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Earth Global Reference Atmospheric Model (Earth-GRAM): User Guide

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September 2021

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Earth-GRAM was originally developed under the leadership of Dr. Carl Gerald (Jere) Justus. The first release of Earth-GRAM occurred in 1974. In 2021, Earth-GRAM was re-released after being converted to the GRAM common framework. A complete history of Earth-GRAM version revisions is contained in appendix F.

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PREFACE

The 2021 version of the NASA Earth Global Reference Atmospheric Model (Earth-GRAM) was developed by the Natural Environments Branch, Spacecraft and Vehicle Systems Department, Engineering Directorate at NASA Marshall Space Flight Center and the Atmospheric Flight and Entry Systems Branch at NASA Langley Research Center.

Information on obtaining Earth-GRAM code and data can be found on the NASA Software Catalog at: https://software.nasa.gov.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

AFB	Air Force Base
AFGL	Air Force Geophysics Laboratory
AFMS	Air Force Midlatitude Summer
AFMW	Air Force Midlatitude Winter
AFSS	Air Force Subarctic Summer
AFSW	Air Force Subarctic Winter
AFTR	Air Force Tropical
AMU	Applied Meteorological Unit
ARL	Air Resources Lab
ASCII	American Standard Code for Information Interchange
BL	Boundary Layer
CDAS	Climate Data Assimilation System
CIRA	Committee on Space Research International Reference Atmosphere
CSS	Cascading Style Sheets
CSV	Comma-separated Values
FTP	File Transfer Protocol
GRAM	Global Reference Atmospheric Model
HWM	Harmonic Wind Model
JB	Jacchia-Bowman
LaRC	Langley Research Center
lat-lon	latitude-longitude
LTST	local true solar time
MAP	Middle Atmosphere Program
MET	Marshall Engineering Thermosphere
MSFC	Marshall Space Flight Center
MSIS	Mass Spectrometer, Incoherent Scatter
MSL	Mean Sea Level
NCEP	National Centers for Environmental Prediction
NRL	Naval Research Laboratory
NRLMSISE	Naval Research Laboratory Mass Spectrometer, Incoherent Scatter Radar Extended model
NAIF	Navigation and Ancillary Information Facility
POR	period-of-record
RRA	Range Reference Atmosphere
SMD	Science Mission Directorate
SPICE	Spacecraft Planet Instrument C-matrix Events
url	uniform resource locator
UT	universal time
UTC	universal time coordinated
WMO	World Meteorological Organization

NOMENCLATURE

A	local wave amplitude
A_Q	large-scale amplification factor
$A(z)$	data set, amplitude
$B(z)$	data set
C	faired variable
C_p	specific heat capacity of a gaseous mixture for isobaric processes
$c(t)$	species concentrations
C_v	specific heat capacity of a gaseous mixture for isochoric processes
d	boundary layer depth
d_N	neutral boundary layer depth
E_l	solar elevation
E_{md}	solar elevation at midday
f	coriolis parameter
$f(z)$	fairing parameter
f_L	large-scale fractional variance
f_{non}	factor for variance of nonsevere perturbation
f_{sev}	factor for variance of severe perturbation
g	acceleration of gravity
$G(E_l)$	time-factor multiplier
L	local vertical correlation scale (small-scale perturbation) or Monin-Obukhov scaling length (stability dependent) in meters
L_{avg}	average scale size
L_h	horizontal scale parameter
L_{max}	maximum scale size
L_{min}	minimum scale size
L_s	solar longitude
L_z	vertical scale parameter
m	wave number in the latitudinal direction
mn	input value of month
n	wave number in the longitudinal direction
n_r	net radiation index
P_{sev}	probability of severe perturbations
P_{tail}	tail probability of a Gaussian distribution
Q	a uniformly distributed random number between 0 and 1
q	Gaussian-distributed random number
R	gas constant
r	autocorrelation value
r_c	cross-correlation
r_q	a correlation coefficient
r_t	concentration rate of change
r_v	a correlation coefficient
r_μ	a correlation coefficient
T	wave period or temperature
t_0	initial time in concentration formula
U_{10}	surface wind speed measured at the standard 10-m height above surface

u_*	friction velocity
V	variable available on two-dimensional grid
$W(U_{10})$	wind speed factor as a function of surface wind speed
x	vector position
x'	trajectory position
z_o	surface roughness
α	a constant used in the computation of surface roughness over water, 0.015 or interpolation constant
β	interpolation constant
Γ	temperature gradient
γ	the ratio of specific heats
δh	horizontal step
δt	time step
δz	vertical step
θ	longitude
λ_z	vertical wavelength
μ	normalized variant
ξ	stability category
ρ	density
ρ_l	large scale density
σ	local standard deviation (small-scale perturbation)
σ^2	total variance of small-scale perturbation
σ_{cos}	standard deviation of the cosine function
σ_L	standard deviation of large scale
σ_p	standard deviation of pressure
σ_S	small-scale standard deviation
σ_T	total standard deviation or standard deviation of temperature
σ_w	standard deviation of the vertical wind component
σ_p	standard deviation of density
σ_{ρ_l}	standard deviation of large-scale density
τ	time scale
ϕ	latitude
φ_q	random wave phase
ψ	boundary layer wind function
ω	Brunt-Vaisala frequency

TECHNICAL MEMORANDUM

EARTH GLOBAL REFERENCE ATMOSPHERIC MODEL (EARTH-GRAM): USER GUIDE

1.0 INTRODUCTION

1.1 Background and Overview

Reference or standard atmospheric models have long been used for design and mission planning of various aerospace systems. The NASA Global Reference Atmospheric Model (GRAM) was originally developed in response to the need for a design reference atmosphere that provides complete global geographical variability, altitude coverage (surface to orbital altitudes), and seasonal and monthly variability of the thermodynamic variables and wind components. A 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). A summary comparing GRAM features to the characteristics and features of other reference or standard atmospheric models, can be found in the Guide to Reference and Standard Atmosphere Models[1].

The original GRAM[2] has undergone a series of improvements over the years with recent additions and changes.[3-9] This software program is now called Earth-GRAM to distinguish it from similar programs for other bodies (e.g. Mars, Venus, Neptune, Titan, Jupiter, and Uranus). An overview of the basic features of Earth-GRAM, including recent additions, are found in section 1. Section 2 provides a more detailed description of Earth-GRAM and how the model output is generated. Section 3 presents sample results and section 4 gives specific user information. Appendix A describes the headers for Earth-GRAM output file. Appendix B provides an example NAMELIST format input file. Appendix C gives a description of the sample output LIST file. Appendix D provides a summary of the files provided with Earth-GRAM. Appendix E provides instructions for building Earth-GRAM. Finally, appendix F provides a history of Earth-GRAM version revisions.

1.2 Basic Description

Earth-GRAM is a collection of empirically based models that represent different altitude ranges and the geographical and temporal variations within these altitude ranges. Figure 1 shows how Earth-GRAM divides the atmosphere into three regions from which mean values of atmospheric parameters are provided. A perturbation model (see section 2.12) then computes variations about these means if dispersions are desired. Monthly mean values and standard deviations in the lower atmosphere come from the National Centers for Environmental Prediction (NCEP) database which was added in Earth-GRAM2010[10] and described in section 2.1. The database read by Earth-GRAM is in binary form, but an American Standard Code for Information Interchange (ASCII) version is also provided. A program is available in the Earth-GRAM distribution file which the user may run on their machine to convert the ASCII version to their machine-specific binary. The middle atmospheric region (20 to 120 km) data set is compiled from Middle Atmosphere Program (MAP) data[11] and other sources referenced in the GRAM-90 and GRAM-95 reports.[5,6] For the highest altitude region (above 90 km), the user has the choice of three thermosphere models (see section 2.3). Fairing techniques provide smooth transition between the altitude regions. 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 overlapping regions (e.g. 20 km to 10 mb level for NCEP 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. In addition to these databases, the user has the option of instructing Earth-GRAM to use the 1983, 2006, 2013, and 2019 Range Reference Atmosphere data set for specific sites or the user can provide an auxiliary profile of mean values and standard deviations.

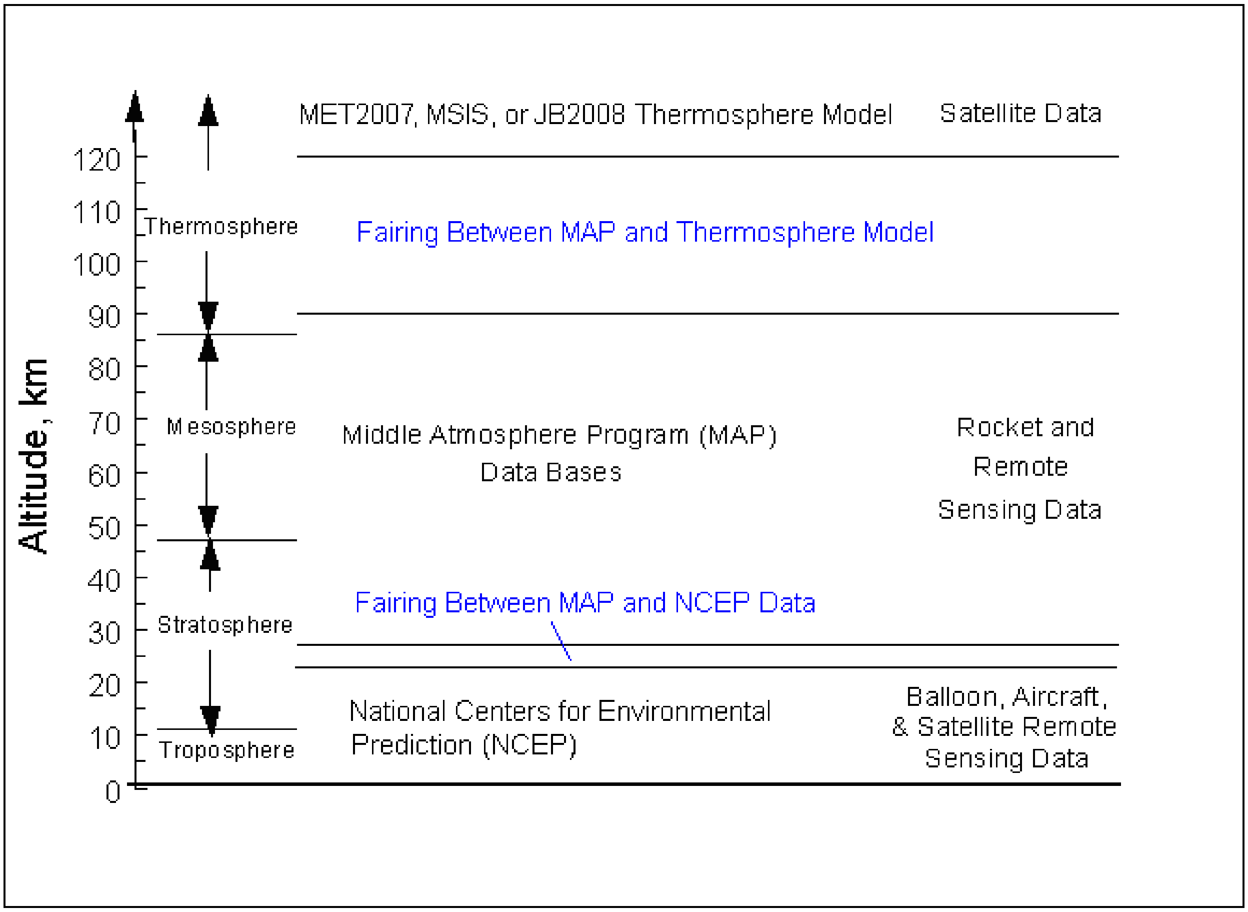

Figure 1. Schematic summary of the atmospheric regions in the Earth-GRAM program, sources for the model, and data on which the mean monthly Earth-GRAM values are based.

