example, in determining landing dispersions of a returning vehicle whose guidance is biased by the initial profile but traverses a slightly different environment that evolved over time. Figure 3 shows a plot of an initial profile generated by Earth-GRAM07 as well as three profiles that developed at two hour intervals.

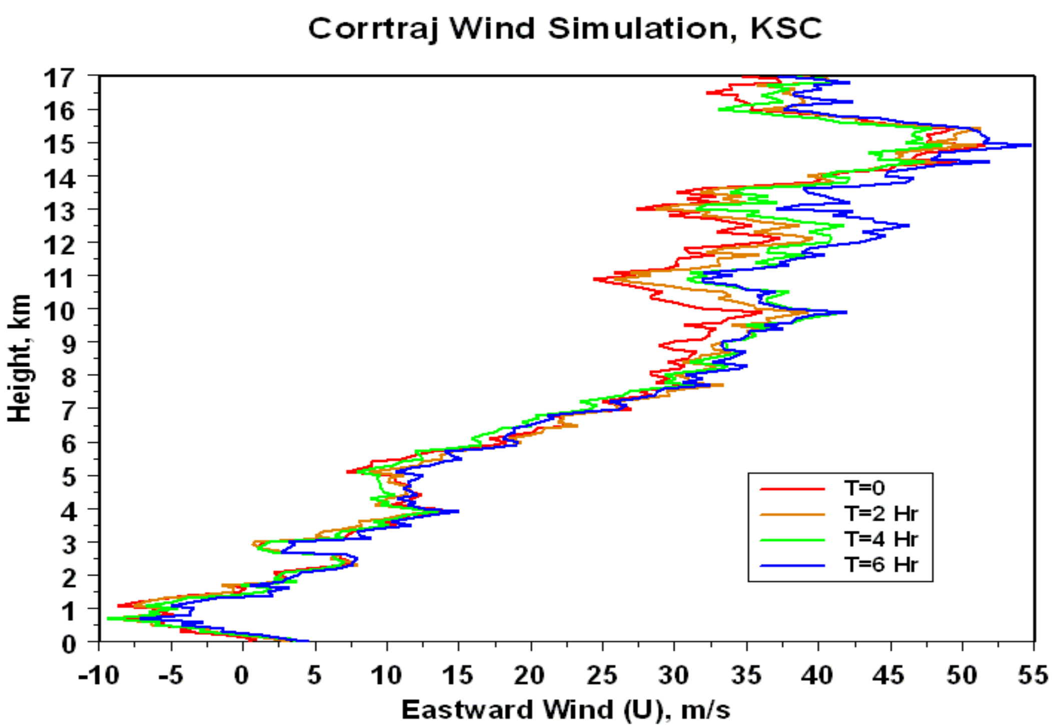

Figure 3. *Time evolution of the eastward wind at the Kennedy Space Center (KSC) as computed by the corrtraj program of Earth-GRAM07.*

(4) Tuning of the length scales to better reproduce wind shears observed at Cape Canaveral, Florida. The original GRAM code was developed in part for Space Shuttle re-entry studies including propellant management. Interest in using GRAM for ascent to examine structural loads led to an evaluation of the wind shears produced by the program. Previous versions tended to underestimate the shears at the higher altitudes. Figure 4 shows a comparison of measured vector wind shear to the GRAM output. Included are measurements from a Jimsphere balloon, the Vector Wind Model (Adelfang, 1994), rawinsonde balloon, and the Automated Meteorological Profiling System (AMPS). The chart shows the 99th percentile 1000-meter vector wind change versus altitude. The Jimsphere is a radar-tracked balloon while AMPS carries a Global Positioning System and both are considered more accurate than the rawinsonde which suffers from errors due to low elevation angles during periods of high winds. Earth-GRAM07 is in good agreement with the Jimsphere and AMPS to a few meters per second.