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 thermosphere models provide the species concentrations for N_2, O_2, O, A, He, and H above 90 km. Air Force Geophysics Laboratory (AFGL) atmospheric constituent profiles[12] are also used extensively for the constituents to a 120-km altitude. The NASA Langley Research Center (LaRC) water vapor climatology[13] includes H2O values from a 6.5- to a 40.5-km altitude. The MAP data[14] include H_2O data from the 100- to 0.01-mb pressure level. Other details of the species concentration model are given in Sections 1.4 and 2.4 of the GRAM-95 report[6].

1.3 Significant Changes in Earth-GRAM

1.3.1 Earth-GRAM Inputs

The Earth-GRAM input parameters have been renamed to be more descriptive. The legacy input parameter names are still accepted to maintain compatibility with existing NAMELIST input files from prior Earth-GRAM versions. Table 4 in section 4.3 provides the new and old input parameter names.

1.3.2 Earth-GRAM Outputs

Due to the increase in computing power and memory since the original release of Earth-GRAM in 1974, the output files have been reformatted. The output is provided in two formats: (1) a comma separated value (CSV) file and (2) a LIST file (formerly LIST.txt, now LIST.md). The CSV file consolidates all of the column formatted output files from the previous Earth-GRAM releases into a single file that can easily be loaded into data centric programs, such as Microsoft Excel or MATLAB®. A detailed list of CSV file parameters and definitions are provided in appendix A. Alternatively, the LIST file can be read using either a standard ASCII reader or a Markdown syntax for enhanced rendering in a web browser. An example of both LIST file formats is provided in appendix C.

1.3.3 Range Reference Atmosphere Updates

Earth-GRAM uses the Range Reference Atmosphere (RRA) site specific data source in addition to the global data sources. This Earth-GRAM update includes the 2019 RRA database for 11 sites. The 2019 sites are listed in table 1. The 2019 RRAs were developed by the Marshall Space Flight Center's Natural Environments Branch. The RRA 2019 update is provided in addition to the previous RRAs of 1983, 2006, and 2013. RRA data is summarized in section 2.4.

1.3.4 Ballistic Trajectory

Earth-GRAM now contains the ability to produce correlated atmospheric dispersions from a ballistic (up-down) trajectory. Previous versions of Earth-GRAM could not ensure correlated atmospheric dispersions. Once a ballistic trajectory began the descending portion of the trajectory, the atmospheric dispersions were not correlated to the ascending potion of the trajectory. This new feature in Earth-GRAM is detailed in section 2.8.

1.3.5 Earth Correlator

Recent code changes from FORTRAN to C++ object-oriented have provided ability to create multiple atmosphere objects. Earth-GRAM now contains the ability to correlate atmospheric dispersions originating from multiple atmosphere objects. This allows users to ensure that multiple nearby bodies can maintain a correlation of atmospheric dispersions.

1.3.6 SPICE

The code has incorporated NASA's Navigation and Ancillary Information Facility (NAIF) Spacecraft Planet Instrument C-matrix Events (SPICE) library for ephemeris calculations. Earth ephemeris values, such as longitude of the Sun and solar time, are computed using the NAIF SPICE library for greater accuracy. The use of the NAIF SPICE library requires the Earth-

GRAM user to download the latest SPICE data before using Earth-GRAM. Instructions for doing so are provided in section 4.2.

1.3.7 GRAM Suite

Earth-GRAM has been rearchitected from Fortran to a common object-oriented C++ framework called the GRAM Suite. This new architecture creates a common GRAM library of data models and utilities that reduces duplicated code, ensures consistent constants across all GRAMs, simplifies bug fixes, and streamlines the interface with trajectory codes. Users should refer to the GRAM Programmer's Manual for additional details.

1.3.8 Speed of Sound

The calculation of the speed of sound has been improved in Earth-GRAM. Earth-GRAM computes speed of sound based on a thermodynamic parameterization using density, pressure, and γ, the ratio of specific heats $\frac{C_p}{C_v}$, for a given constituent gas mixture. C_p is the specific heat capacity of a gaseous mixture for isobaric processes and C_v is the specific heat capacity of a gaseous mixture for isochoric processes. Earth-GRAM previously used a constant γ, which is physically unrealistic and overestimates the speed of sound by as much as 10%. Earth-GRAM uses an improved methodology for computing γ, involving temperature and pressure dependent tables of C_p and C_v evaluated in run-time for the current constituent combination[15].

2.0 TECHNICAL DESCRIPTION OF THE MODEL

2.1 Lower Atmosphere Section (Surface to 10 mb)

For the lower atmosphere, Earth-GRAM uses climatological data derived from a NCEP Global Reanalysis Database. The NCEP data consist of means and standard deviations (at a global latitude-longitude resolution of 2.5° × 2.5°) for four hours of the day (00, 06, 12, and 18 Coordinated Universal Time (UTC)), as well as for all four times-of-day combined in an average, at the surface and at each of 17 pressure levels. Averages and standard deviations are by month, over a period-of-record from 1997 through 2015. More information about the reanalysis project and data are available in Kalnay, et al.[16]. As part of validation studies conducted for Earth-GRAM-2010, NCEP hourly and daily averages of surface winds and temperatures were compared with statistics from more directly-observed surface winds and temperatures. During these studies, it was found that NCEP average surface winds and temperatures did not have nearly as much variation with hour-of-day as did observed surface winds and temperatures. Consequently, a more detailed study of surface and near-surface NCEP data and observed winds and temperatures was undertaken and the results are included in section 2.3 of the Earth-GRAM 2010 report[10].

2.2 Middle Atmosphere Section (20 to 120 km)

The MAP in Earth-GRAM characterizes the monthly mean middle atmosphere (20 to 120 km) by two gridded data sets, one representing the zonal mean atmospheric values (gridded by height and latitude) and the other the monthly-mean stationary wave patterns (i.e., stationary perturbations about the monthly mean, gridded by height, latitude, and longitude). The zonal mean data set was merged from six separate data sets covering the 20 to 120 km altitude range. The zonal monthly mean data set (pressure, density, temperature, and mean eastward wind component) is gridded in 10° latitude and 5-km height increments (-80° to +80° latitude and 20 to 120 km). Zonal mean values at ±90° are computed by an across-the-pole interpolation scheme discussed in section 2.11.3. Zonal mean values between the gridded data set values are interpolated vertically by hydrostatic and perfect gas law assumptions and horizontally by two-dimensional (latitude-longitude) interpolation methods.

The stationary perturbation data set (standing wave perturbations in pressure, density, temperature, and eastward and northward wind components) was merged from three sources of data on planetary scale standing wave patterns[5]. This data set is gridded in 10° latitude increments (-80° to +80°), 20° longitude increments (180°, 160°W, 140°W,... 140°E, 160°E), and 5-km height intervals (20 to 90 km). Stationary perturbations are identically zero at the poles. Stationary perturbation values are linearly interpolated in the vertical dimension and horizontally by two-dimensional (latitude-longitude) interpolation methods.

2.3 Upper Atmosphere Section (Above 90 km)

Earth-GRAM has the option of three different thermosphere models for use above 90 km. The Marshall Engineering Thermosphere (MET) 07 (MET-07) constitutes the default upper atmosphere model.[17-23] The Jacchia model[23] in MET-07 for the thermosphere and exosphere was originally implemented to compute atmospheric density and temperature at satellite altitudes. It represents total atmospheric density by summing the densities of six, separately modeled, atmospheric constituents (N_2, O_2, O, Ar, He, and H). The Jacchia model accounts for temperature and density variations due to solar and geomagnetic activity, diurnal, seasonal, and latitude-longitude variations throughout the height range above 90 km. The Jacchia model assumes a uniformly mixed composition below 105 km, with diffusive equilibrium among the constituents above 105 km. Fixed (time-independent) boundary values for temperature and density are assumed at 90 km. Alterations, described in Justus et al.[2], were made to allow atmospheric pressure to be computed from the density and temperature. Geostrophic wind components, modified by the effects of molecular viscosity[5], are evaluated in the Jacchia section by using the Jacchia model to estimate horizontal pressure gradients. This wind model has been used in Earth-GRAM since the 1990 version[5]. Between 90 and 120 km a fairing process, described in Section 2.11.4, ensures smooth transition between the MET model values and the middle atmosphere data.

As an alternative to MET, an option is provided to use the 2000 version Naval Research Laboratory (NRL) Mass Spectrometer and Incoherent Scatter (MSIS) Radar Extended model, NRLMSISE-00, for thermospheric conditions. If this option is selected, thermospheric winds are evaluated using the NRL 1993 Harmonic Wind Model (HWM), HWM-93. Information on the MSIS and HWM models is available at the following uniform resource locators (URLs):

• <http://adsabs.harvard.edu/abs/2006AGUFMSA11A..07D>.

Minor corrections in MSIS and HWM have been made. Therefore, MSIS/HWM output from Earth-GRAM will not agree totally with output from the original NRLMSISE-00 version.