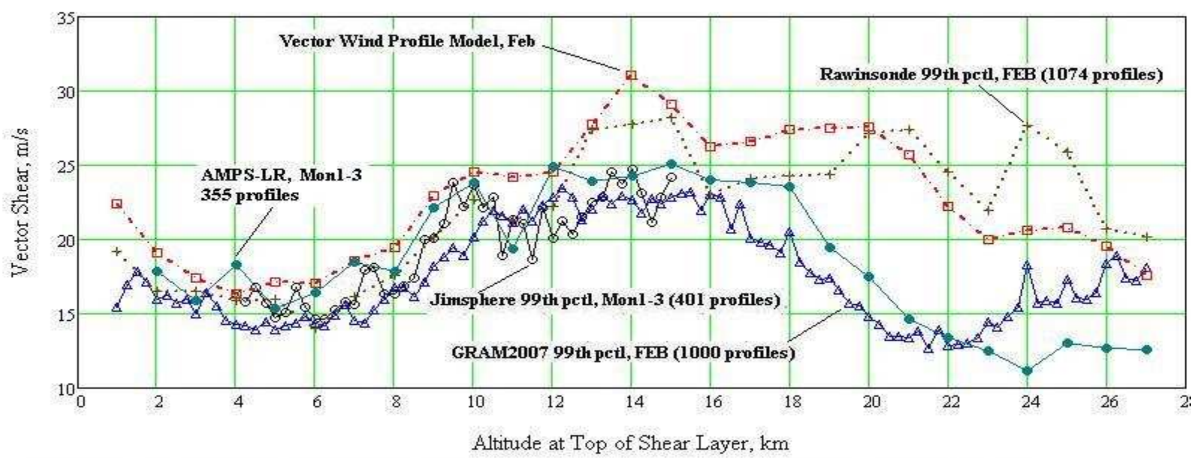

Figure 4. *A comparison of Earth-GRAM07 generated wind shears with various measurement systems at the Kennedy Space Center.*

2.2 *New Range Reference Atmospheric Model Option*

A major feature, new in GRAM-99 and expanded in Earth-GRAM07, is the (optional) ability to use data (in the form of vertical profiles) from a set of Range Reference Atmospheres (RRA), as an alternate to the usual GRAM climatology, at a set of RRA site locations. With this feature it is possible, for example, to simulate a flight profile that takes off from the location of one RRA site (e.g. Edwards AFB, using the Edwards RRA atmospheric data), to smoothly transition into an atmosphere characterized by the GRAM climatology, then smoothly transition into an atmosphere characterized by a different RRA site (e.g. White Sands, NM), to be used as the landing site in the simulation.

RRA data includes information on both monthly means and standard deviations of the various parameters at the RRA site. Under the RRA option, when a given trajectory point is sufficiently close to an RRA site, then the mean RRA data replace the mean values of the conventional GRAM climatology, and the RRA standard deviations replace the conventional GRAM standard deviations in the perturbation model computations. New in Earth-GRAM07 is the feature to replace GRAM surface data with surface data from the appropriate RRA site.

A total of 18 sites are provided for 1983 RRA data. A slightly different set of 22 sites are available for 2006 RRA data. The data period-of-record varies from site to site, but is generally late 1950's to late 1970's for the 1983 RRA data, and 1990 to 2002 for the 2006 RRA data. Exceptions for 2006 RRA period-of-record are El Paso (1990-95), Great Falls (1990-94), Taguac (1990-99), China Lake (1948-2000), and White Sands (1949-1993). El Paso RRA data(0-30 km) are augmented with White Sands rocketsonde data from 30-70km. The White Sands RRA file includes only 0-30 km data. The user can also prepare (in the appropriate format) data for any other site desired, for use in the RRA mode. Table 1. lists the 2006 RRA sites available in Earth-GRAM07 denoting the station code, year, latitude, longitude, height above sea level, World Meteorological Organization station number, and name.

Table 1. *Range Reference Atmosphere (RRA) sites in Earth-GRAM07*

Code	Year	GdLat	LonE	Hgt(m)	WMO #	Name
asc	1983	-7.93	-14.42	20.	619020	Ascension Island, Atlantic
bar	1983	22.03	-159.78	5.	911620	Barking Sands, Hawaii
cap	1983	28.47	-80.55	3.	747940	Cape Canaveral, Florida
dug	1983	40.77	-111.97	1288.	725720	Dugway Proving Ground (Salt Lake City), UT
eaf	1983	34.92	-117.90	705.	723810	Edwards Air Force Base, California
egl	1983	30.48	-86.52	20.	722210	Eglin AFB, Florida
kmr	1983	8.73	167.75	2.	913660	Kwajalein Missile Range, Pacific
ptu	1983	34.12	-119.12	4.	723910	Point Mugu Naval Air Weapons Center, CA
tag	1983	13.55	144.85	111.	912170	Taguac, Guam
vaf	1983	34.75	-120.57	100.	723930	Vandenberg AFB, California
wal	1983	37.85	-75.48	3.	724020	Wallops Island, Virginia
wsm	1983	32.38	-106.48	1246.	722696	White Sands, New Mexico
fad	1983	64.82	-147.87	135.	702610	Fairbanks, Alaska
nel	1983	36.62	-116.02	1007.	723870	Nellis AFB, Nevada
shm	1983	52.72	174.12	39.	704140	Shemya, Alaska
thu	1983	76.52	-68.50	59.	042020	Thule, Greenland
wak	1983	19.28	166.65	5.	912450	Wake Island, Pacific
kod	1983	57.75	-152.50	0.	703500	Kodiak, AK (unofficial: Developed by MSFC)
anf	2006	47.62	-52.73	140.	718010	Argentia, Newfoundland (St. Johns Airport)
asc	2006	-7.93	-14.42	79.	619020	Ascension Island, Atlantic
bar	2006	21.98	-159.34	31.	911650	Barking Sands, Hawaii (Lihue)
cap	2006	28.47	-80.55	3.	747940	Cape Canaveral, Florida
chl	2006	35.68	-117.68	665.	746120	China Lake Naval Air Weapons Center, CA
dug	2006	40.77	-111.97	1288.	725720	Dugway Proving Ground (Salt Lake City), UT
eaf	2006	34.92	-117.90	724.	723810	Edwards Air Force Base, California
egl	2006	30.48	-86.52	20.	722210	Eglin AFB, Florida
elp	2006	31.81	-106.38	1199.	722700	El Paso, Texas
fad	2006	64.80	-147.88	135.	702610	Fairbanks, Alaska
fha	2006	32.12	-110.93	787.	722740	Ft. Huachuca Elec Prvng Grnd (Tucson), AZ
gtf	2006	47.47	-111.38	1118.	727750	Great Falls, MT
kmr	2006	8.73	167.75	2.	913660	Kwajalein Missile Range, Pacific
ncf	2006	43.87	4.40	62.	076450	Nimes-Courbessac, France (STS TAL Site)
nel	2006	36.62	-116.02	1007.	723870	Nellis AFB, Nevada (Mercury)
ptu	2006	34.12	-119.12	2.	723910	Point Mugu Naval Air Weapons Center, CA
rrd	2006	18.43	-66.00	3.	785260	Roosevelt Roads (San Juan), Puerto Rico
tag	2006	13.55	144.85	78.	912170	Taguac, Guam (Anderson AFB)
vaf	2006	34.75	-120.57	121.	723930	Vandenberg AFB, California
wal	2006	37.85	-75.48	13.	724020	Wallops Island, Virginia (NASA)
wsm	2006	32.38	-106.48	1207.	722690	White Sands Missile Range, New Mexico
ysd	2006	32.87	-117.14	134.	722930	Yuma Proving Ground, AZ (San Diego, CA)

2.3 *Auxiliary Profile Option*

In addition to RRA options, an "auxiliary profile" feature has been implemented. This allows the user to input a data profile of pressure, density, temperature, and/or winds versus altitude, with the auxiliary profile values used in place of conventional climatology (GUACA/MAP/etc.) values. This option is controlled by setting parameters in the input file. Parameter *profile* gives the file name containing the profile data values. Parameter *sitenear* is the latitude-longitude radius (in degrees) within which weight for the auxiliary profile is 1.0. Parameter *sitelim* is the latitude-longitude radius (in degrees) beyond which weight for the auxiliary profile is 0.0. A weighting factor for the profile data, having values between 0 and 1, is applied between radii *sitelim* and *sitenear*.

Mean conditions are as given in the *profile* file if the desired point is within a lat-lon radius of *sitenear* from the profile lat-lon at the given altitude; mean conditions are as given by the original GUACA/MAP/etc. data if the desired point is beyond a lat-lon radius of *sitelim* from the lat-lon of the profile at the given altitude. If *sitenear* = 0, then profile data are NOT used. When using an auxiliary profile, the standard deviations used to drive the perturbation model will come from GRAM climatology. The profile weight factor (*profwgt*) for the auxiliary profile also varies between 0 at the first profile altitude level and 1 at the second profile altitude level (and between 1 at the next-to-last profile altitude level and 0 at the last profile altitude level). First and second profile points (and next-to-last and last profile points) should therefore be selected widely enough apart in altitude that a smooth transition can occur as *profwgt* changes form 0 to 1 near these profile end points. NOTE: the auxiliary profile option and RRA data option cannot both be invoked simultaneously.

Each line of the auxiliary profile input file consists of: (1) height, in km [height values greater than 6000 km are interpreted as radius values, in km], (2) latitude, in degrees, (3) longitude, in degrees (East positive), (4) temperature, in K, (5) pressure, in N/m^2, (6) density, in kg/m^3, (7) Eastward wind, in m/s, and (8) Northward wind, in m/s. Heights are relative to the reference ellipsoid, except that values greater than 6000 km are interpreted as radius values, rather than altitudes. Latitudes are planetocentric. Regular climatological values are used if temperature, pressure, and density data are all three input as zero in the auxiliary profile. Regular climatological values of wind components are used if BOTH wind components are zero in the auxiliary profile file. It is worth noting that the auxiliary profile need not be a simple vertical profile at a fixed lat-lon, but can consist of a data set along a specified trajectory.