Another thermosphere option is the Jacchia-Bowman 2008 (JB2008) model[24] which replaces JB2006 used in the previous version of Earth-GRAM. The model was developed using the CIRA72 (Jacchia 71) model as the basis for the diffusion equations. If JB2008 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. Other information and references to developmental papers for JB2008 are provided at the JB2008 web sites at the following URLs:

• <http://sol.spacenvironment.net/~JB2008/code.html>.

• <http://adsabs.harvard.edu/abs/2008cosp...37..367B>.

2.4 RRA data

An option exists to use data (in the form of vertical profiles) from a set of RRAs, as an alternative to the usual Earth-GRAM climatology, at a set of RRA site locations. Data for several RRA site locations are delivered with Earth-GRAM and are listed in table 1. 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 Earth-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 (see description below). Under the RRA option, when a given trajectory point is sufficiently close to an RRA site (latitude-longitude radius from site is less than *RRAInnerRadius*, see below), then the mean RRA data replace the mean values of the conventional Earth-GRAM climatology, and the RRA standard deviations replace the conventional Earth-GRAM standard deviations in the perturbation model computations. In Earth-GRAM 2007 a feature was introduced to replace Earth-GRAM surface data with surface data from the appropriate RRA site when the RRA option is used.

RRA options include the 1983, 2006, 2013, and 2019 databases. The 2013 and 2019 RRA databases were developed by the Natural Environments Branch at NASA's Marshall Space Flight Center. Table 1 displays all the RRA sites for each year. The *Code* column provides a three character site designation, *GdLat* and *GcLat* provide values of the site's geodetic and geocentric latitude respectively. Lon represents longitude as measured positive East from the prime meridian. Latitude and longitude values are in degrees. *Hgt* is the site's surface altitude in meters. Zmax represents the maximum altitude of the data set in kilometers, and WMO# represents the World Meteorological Organization 5 digit station identifier.

Table 1. List of RRA site data provided, file "rrasites1.txt"

Code	Year	GdLat	GcLat	Lon (E+)	Hgt (m)	Zmax	WMO #	Site Name
asc	1983	-7.93	-7.88	-14.42	0.02	70	619020	Ascension Island, Atlantic
bar	1983	22.03	21.9	-159.78	0.005	70	911620	Barking Sands, Hawaii
cap	1983	28.47	28.31	-80.55	0.003	70	747940	Cape Canaveral, Florida
dug	1983	40.77	40.58	-111.97	1.288	70	725720	Dugway Proving Ground, UT
eaf	1983	34.92	34.74	-117.9	0.705	70	723810	Edwards Air Force Base, California
egl	1983	30.48	30.31	-86.52	0.02	30	722210	Eglin AFB, Florida
kmr	1983	8.73	8.67	167.75	0.002	70	913660	Kwajalein Missile Range, Pacific
ptu	1983	34.12	33.94	-119.12	0.004	70	723910	Point Mugu, CA
tag	1983	13.55	13.46	144.85	0.111	30	912170	Taguac, Guam
vaf	1983	34.75	34.57	-120.57	0.1	70	723930	Vandenberg AFB, California
wak	1983	19.28	19.16	166.65	0.005	30	912450	Wake Island, Pacific
wal	1983	37.85	37.66	-75.48	0.003	70	724020	Wallops Island, Virginia
wsm	1983	32.38	32.21	-106.48	1.246	70	722696	White Sands, New Mexico
fad	1983	64.82	64.67	-147.87	0.135	30	702610	Fairbanks, Alaska
nel	1983	36.62	36.44	-116.02	1.007	30	723870	Nellis AFB, Nevada
shm	1983	52.72	52.53	174.12	0.039	70	704140	Shemya, Alaska
thu	1983	76.52	76.43	-68.5	0.059	70	42020	Thule, Greenland
anf	2006	47.62	47.43	-52.73	0.14	30	718010	Argentia, Newfoundland
asc	2006	-7.93	-7.88	-14.42	0.079	70	619020	Ascension Island, Atlantic
bar	2006	21.98	21.85	-159.34	0.031	30	911650	Barking Sands, Hawaii (Lihue)
cap	2006	28.47	28.31	-80.55	0.003	70	747940	Cape Canaveral, Florida
chl	2006	35.68	35.5	-117.68	0.665	30	746120	China Lake, CA
dug	2006	40.77	40.58	-111.97	1.288	30	725720	Dugway (Salt Lake City), UT
eaf	2006	34.92	34.74	-117.9	0.724	30	723810	Edwards Air Force Base, California
egl	2006	30.48	30.31	-86.52	0.02	30	722210	Eglin AFB, Florida
elp	2006	31.81	31.64	-106.38	1.199	70	722700	El Paso, Texas
fad	2006	64.8	64.65	-147.88	0.135	30	702610	Fairbanks, Alaska
fha	2006	32.12	31.95	-110.93	0.787	30	722740	Ft. Huachuca (Tucson), AZ
gtf	2006	47.47	47.28	-111.38	1.118	30	727750	Great Falls, MT

kmr	2006	8.73	8.67	167.75	0.002	70	913660	Kwajalein Missile Range, Pacific
ncf	2006	43.87	43.68	4.4	0.062	30	76450	Nimes-Courbessac, France
nel	2006	36.62	36.44	-116.02	1.007	30	723870	Nellis AFB, Nevada (Mercury)
ptu	2006	34.12	33.94	-119.12	0.002	70	723910	Point Mugu, CA
rrd	2006	18.43	18.31	-66	0.003	30	785260	Roosevelt Roads, Puerto Rico
tag	2006	13.55	13.46	144.85	0.078	30	912170	Taguac, Guam (Anderson AFB)
vaf	2006	34.75	34.57	-120.57	0.121	30	723930	Vandenberg AFB, California
wal	2006	37.85	37.66	-75.48	0.013	30	724020	Wallops Island, Virginia (NASA)
wsm	2006	32.38	32.21	-106.48	1.207	30	722690	White Sands Missle Range, NM
ysd	2006	32.87	32.69	-117.14	0.134	30	722930	Yuma, AZ (San Diego, CA)
wak	2013	19.28	19.16	166.65	0.005	30	912450	Wake Island, Pacific
bar	2013	21.98	21.85	-159.34	0.036	30	911650	Barking Sands, Hawaii (Lihue)
cap	2013	28.47	28.31	-80.57	0.004	30	747940	Cape Canaveral, Florida
dug	2013	40.77	40.58	-111.97	1.288	30	725720	Dugway (Salt Lake City), UT
eaf	2013	34.91	34.74	-117.88	0.723	30	723810	Edwards Air Force Base, California
vaf	2013	34.73	34.53	-120.57	0.1	30	722930	Vandenberg AFB, California
wsm	2013	32.94	32.88	-106.42	1.251	30	722690	White Sands Missle Range, NM
kod	2013	57.75	57.56	-150.5	0.004	30	703500	Kodiak, Alaska
kmr	2013	8.73	8.67	167.75	0.002	30	913660	Kwajalein Missile Range, Pacific
chl	2013	35.68	35.5	-117.68	0.667	30	746120	CHINA LAKE NAWS, CA
egl	2013	30.48	30.31	-86.52	0.026	30	722210	Eglin AFB, Florida
ptu	2013	34.12	33.94	-119.12	0.004	30	723910	Point Mugu, CA
thu	2013	76.52	76.43	-68.5	0.077	30	42020	Thule, Greenland
ypg	2013	32.87	32.69	-117.14	0.139	30	722930	Yuma, AZ (San Diego, CA)
wal	2013	37.85	37.66	-75.48	0.004	30	724020	Wallops Island, Virginia
bar	2019	21.98	21.85	-159.34	0.036	30	911650	Barking Sands, Hawaii (Lihue)
cap	2019	28.47	28.31	-80.57	0.004	30	747940	Cape Canaveral, FL
chl	2019	35.68	35.5	-117.68	0.665	30	746120	CHINA LAKE NAWS, CA
dug	2019	40.77	40.58	-111.97	1.289	30	725720	DUGWAY PROVING GROUNDS, UT
eaf	2019	34.91	34.73	-117.88	0.723	30	723810	Edwards AFB, CA
kmr	2019	8.73	8.67	167.75	0.004	30	913660	KWAJLEIN MISSILE RANGE, Pacific
ptu	2019	34.12	33.94	-119.12	0.004	30	723910	Pt. Mugu Naval Air Station, CA
vaf	2019	34.73	34.55	-120.57	0.1	30	722930	Vandenberg AFB, CA
wal	2019	37.85	37.66	-75.48	0.004	30	724020	WALLOP ISLAND, VA
wsm	2019	32.94	32.77	-106.42	1.219	30	722690	White Sands Missile Range, NM
ypg	2019	32.87	32.69	-117.14	0.098	30	722930	YUMA PROVING GROUNDS, AZ

Depending on the value of the user specified *RRAOuterRadius*, and the proximity of the various RRA sites used, it may be possible that a given trajectory location is in the vicinity of more than one RRA site (e.g. for locations near Point Mugu, Edwards AFB and Vandenberg AFB). If a given trajectory location could be influenced by more than one RRA site, only data from the nearest (highest weight) site is used. Note that if the user desires to always use a specific RRA site (e.g. Edwards) and never use a nearby RRA site (e.g. Point Mugu), then the name and information for the undesired nearby RRA site should be removed from the file list, and the modified site list used, as specified by input parameter *RRASiteList*.

RRA data apply from 0 km to at most 70 km above mean sea level. There is also a smooth interpolation process to transition from the RRA data to Earth-GRAM data as the top of the RRA data is approached. This transition takes place between the next-to-highest RRA altitude (at which RRA weight = 1) and the highest RRA altitude (at which the RRA weight becomes 0).

RRA data files for a given site consist of three data files, T1sssyy.txt, T2sssyy.txt, and T3sssyy.txt, where sss is the three-character site code from the list of sites given above, and yy is the year of RRA database. The RRA data files are in the format given in the series of Range Reference Atmosphere reports (e.g. Document 361-83, Cape Canaveral Range Reference Atmosphere 0-70 km Altitude, February, 1983, Meteorology Group, Range Commanders Council). Files Txsssyy.txt correspond to Table x (x = 1-3) in the RRA reports.

Each Txsssyy.txt file contains an annual average data set, as well as 12 monthly data sets. Only the RRA data for the desired month are used by Earth-GRAM, and the annual average data are always ignored on read-in. For 2006, 2013, and 2019 RRA data, the annual average data follows the 12 monthly data sets. Annual data precedes the 12 monthly data sets in the 1983 RRA data files.

RRA Table-1 data contain wind statistical parameters: height, mean Eastward wind, standard deviation of Eastward wind, correlation between Eastward and Northward wind, mean Northward wind, standard deviation of Northward wind, mean wind speed, standard deviation of wind speed, skewness of wind speed(*), and number of observations(*). Asterisks denote parameters that are not used or output by Earth-GRAM (although any RRA data having number of observations less than 10 is ignored by the RRA read routines).

RRA Table-2 data contain thermodynamic statistical parameters: height, mean pressure, standard deviation of pressure, skewness of pressure(*), mean temperature, standard deviation of temperature, skewness of temperature(*), mean density, standard deviation of density, skewness of density(*), number of pressure observations(*), number of temperature observations(*), and number of density observations(*). Again, any data having fewer than 10 observations are ignored by the RRA read routine.

RRA Table-3 data contain moisture related statistical parameters: height, mean vapor pressure, standard deviation of vapor pressure, skewness of vapor pressure(*), mean virtual temperature(*), standard deviation of virtual temperature(*), skewness of virtual temperature(*), mean dewpoint temperature, standard deviation of dewpoint temperature, skewness of dewpoint temperature(*), number of observations of vapor pressure and dewpoint temperature(*), and number of observations of virtual temperature(*).

User-provided RRA data can also be used if the following conditions are adhered to. Each new RRA site must be entered into the rralist file (maximum total number of sites allowed is 99). The site code can be any 3-character code not already being used. Heights for any new RRA data must be in the range from 0 to altitude Zmax (km), as given in the rralist file. Heights should be given in ascending order in the Txsssyy.txt files, with 300 or fewer heights entered (height increments can be any value, and fixed height increments do not have to be used). The first data line of each Txsssyy.txt may have descriptive information (such as site name). However, the first data line of each file MUST contain the site geodetic latitude and longitude.

Latitude is given as xx.xxN or xx.xxS; longitude is given as xxx.xxE or xxx.xxW. Latitude and longitude values from the first data line are compared with the latitude and longitude in the rralist file, to ensure that the appropriate site data are being used. In the rralist file, north latitudes are positive (and south latitudes are negative), while east longitudes are positive (and west longitudes are negative). Each file T1sssyy.txt or T2sssyy.txt must have five header lines preceding each monthly set of data values. Each file T3sssyy.txt must have six header limes preceding each monthly set of data values. Monthly data values for all 12 months must be provided. The data lines may be in free-field (list directed) format, but must contain a numerical value for each of the parameters expected, specific to each Table type. Parameters not used by Earth-GRAM (those indicated by asterisks, above) may be input as zero values (except for number of observations, which can be any number greater than 10). Missing values (i.e. those that will be ignored) may be indicated by using 99.99 or 999.99.

2.5 Water Vapor and Other Atmospheric Species Concentrations

Water vapor and other atmospheric species concentrations were introduced in GRAM-95, with values above 90 km from the MET model and provided by a species concentration database discussed in section 4.3 of Justus et al.[6]. Water vapor output from Earth-GRAM includes both monthly means and standard deviations. The water vapor values vary with month, height, latitude, and longitude.

Means and standard deviations in water vapor are represented in the form of vapor pressure (N/m^2), vapor density (kg/m^3), dewpoint temperature (K), and relative humidity (%). Mean water vapor values in the form of volume concentration (ppmv) and number density ($molecules/m^3$) are also output. Only monthly mean concentration values are output for species, other than water vapor, in the form of volume concentration and number density values.

Interpolation of the dewpoint temperature for altitudes between the input pressure levels and for latitude and longitude between the input grid points is handled the same as the other variables. Height and latitude interpolation between input height-latitude grid points for water vapor above the 10 mb level, and for the other species, is done by an adaptation of the two-dimensional interpolation discussed in section 2.11.2 (to do height-latitude interpolation rather than latitude-longitude interpolation).

Species concentrations $c(t)$ are assumed to change with year, t, according to the relation

$$\boldsymbol{c(t) = c(t_0)(1 + r_t)^{t-t_0}} \tag{1}$$

where t_0 is 1976 for the AFGL data and 1981 for the MAP concentration data and r_t is 0.005 for CO_2, 0.009 for CH_4, 0.007 for CO, and 0.003 for N_2O. For ozone, r_t varies linearly from 0.003 at the surface to 0 at 15 km, linearly from 0 at 30 km to -0.005 at 40 km, and again linearly from -0.005 to 0 at 120 km. The rate of change, r_t, for water vapor and the other constituents is assumed to be zero.

2.6 The Model Data Locations

The "modeldata" folder consists of several types of data in several formats easily readable as ASCII characters. This folder contains zonal-mean data in "zdata.txt", stationary perturbations in "sdata.txt", and topographic data in "topo.txt". Smaller data sets have been embedded into the code to speed up initialization and to localize data within the appropriate model. The particular data locations will be described below.

2.6.1 Zonal-Mean Data

The zonal-mean data consists of 12 monthly sets of zonal-mean values for pressure, density, temperature, and zonal wind, tabulated at 10° latitude intervals from -90° to +90° and 5-km height increments from 20 km to 120 km. Prefix codes, ZP, ZD, ZT, and ZU indicate pressure, density, temperature, and zonal wind, respectively. Each record contains the code, month, height in km, and -90°, -80°, ..., 80°, 90° latitude values of the parameter expressed as a four-digit integer with an exponent common to all values in the field appearing at the end of the record. Thus, a value of 2761 with an exponent at the end of the record of -6 would be the same as $2761 \times 10^{-6} = 2.761 \times 10^{-3}$. Pressure data are in units of N/m^2, density values kg/m^3, temperatures K, and zonal winds m/s. The zonal-mean data set contains 1008 readable records, the code, and 22 integer values in each record.

2.6.2 Stationary Perturbations

The stationary perturbations are latitude-longitude dependent, relative perturbations, to be applied to the zonal-mean values. Data for each of 12 months are given for the Northern and Southern Hemisphere latitudes. Prefix codes SP, SD, ST, SU, and SV indicate stationary perturbation values for pressure, density, temperature, zonal (eastward), or meridional (northward) wind components, respectively. Each record contains the code, month, height in km, latitude (-80 to +80) in degrees, and 18 values of stationary perturbations, in per mil (%/10) for thermodynamic variables, and 0.1 m/s for winds at longitude 180, 160 W, 140 W, ..., 140 E, and 160 E degrees. The monthly mean value, y_m, for parameter, y (pressure, density, or temperature), at any latitude and longitude is computed from the zonal-mean value, z_y, at the latitude and stationary perturbation, s_y (in per mil) at the latitude and longitude, by the relation

$$y_m = z_y\,(1 + s_y/1000). \qquad (2)$$

For zonal (eastward) wind components, the monthly mean is $u_m = z_u + s_u$, while meridional (northward) mean winds are equal to the stationary perturbation value, i.e., $v_m = s_v$. Note that the stationary perturbation values at 90° latitude are always zero. The stationary perturbation data consists of 15 300 readable records with a code and 21 integer values in each record.

2.6.3 Topographic and Land Code Data

The last group of data in the “modeldata” data folder contains global information used for the boundary layer model. The first column and second column contain longitude and latitude, respectively, in degrees. The third column is the land code as shown in table 2 of section 2.10.1. The fourth column is the elevation of the surface in meters above sea level.

2.6.4 Random Perturbations

Random perturbation magnitudes (standard deviations) are dependent only on latitude. Prefix codes RP, RD, RT, RU, and RV indicate random perturbation magnitudes in pressure, density, temperature, zonal (northward) wind, and meridional (eastward) wind components, respectively. This data is embedded into the MapData.cpp source file as rpData, rdData, etc.

Each random perturbation record has the code, month, and height in km, followed by 19 values of random perturbation magnitude at 10° latitude increments from -90° to +90° followed by a common exponent value. These data give the relative standard deviations σ_p/p, σ_ρ/ρ, and σ_T/T (in percent) for use in the random perturbation model. The code RU and RV data are similar, except the wind perturbations are absolute deviations in m/s and cover the height range 0 to 200 km, whereas the RP, RD, and RT data cover 20 to 200 km. Random perturbation magnitudes for 0 km to the 10 mb level altitudes are provided by the NCEP database for both the thermodynamic and wind variables. The random perturbation data consist of 1 596 readable records with code and 22 integer values in each record.

2.6.5 Large-Scale Fraction Data

From daily difference analysis described in section 2 of Justus *et al.*[3], the fraction of the total variance (σ^2 from the random perturbation data) contained in the large-scale perturbations was determined as a function of height and latitude. The model data includes the annual average fraction (expressed as per mil) of total variance contained in the large-scale. Large- and small-scale magnitudes, σ_L and σ_S, are computed from the fractional data, f_L, in per mil (code PT for pressure, density, and temperature or code PW for winds), by the relations

$$\sigma_L = (f_L/1000)^{\frac{1}{2}}\sigma_T \tag{3}$$

$$\sigma_S = \left(1-(f_L/1000)\right)^{\frac{1}{2}}\sigma_T \tag{4}$$

where σ_T is the total perturbation magnitude. The code PT and PW data sets contain 25 readable records, with code word PT or PW, followed by 17 integer values in each record for code PT and 12 integer values for PW code records. This data in embedded in the EarthAtmosphereData.cpp source file as ptData and pwData.

2.6.6 Density-Velocity Correlations

Daily difference analysis was also used to evaluate the cross correlations for use in the velocity perturbation model described in section 2 of Justus *et al.*[6] and in Justus *et al.* [3,4]. Both large-scale and small-scale values of the density-velocity correlations were evaluated and are given in the model data (codes CL and CS) in per mil (i.e., divide by 1000 to get correlations in the range -1 to +1). The code CL and CS data consist of 50 readable records with code word CL or CS followed by 12 integer values in each record . This data in embedded in the EarthAtmosphereData.cpp source file as clData and csData.

2.6.7 Variable-Scale Random Perturbation Model Data

Variable-scale random perturbation model data are also embedded in the EarthAtmosphereData.cpp source file as rsData. They consist of 29 readable records containing a code (RS) and 10 real (floating-point) values each. For a description of these parameters, see page 12 of Justus, *et al.*[6].