2.4 *New Thermosphere Model Options*

EARTH-GRAM07 now allows the user to select one of three thermosphere models for use above 90 km: the Marshall Engineering Thermosphere, the Naval Research Labs Mass Spectrometer, Incoherent Scatter Radar Extended Model thermosphere (NRL MSIS E-00) with the associated Harmonic Wind Model (HWM-93), or the Jacchia-Bowman 2006 thermosphere model (JB2006). The default model is the Marshall Engineering Thermosphere (Hickey, 1988a, 1988b, 1994, 2006) which has been updated to include:

(1) A correction of number density and molecular weight, according to discussion in Justus *et al*. (2006);

(2) A change from spherical-Earth approximation to latitude-dependent surface gravity and effective Earth radius;

(3) A change from time resolution only to the nearest integer minute to (real) seconds time resolution;

(4) A correction of small discontinuities in the semi-annual variation term by converting day-of-year to real instead of integer, and treating each year as having either 365 or 366 days (as appropriate), rather than all years being treated as of length 365.2422 days;

(5) An additional output from MET07_TME subroutine of modified Julian Day, right ascension of Sun, and right ascension at local lat-lon (used for input to new JB2006 thermosphere model).

As an alternative to the MET model, the option is now provided to use the 2000 version Naval Research Laboratory (NRL) MSIS Extended model, NRLMSISE-00, for Earth-GRAM07 thermospheric conditions. If this option is selected, thermospheric winds are evaluated using the NRL 1993 Harmonic Wind Model, HWM-93. If the MET option is selected, winds are computed from a geostrophic wind model, with modifications for thermospheric effects of molecular viscosity. This wind model has been used in GRAM since the 1990 version (Justus *et al*., 1991).

Information on the MSIS and HWM models is available at the following URLs:

http://www.nrl.navy.mil/content.php?P=03REVIEW105

http://uap-www.nrl.navy.mil/models_web/msis/msis_home.htm

http://modelweb.gsfc.nasa.gov/atmos/nrlmsise00.html

http://www.answers.com/topic/nrlmsise-00 http://fact-archive.com/encyclopedia/NRLMSISE-00

http://nssdc.gsfc.nasa.gov/space/model/models_home.html#atmo

http://uap-www.nrl.navy.mil/models_web/homepage.htm

Minor corrections in MSIS and HWM (along the lines of corrections 3 and 4 for MET, above) have been made. Therefore, MSIS/HWM output from Earth-GRAM07 will not agree totally with output from the original NRLMSISE-00 version.

A third option for the thermosphere is the Jacchia-Bowman 2006 (JB2006) model. It was developed using the CIRA72 (Jacchia 71) model as the basis for the diffusion equations. New solar indices have been used for the solar irradiances in the extreme and far ultraviolet wavelengths. New exospheric temperature and semiannual density equations were created to represent the major thermospheric density variations. Temperature correction equations were also developed for diurnal and latitudinal effects, and finally density correction factors have been included for model corrections required at high altitudes (1500- 4000 km). This model has been validated through comparisons of accurate daily density drag data previously computed for numerous satellites. For 400 km altitude the standard deviation of 16% for the Jacchia 1971 model has been reduced to 10% in the JB2006 model during periods of low geomagnetic storm activity. References to developmental papers for JB2006 are given in the code and at the JB2006 web site:

http://sol.spacenvironment.net/~JB2006/

This site also has links to new solar indices required by JB2006 (s10 and xm10), JB2006 source code, publications, contacts, figures, and the Space Environment Technologies Space Weather site.

The starting point for the GRAM implementation of JB2006 is REV-A October, 2006. Changes were made, mostly cosmetic, to make the code more transportable among various compilers. If JB2006 is selected for calculation of thermospheric density and temperature, winds are computed with the Harmonic Wind Model (HWM 93), used in conjunction with the MSIS model.

A two-scale perturbation model is also used in the Earth-GRAM07 thermospheres. Small-scale perturbations are computed by a one-step Markov process (a 1st order auto-regressive approach, equivalent to the 1st order autoregressive model of Hickey, 1994). A wave model for treating large-scale perturbations was introduced in GRAM-99. This model uses a cosine wave, with both horizontal and vertical wavelengths. For use in Monte-Carlo simulations, a degree of randomness is introduced into the large-scale wave model by randomly selecting the phase of the cosine wave (under control of the same random number seed values as used for the small-scale perturbations). Parameters for the small-scale perturbation model in GRAM-99 and Earth-GRAM07 were re-calculated, to produce good agreement with data given in Table 2 of Hickey (1994). The one-step correlation over 15 seconds of movement for the Atmospheric Explorer (AE) satellites is equivalent to an average value of 0.846 (with a standard deviation of 0.040). The length scales used in the perturbation model of GRAM-99 and Earth-GRAM07 yield a correlation value of 0.870 over the distance which the AE satellite moves in 15 seconds, well within the range of variability of the correlation data from Hickey. See further discussion of the thermospheric perturbation model in Section 3.3 of Justus, *et al.* (1999). The large-scale wave model for perturbations in Earth-GRAM07 is used at all altitudes, not just in the MET or MSIS model altitude range.

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