2.6.8 Langley Research Center Data

The MapData.cpp source file contains the NASA Langley Research Center (LaRC) concentration data[12] for the atmospheric constituent H_2O encoded in the lData array. The data consist of 4 groups of 35 records of a code and nine data values each (one height and 8 associated array values at latitudes -70° through +70°). The four record groups present seasonal data at latitudes -70° through +70° for heights 6.5 through 40.5 km. Codes are LDJF for Dec-Jan-Feb, LMAM for Mar-Apr-May, LJJA for Jun-Jul-Aug, and LSON for Sep-Oct-Nov.

2.6.9 Air Force Geophysics Lab Data

The MapData.cpp source file also contains the Air Force Geophysics Laboratory (AFGL) concentration data[11] for the atmospheric constituents, H_2O, O_3, N_2O, CO, and CH_4 within the aData array. The data consist of five groups of 50 records of 6 values each (one height and 5 associated array values for each of the five constituents). The five record groups present tropical (AFTR), mid-latitude summer (AFMS), mid-latitude winter (AFMW), sub-arctic summer (AFSS), and sub-arctic winter (AFSW) data. Tropical data are for latitudes of ±15°, mid-latitude data are for ±45°, and sub-arctic data are for ±60°. As necessary, a 6-month displacement is used to estimate southern hemisphere values from northern hemisphere values.

2.6.10 Middle Atmosphere Program Data

The Middle Atmosphere Program (MAP) concentration data[13] for the years 1979 to 83 is found in the MapData.cpp source file. The code O3 data are for ozone at 24 pressure levels (0.003 to 20 mb) for 12 months is encoded into the o3Data array. Each of the 288 records consists of the code, month, pressure level (mb), and data values for 17 latitudes (-80° to +80°) and a common exponent value. The code H2O data are for water vapor at 11 pressure levels (1.5 to 100 mb) for 12 months, followed by 8 annual values (denoted by month 13) for the pressure levels 0.01 to 1.0 mb. There are a total of 140 H2O records. Each contains the code, month, pressure level (mb), and five mean values at latitudes -60°, -45°, ±15°, +45° and +60° (with -60° estimated by 6-month displacement of +60° data), followed by five standard deviation values at these latitudes. The code N2O data are for MAP nitrous oxide (code CH4 data for methane). The N2O and CH4 data consist of 204 records each. Each record contains the code, month (1 to 12), pressure level (17 levels, 0.1 to 20 mb), data at 15 latitudes (-70° to +70°) and a common exponent. The code OX data is for atomic oxygen at 19 altitudes (130 to 40 km) for each month. There are 228 total records, each containing the code, month, height (km), data values at 17 latitudes (-80° to +80°), and a common exponent. Units of the MAP code OX data are atoms/cm^3. The MAP code O3, H2O, and CH4 species data values are volume concentrations in units of parts per million by volume (ppmv) while the code N2O data are in parts per billion by volume (ppbv).

2.7 CorrMonte

CorrMonte is a tool in Earth-GRAM developed for release in Earth-GRAM 2010. CorrMonte is a program that provides hourly atmospheric dispersions as opposed to typical monthly atmospheric dispersions provided in Earth-GRAM. CorrMonte employs an exponential correlation from equation (39) in section 2.12.1 to correlate dispersed data points on an hourly time scale. This correlation is also used for calculating the small-scale perturbation as detailed in section 2.12.1. The correlation is then used to recalculate the small-scale perturbation. This process limits the dispersions to an hourly time scale. CorrMonte provides hourly dispersions about a random profile or the mean profile. Plots of CorrMonte output are provided in section 3.0.

2.7.1 CorrMonte Comparison to Hourly Wind Pairs Data Sources

A comparison study was performed with CorrMonte hourly dispersions, the Jimsphere balloon hourly wind pairs database, the Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2) wind pairs, and the NASA Launch Service Provider (LSP) hourly wind pairs. The LSP pairs consist of data from the 50-MHz Doppler Radar Wind Profiler and the 915-MHz Doppler Radar Wind Profiler. The comparison was conducted at Cape Canaveral, Florida for January and October. The comparison analyzed the standard deviation of dispersed 3-hour east-west and north-south winds. Figure 2 is the 3-hour comparison plot of January east-west wind standard deviations. The plot shows CorrMonte comparing favorably to the Jimsphere and LSP pairs, with CorrMonte enveloping the two databases.

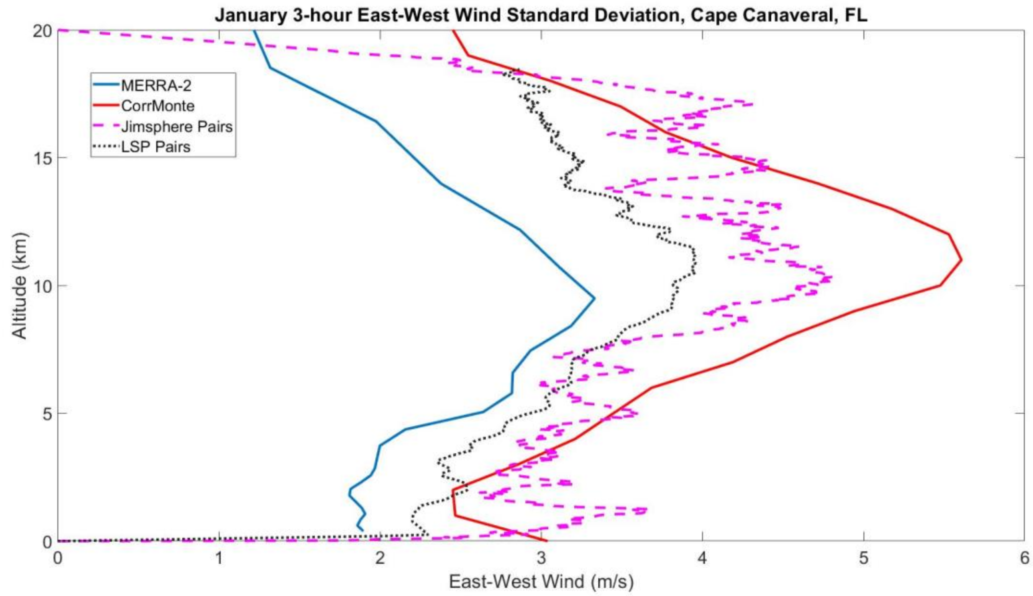

Figure 2. January 3-hour Comparison of East-West Wind Standard Deviation.

Figure 3 is the 3-hour comparison plot of January north-south wind standard deviations. CorrMonte compares favorably with the three comparison datasets, with the Jimsphere and LSP pairs enveloping CorrMonte.

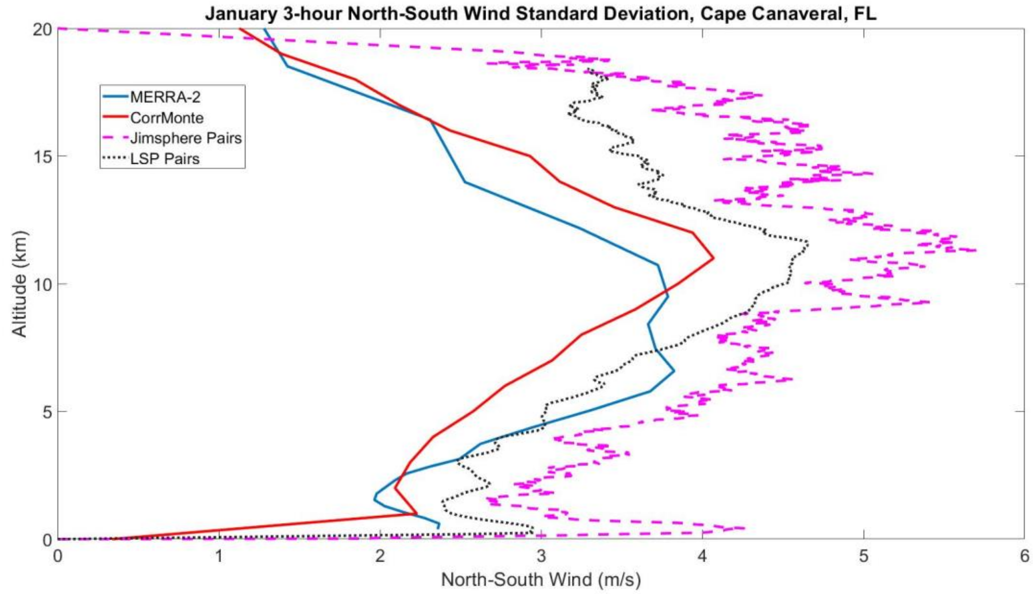

Figure 3. January 3-hour Comparison of North-South Wind Standard Deviation.

Figure 4 is the 3-hour comparison plot of October east-west wind standard deviations. CorrMonte compares favorably to the Jimsphere and LSP pairs datasets. Figure 5 is the 3-hour comparison plot of October north-south wind standard deviations. CorrMonte compares favorably to the pairs datasets, with the Jimsphere and LSP pairs enveloping CorrMonte.

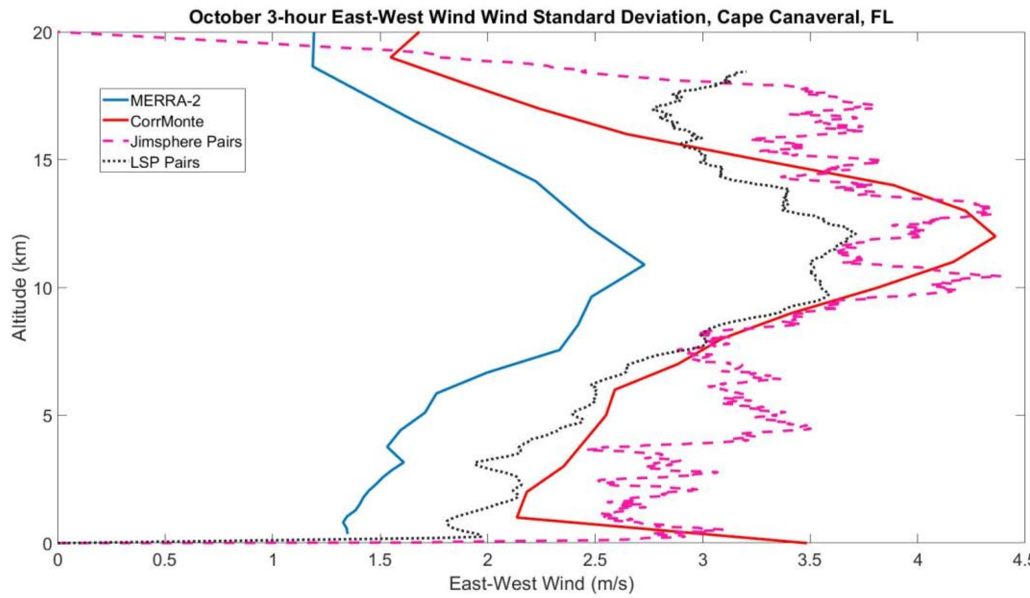

Figure 4. October 3-hour Comparison of Earth-West Wind Standard Deviation.

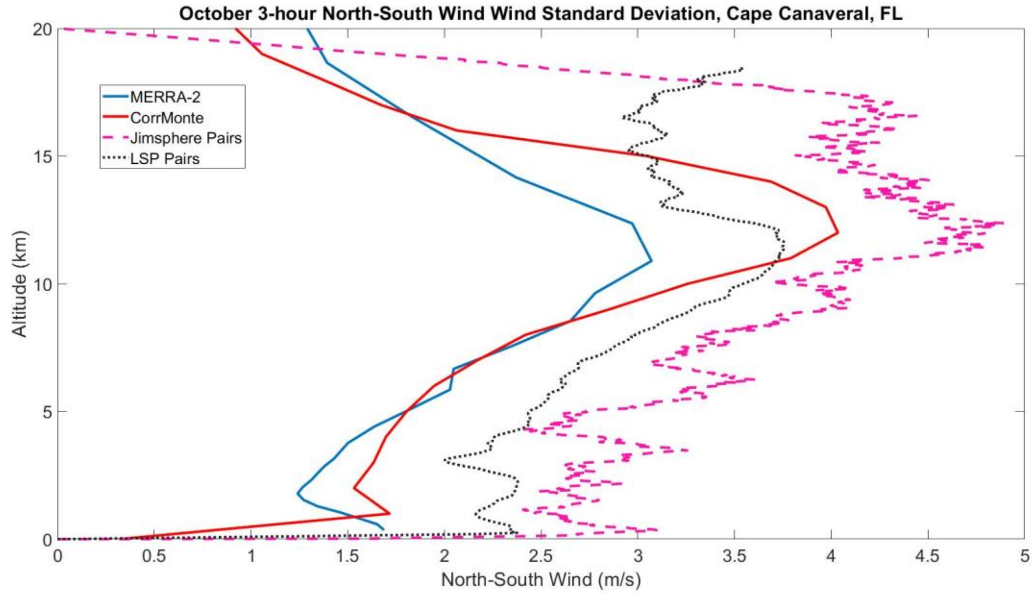

Figure 5. October 3-hour Comparison of North-South Wind Standard Deviation.

This comparison study validates CorrMonte to be a good tool at estimating 3-hour wind change. CorrMonte compares well to wind pairs datasets consisting of reliable wind measurement sources when analyzing east-west and north-south wind.

2.8 Ballistic Trajectory

The Ballistic Trajectory is a feature in Earth-GRAM that is utilized to correlate the dispersions in a ballistic (up-down) trajectory. Due to the Markov statistical method used in calculating the small-scale perturbations in Earth-GRAM, the dispersions are not correlated for a ballistic trajectory resulting in the need for this feature. The ballistic trajectory feature employs the exponential correlation equation (39) to correlate dispersions between the nearby ascending and descending trajectory data points. Plots of Ballistic Trajectory output is provided in Section 3 Sample Output.

2.9 Earth Correlator

The Earth Correlator feature in Earth-GRAM is used to correlate dispersions between multiple objects. The Earth Correlator uses the exponential correlation calculation from equation (39) in section 2.12.1 to correlate dispersion between multiple nearby objects. Plots of Earth Correlator output are provided in Section 3 Sample Output.

2.10 The Boundary Layer Model for Vertical Velocity

2.10.1 Background

A small-scale vertical wind perturbation model has been part of the Earth-GRAM since its 1995 release[6]. Height-dependent standard deviations of vertical winds were taken from Justus et al.[27]. This vertical wind model continued in Earth-GRAM through the 1999 release[8] and Version 1.1 of the 2007 release[9]. Recent interest in capsule parachute landing simulations led to including a vertical wind distribution as a function of horizontal wind and underlying surface characteristics (surface roughness). An earlier version of the vertical wind model, designed to address these issues, was released in October 2008 as Earth-GRAM 2007 Version 1.2. That model incorporated many features of boundary layer (BL) effects on vertical wind standard deviations. However, time-of-day effects were not addressed, atmospheric stability influence was represented in only an approximate fashion, and boundary layer depth was assumed to be a constant value of 1500 m. A revised vertical wind model was released in Earth-GRAM 2010 and incorporated the effects of these additional factors. This model computed standard deviation for BL vertical wind as a function of surface type (water or various land types) and surface horizontal wind at 10 m height. Surface height above Mean Sea Level (MSL) is interpolated from the 1-by-1 degree topographic database of Gates and Nelson[25] or from Range Reference Atmosphere surface altitude, if the Earth-GRAM RRA option is selected. Boundary layer depth is computed from a time-of-day and stability-dependent model. Land cover type is given at 1 degree resolution from the database of DeFries and Townshend[26]. Surface Type codes are shown in table 2. Surface roughness (z_o) values assumed for each surface type were computed as the geometric mean value from a variety of sources and are also given in table 2. To account, in an approximate way, for the influence of mountainous topography on z_o, values from table 2 are increased linearly for surface altitudes above 1.5 km MSL, up to either a maximum surface height of 4.5 km, or to a maximum z_o of 3 m, whichever is appropriate. Surface wind dependence is based on hourly average wind speed, computed from wind components given by monthly mean wind at 10 m plus Earth-GRAM large-scale perturbed wind components at the surface. Since Earth-GRAM large-scale wind perturbations change from profile-to-profile in a Monte-Carlo run, the surface wind speed changes from profile-to-profile.

Table 2. Surface codes and associated z_o values.

Code	Land Cover Class	z_o (m)
0	water	u-dependent
1	broadleaf evergreen forest	0.6
2	coniferous evergreen forest and woodland	0.48
3	high latitude deciduous forest and woodland	0.42
4	tundra	0.0056
5	mixed coniferous forest and woodland	0.45
6	wooded grassland	0.12
7	grassland	0.046
8	bare ground	0.015
9	shrubs and bare ground	0.042
10	cultivated crops	0.065
11	broadleaf deciduous forest and woodland	0.45
12	data unavailable (re-assigned to Codes 4, 6, or 13, as appropriate)	-.-
13	ice	3.2E-4

While the surface roughness over land is determined from table 2, z_o over water is based on the formulation of Donelan, et al.[28] as

$$z_o = \frac{\alpha u_*^2}{g} \quad (5)$$

where g is the gravitational acceleration and u_* is the friction velocity. The co-dependence of z_o and u_* is solved by a 4-step iteration process. There is also an option whereby the user may supply any desired z_o value (between 10^{-3} m and 3 m), to be used in place of these prescribed values.

Friction velocity is computed from the standard logarithmic "law of the wall" for neutral atmospheric stability, modified by a stability-dependent term (ψ)

$$u_* = \frac{0.4U_{10}}{ln\left(\frac{10}{z_O}\right) - \psi\left(\frac{10}{L}\right)} \tag{6}$$

where U_{10} is the wind speed at 10 m height, L is the Monin-Obukhov length. The boundary layer wind profile function is given by

$$\psi\,(10/L) = \begin{cases} -50 / L & \text{if } 1/L > 0 \quad \text{(stable)} \\ 0.0 & \text{if } 1/L = 0 \quad \text{(neutral)} \\ 1.0496\,(-10/L)^{0.4591} & \text{if } 1/L < 0 \quad \text{(unstable).} \end{cases} \tag{7}$$

the unstable formulation for ψ is from Hsu *et al*.[29], and is a simplification of an often used, but more complicated expression derived by Paulson[30].

The inverse of the Monin-Obukhov length ($1/L$) is calculated by a 4-step process, based on information derived from table 4-7, table 4-8, and figure 4-9 of Justus[31]. First a net radiation index (n_r) is computed that depends on solar elevation angle and time-of day (or night), where n_r ranges from -3.5 (strong outgoing net radiation) to + 4.5 (strong incoming net radiation). See Justus[31], table 4-7. Then a wind-speed factor $W(U_{10})$ is computed from empirically-derived functions:

$$W(U_{10}) = \begin{cases} (1 - U_{10} / 7.5) & \text{if } U_{10} < 6 \text{ m/s} \\ 0.2 & \text{if } U_{10} = 6 \text{ m/s} \\ 0.2\,\text{Exp}(12 - 2\,U_{10}) & \text{if } U_{10} > 6 \text{ m/s} \end{cases} \tag{8}$$

A stability category ξ is computed as a function of $W(U_{10})$ and n_r by

$$\xi = 4.229 - n_r\,W \tag{9}$$

which is an empirical fit to Justus[31] table 4-7. Values of ξ are limited to 0.5 on the low side (most unstable) and 7.5 on the high side (most stable). Finally, the inverse Monin-Obukhov length versus stability category ξ and surface roughness length is determined using

$$1/L = (1/4)\,(-0.2161 + 0.0511\,\xi)\,\text{Log}_{10}(10/z_o) \tag{10}$$

which is an empirical fit to figure 4-9 of Justus[31]. These steps are similar to the methodology of Blackadar *et al*.[32] for the estimation of L.

The standard deviation of vertical wind is now computed as a function of height above the surface and stability-dependent Monin-Obukhov length by relations:

$$\sigma_w = \begin{cases} 1.25\,u_*\,(1 + 0.2\,z/L) & \text{(stable; } 1/L > 0) \\ 1.25\,u_* & \text{(neutral; } 1/L = 0) \\ 1.25\,u_*\,(1 - 3\,z/L)^{1/3} & \text{(unstable; } 1/L < 0) \end{cases} \tag{11}$$

where the stable relation is from equation 1.33 of Kaimal and Finnigan[33] and Pahlow et al.[34], and the unstable relation is from equation (2), Page 161, of Panofsky and Dutton[35], a relation which has been widely used to represent this factor for the unstable atmospheric surface layer (e.g. Kaimal and Finnigan[33], Blackadar[36], Johansson, et al.[37], Dardier, et al.[38]). A variety of different formulations for σ_w in stable situations have been suggested, including a formula equivalent to the unstable relation in equation (11) [e.g. equation (8) and table 1 of Mahrt et al.[39]]. However, a simple linear relationship for the stable case, such as given in equation (11), has been more widely used.

As shown by Panofsky[40], Caughey and Palmer[41], and in Panofsky and Dutton's[35] discussion of their figure 7.2, equation (11) is not expected to apply above about z = 0.1 d, where d is the boundary layer depth. Therefore, for stable and neutral cases, σ_w is limited to a value of 3.75 u_*, while for unstable cases, σ_w is limited by the magnitude of the convective velocity w_*, to a value of σ_w < 0.62 w_*, where w_* is given by

$$w_* = u_*[-d/(0.4L)]^{1/3} \tag{12}$$

(equation 4 of Panofsky[40]). These limiting values account for transition from the surface layer to the convective layer (z/L < 0) or to the stable boundary layer (z/L > 0).

The boundary layer depth d is calculated from simplifications of methodologies given by Sugiyama and Nasstrom[42], Batchvarova and Gryning[43], and Seibert[44]. For stable-to-neutral cases, the methodology of Section 2.1 of Sugiyama and Nasstrom[42] is used:

$$d = 2d_N/\left[1 + (1 + 4d_N/L)^{1/2}\right] \tag{13}$$

except that their form for the neutral boundary layer depth (d_N) is changed from

$$d_N = 0.2u_*/f \tag{14}$$

to

$$d_N = u_*[80/(\omega^2 f)]^{1/3} \tag{15}$$

where f is the Coriolis parameter and ω is the Brunt-Vaisala frequency.

For the unstable boundary layer, the time-dependent differential equation solution of Batchvarova and Gryning[43], as expressed in Seibert[44], is converted to an algebraic equation by assuming that the time rate of change of d can be replaced by $d\,f$ / 2. This operation yields an analytical equation for d

$$d = d_N(1 - 0.1125d/L)^{1/3} \tag{16}$$

whose solution can be found by iteration.

For time variation between sunrise (if applicable) and mid-day, a time-factor multiplier $G(E_l)$, given by

$$G(E_l) = 0.3 + 0.7E_l/E_{md} \tag{17}$$

is applied, where E_l is at the current time and E_{md} is mid-day solar elevation. This allows for time variation of boundary layer depth to be accounted for in an analytical fashion, rather than the solution of a differential equation versus time.

Subject to the above-mentioned limiting values, the height-dependent equations given in equation (11) of this paper are used to compute σ_w from the surface to the top of the boundary layer. As part of its vertical wind model, Earth-GRAM contains values of σ_w at 5 km intervals (above MSL). Between the top of the boundary layer and the next height for which σ_w is available, linear interpolation is used to estimate σ_w.

Calculation of the vertical wind perturbations in Earth-GRAM did not change as a result of the additions made to Earth-GRAM 2010. The only changes made were to the methodology for computing standard deviation of vertical wind. Values of σ_w were constrained to be 0.1 m/s or greater since the perturbation calculation methodology does not work properly if σ_w is zero. Calculation of mean vertical winds (typically a few cm/s or less) is still done by a Montgomery stream function approach, first implemented in GRAM-90 as shown in section 2.7 of Justus et al.[5], and the perturbations are determined from a 1-step Markov algorithm.

2.11 Interpolation and Fairing

2.11.1 Vertical Interpolation

Pressure, $p(z)$, temperature, $T(z)$ and density, $\rho(z)$, obey the perfect gas law

$$p = \rho RT \tag{18}$$

where R is the gas constant. They also agree very closely with the hydrostatic assumption

$$dp/dz = -\rho g \tag{19}$$

where g is the acceleration of gravity. If we have grid-point pressure values, p_1 and p_2, and temperature values, T_1 and T_2, at heights, z_1 and z_2, then vertical interpolation to any height z (between z_1 and z_2) is done by assuming a linear temperature variation

$$T(z) = T_1 + \Gamma(z - z_1) \tag{20}$$

where Γ is the temperature gradient and given by,

$$\Gamma = (T_2 - T_1)/(z_2 - z_1) \tag{21}$$

The hydrostatic relation, with a constant temperature gradient implies a power-law variation with pressure. So pressure, $p(z)$, may be computed by

$$p(z) = p_1 \left[\frac{T(z)}{T_1}\right]^{-a} \tag{22}$$

where the exponent, a, is given by

$$a = g/(R\Gamma). \tag{23}$$

In the NCEP height range, this vertical interpolation is complicated by the fact that the moisture varies with height and the gas constant for moist air depends on the moisture concentration. For the NCEP data, a variant of equation (23) uses an interpolated gas constant, R.

The exponent *a* can be evaluated using two levels where temperature and pressure are known:

$$a = log(p_2/p_1)/\, log(T_1/T_2) \qquad (24)$$

For an isothermal layer where $T_1 = T_2$, then equation (22) becomes

$$p(z) = p_1\, exp\left[\frac{-g(z-z_1)}{RT_1}\right] \qquad (25)$$

The density, $\rho(z)$, is found by solving the perfect gas law relation [equation (18)].

The form of vertical interpolation given by equation (22) is used to fill in mean values of pressure, density, and temperature between the input pressure levels of the NCEP data (with z the geopotential height) and the zonal mean values between the input height grids of the MAP database. Other variables that do not obey perfect gas law relationships (e.g., wind components, dewpoint temperature, and all standard deviations) are interpolated linearly in the vertical.

2.11.2 Two-Dimensional Interpolation

Let V be a variable that is available on a two dimensional grid array (x and y) and consider the grid point values $V_{11} = V(x_1, y_1), V_{12} = V(x_1, y_2), V_{21} = V(x_2, y_1)$ and $V_{22} = V(x_2, y_2)$. Then any value $V(x, y)$ (for x between x_1 and x_2 and y between y_1 and y_2) may be found by the interpolation scheme

$$V(x, y) = \alpha'\beta' V_{11} + \alpha'\beta V_{12} + \alpha\beta' V_{21} + \alpha\beta V_{22}, \qquad (26)$$

where $\alpha = (x - x_1)/x_2 - x_1), \alpha' = 1 - \alpha, \beta = (y - y_1/(y_2 - y_1)$, and $\beta' = 1 - \beta$. This interpolation relation is mathematically equivalent to that used (for latitude-longitude interpolation) in earlier Earth-GRAM versions but is expressed here in a more symmetric notation.

Equation (26) is used to interpolate between latitude-longitude grid points (x = longitude, y = latitude) for the NCEP grids and the stationary perturbation grids of the MAP data. For variables dependent on a height-latitude (or a pressure-latitude) grid (such as the species concentration data), then equation (26) is used with y = latitude and x = height (or x = log pressure). The variables actually interpolated for concentration data are the logarithms of the concentration values.

2.11.3 Interpolation Across the Poles

Several Earth-GRAM databases that are height-latitude dependent lack values at or near the poles. These are filled in by an interpolation procedure that assumes a parabolic variation (across both sides of the pole) that fits the last and next-to-last available latitude. The results are a weighted average of these last and next-to-last latitude values. For example, if values of a parameter are available at ±70° and ±80°, but not at ±90°, then the missing polar values are supplied by

$$y_{\pm 90} = (4\, y_{\pm 80} - y_{\pm 70}) / 3 \quad (27)$$

If values are available at ±60° and ±70° but not at ±80° or ±90°, then the missing values are supplied by

$$y_{\pm 90} = (9\, y_{\pm 70} - 4\, y_{\pm 60}) / 5, \quad (28)$$

and

$$y_{\pm 80} = (8\, y_{\pm 70} - 3\, y_{\pm 60}) / 5. \quad (29)$$

For the species concentration data, this interpolation is done on the logarithm of the concentration values.

2.11.4 Fairing Between Two Data Sets

If there are two data sets, $A(z)$ and $B(z)$, that overlap throughout the height range from z_1 to z_2 (with A valid below z_2 and B valid above z_1 and $z_2 > z_1$), then a fairing process

$$C(z) = f(z)A(z) + [1 - f(z)]B(z) \quad (30)$$

ensures a smooth transition for the faired variable, C, across the height interval from z_1 to z_2 if $f(z_1) = 1$ and $f(z_2) = 0$. Thus, $A(z)$ is used below z_1, $B(z)$ above z_2, and the faired variable, $C(z)$, varies smoothly between $A(z)$ and $B(z)$ as z varies from z_1 to z_2. A linear form is used for f

$$f(z) = (z_2 - z)/(z_2 - z_1), \quad (31)$$

or, with variables for which continuity of vertical derivatives is important, f is taken as

$$f(z) = cos^2[\,(\pi/2)(z - z_1)/(z_2 - z_1)]. \quad (32)$$

Equation (32) is used in fairing between the NCEP and MAP data between 20 and 27 km, between the thermosphere model and MAP data between 90 and 120 km, and the helium number density in the MET model between 440 and 500 km. For fairing the species concentration data, equation (31) is used with the logarithm of the species concentration as the variable to fair.

2.11.5 Seasonal and Monthly Interpolation

Some of the species concentration databases do not contain monthly data. For example, the AFGL concentrations are seasonal averages (summer and winter), the LaRC water vapor data contain four seasonal averages, and the MAP water vapor data contain only certain months of the year (November through May). The initialization routines in Earth-GRAM use an annual harmonic temporal variation model to estimate the concentration data for the specific month to be simulated. For the AFGL data, this is accomplished by applying pre-computed weights to obtain a weighted average of the summer and winter values used to estimate the value for the specific month. For the LaRC water vapor data, a weighted average of the two adjacent seasonal values is used to estimate the monthly value (i.e., Mar-Apr-May and Jun-Jul-Aug values are used to estimate the monthly values for May and June with different weights applied for month). For the MAP water vapor data, a combination of annual harmonic Fourier fit and 6-month displacement from northern to southern hemisphere (and vice-versa) is used at initialization to establish the global values for each month from the monthly values of November through May in the database.

2.12 Perturbation Model

2.12.1 Small Scale Perturbation Model

Earth-GRAM uses a simple, first-order, auto-regressive model to compute a perturbation at each new position from the correlated perturbation value at the previous position. In addition to maintaining the correlation necessary between these successive perturbation values, the model accounts for the effects of variation in the mean values and the standard deviation from one position to another. Consider a normalized variate $\mu(x)$ (i.e., μ is the deviation of the value from the mean value, divided by the standard deviation, all at the vector position x). The perturbation model computes $\mu(x')$ at the next trajectory position x'

$$\mu(x') = r\mu(x) + (1\text{-}r^2)^{1/2}\, q(x), \tag{33}$$

where q is a Gaussian-distributed random number with a mean of 0 and standard deviation of 1, and r is the auto-correlation between the successive values of the normalized variate, i.e.,

$$r = < \mu(x')\mu(x) >, \tag{34}$$

where the angle brackets denote an average. The auto-correlation value, r, is obviously a function of the vector displacement, $\delta x = x' - x$.

Consider two normalized variates, $\mu(x)$ and $v(x)$, (each relative to its own mean value and each normalized by its own standard deviation), that have a cross-correlation r_c between them (i.e., $r_c =< \mu(x)v(x) >$). Variate $v(x')$ at the new position is computed from $v(x)$ and $\mu(x')$ by

$$v(x') = r_v v(x) + r_\mu \mu(x') + r_q q(x), \tag{35}$$

where the coefficients are given by

$$r_v = r(1 - r_c^2)/[1 - (rr_c)^2], \tag{36}$$

$$r_\mu = r_c(1 - r^2)/[1 - (rr_c)^2] , \tag{37}$$

and

$$r_q = (1 - r_v^2 - r_\mu^2 - 2r_v r_\mu r_c r)^{1/2}. \tag{38}$$

Auto-correlation values, r, are computed by assuming an exponential correlation function

$$r(\delta x) = exp(-\delta h/L_h)\, exp(-\delta z/L_z)\, exp(\delta t/\tau) \tag{39}$$

where δh and δz are the magnitudes of the horizontal and vertical components of $\delta x = x' - x$ and L_h and L_z are horizontal and vertical scale parameters that are functions of height and latitude only. Time correlation (even in the special case when the users selects $\delta h = 0$ and $\delta z = 0$) is accounted for by the third exponential term in equation (39), where τ is a time scale that varies with height and δt is the magnitude of the time step between data points.

Earth-GRAM computes the density and vertical velocity perturbations using only auto-correlation by utilizing a form of equation (33) with the correlation coefficient from equation (39)). Pressure perturbations are computed with cross correlation to density using a form of equation (35), correlation coefficients from equations (36) – (39), and a Buell[49,50] formulation for the pressure-density correlation. The temperature perturbation is computed from a first order version of the ideal gas law and Buell relations. The horizontal wind perturbations are also cross correlated with density with the wind-density correlation detailed in section 2.6. Additional discussion of the perturbation model is provided in sections 2.6 and 2.7 of Justus et al.[6].

Generation of Earth-GRAM perturbations starts with the observed (climatological) values of total standard deviation of observations about the monthly mean. Total variance (square of the standard deviation) is partitioned into variance contributed by two perturbation components: (1) a large-scale, wave-like perturbation, and (2) a small-scale stochastic (random) perturbation.

Vertical shears from the large-scale, wave-like perturbations in Earth-GRAM are proportional to A/λ, where A is the local wave amplitude and λ is the local vertical wavelength. Vertical shears from the small-scale, stochastic perturbations in Earth-GRAM are proportional to σ/L, where σ is the local standard deviation of the small-scale perturbations, and L is the local vertical correlation scale for the small-scale perturbations. An increase in vertical wavelength λ therefore yields smaller vertical shears from the large-scale, wave-like perturbations. A height-dependent factor on vertical and horizontal correlation scales increases L below about 15 km, while decreasing L above about 15 km. This effect decreases (increases) small-scale shears at heights below (above) 15 km., while leaving small-scale shears above 30 km unchanged. The addition of time dependence for the large-scale perturbations allows Earth-GRAM to simulate synoptic-scale variations in time as well as space.

The small-scale dispersions have a Dryden Power Spectrum. Since the small-scale dispersions are modeled with a one step Markov technique having a correlation coefficient that decreases exponentially with distance (and time), the energy spectrum is inversely proportional to the square of the length (and time) scale. Thus, most of the observed variance occurs over large length (and time) scales.

2.12.2 Patchy Severe Turbulence

To approximate intermittency or patchiness in the perturbations, a variable scale model was introduced in GRAM-95 (as shown in section 2.6 of Justus et al.[6]) and also used in Earth-GRAM 2010. The Earth-GRAM database (described in section 2.6) includes for both horizontal and vertical scales values for average scale size (L_{avg}), minimum scale size (L_{min}), and standard deviation of the variable scale size (σ_L). Periods of severe perturbations are characterized as having a scale size of L_{min}.

In the perturbation model "non-severe" (i.e., light-to-moderate) perturbations are characterized as having a scale size of L_{max}, such that

$$L_{avg} = P_{sev} L_{\min} + (1 - P_{sev}) L_{\max} \tag{40}$$

where P_{sev} is the probability of encountering severe perturbations, given by

$$P_{sev} = P_{tail}((L_{avg} - L_{\min}) / \sigma_L) \tag{41}$$

where P_{tail} is the tail probability of a Gaussian distribution. From equation (40) the scale for non-severe perturbations is given by

$$L_{\max} = (L_{avg} - P_{sev} L_{\min}) / (1 - P_{sev}) \tag{42}$$

In summary, when in severe turbulence, the length scales used in equation are the minimum length scale read in and height-interpolated from the Model Data Location (section 2.6). When in non-severe turbulence, the length scales in equation are the maximum value computed from equation (42). The triggering of severe turbulence occurs by tracking an artificial horizontal scale that is auto-correlated (using a form of equation (33)) and an artificial vertical scale that is cross-correlated with the horizontal scale (using a form of equation (35)). If either of these scales go below a minimum value, severe turbulence is initiated.

Furthermore, the variance of the severe perturbations is assumed to be $f_{sev}\sigma^2$, and the variance of the non-severe perturbations is assumed to be $f_{non}\sigma^2$, where σ^2 is the total variance of the small-scale perturbations (σ, the standard deviation of the small-scale perturbations is also given in the "model data" file data). Considering the probability of occurrence, σ^2 is given by

$$\sigma^2 = P_{sev} f_{sev} \sigma^2 + (1 - P_{sev}) f_{non} \sigma^2. \tag{43}$$

From standard deviation data in Justus et al.[27], the factor f_{sev} is approximated as varying with height, z, having values ranging from 6 at z = 0, to 12 at z = 10 km back to 6 at z = 16 km and higher. With f_{sev} thus specified, f_{non} is calculated from equation (43) by

$$f_{non} = (1 - f_{sev} P_{sev}) / (1 - P_{sev}). \tag{44}$$

As Earth-GRAM simulates perturbations along a given trajectory, it uses a random number generator to decide when (with probability P_{sev}) the perturbations are in the severe category. During this time, the variance is adjusted from its non-severe magnitude ($f_{non}\sigma^2$) to its severe magnitude ($f_{sev}\sigma^2$). Patchy severe turbulence is applied only to the small scale perturbations and not the large scale, and is enabled only when the parameter *patchy* (in the input file) has a nonzero value.

2.12.3 Large Scale Perturbation Model

While the small-scale perturbations are modeled using a stochastic process that is approximately Gaussian distributed, the large scale perturbations are modeled with a sinusoidal formulation to represent the atmospheric wave phenomena observed at this scale. The large scale density (again normalized by its mean value) is given by

$$\frac{\rho_l}{\sigma_{\rho_l}} = A_Q \frac{cos\left(n\theta + m\varphi + 2\pi\frac{z}{\lambda_z} + 2\pi\frac{t}{T} + \phi_q\right)}{\sigma_{cos}}, \quad (45)$$

where ρ_l is the large scale density, σ_{ρ_l} is the large scale standard deviation, A_Q is an amplification factor, *m* is the number of waves in the north-south direction, *n* is the number of waves in the east-west direction, *z* is height, λ_z is the vertical wavelength, *t* is the elapsed time, *T* is a randomized wave period, φ_q is a random wave phase, and σ_{cos} is the standard deviation of the cosine function and equal to $1/\sqrt{2}$. A_Q was added to this model in Earth-GRAM in order to provide exceedances beyond $\sqrt{2}$ sigma that would otherwise not occur. A_Q was determined empirically (but constrained so that the standard deviation of density is unchanged) as

$$A_Q = 0.4808 + 0.96 \bullet Q \quad (46)$$

where Q is a uniformly distributed random number between 0 and 1. Therefore A_Q varies from .4808 to 1.4408 and thus allows for 2 sigma exceedances. The same value is used for both horizontal waves number n and m. They are determined randomly for a given Monte-Carlo run from

$$m = n = \text{IntegerOf}[4.0 + 0.833 * Q_{nm}] \quad (47)$$

where Q_{nm} is a Gaussian-distributed random number with a mean of zero and sigma of 1. This formulation is derived so that the horizontal wave numbers are between 2 and 6 waves. The vertical wavelength λ_z is computed as a function of height with parameters a_v (which is randomized) and b_v which is equal to 0.045:

$$\lambda_z = a_v + b_v\sqrt{|z^3|} \quad (48)$$

The large scale pressure is similarly calculated except that an additional phase term is added to the cosine argument so that pressure and density are properly correlated. The large scale temperature is then calculated from the Buell relation and rescaled so that it reproduces the observed variance. The large scale horizontal wind components are also modeled with a cosine function and a phase shift is used for proper correlation. This correlation is taken from the RRA data or the NCEP data as appropriate. There is no model for large scale vertical velocity, only small scale values and mean (Montgomery stream function) values. Once the small and large scale perturbations are determined, they are added to the mean for the total atmospheric value.

2.13 Perturbation Model Initialization

Initial values for the perturbation model may be selected by user input, as described in the next section, or they may be random values, automatically selected by the program, as described here. Because large-scale perturbations (section 2.12.3) are wave-like and small-scale perturbations (section 2.12.1) are Gaussian-distributed random values, two different processes are used for their initialization.

2.13.1 Small-Scale Perturbations

Initial values for small-scale perturbations in density, pressure, and all three components of wind are selected randomly, from Gaussian distributions having the appropriate standard deviation for each of these quantities (at the initial position to be simulated). Initial small-scale temperature perturbation is then computed by the first-order perfect gas law, from the initial small-scale pressure and density perturbations. This initial small-scale temperature perturbation is then rescaled so that it reproduces the appropriate small-scale temperature variance.

2.13.2 Large-Scale Perturbations

Initial values for large-scale perturbations are computed from a randomly selected-wave amplitude (A_Q in equation (45)) and a randomly-selected phase for density perturbation (ϕ_q in equation (45)). Phases for other large-scale perturbations are selected to produce appropriate phase differences among all the large-scale perturbations. Once these initial wave phase values have been selected for a particular program run, variation of wave phases progress in time and space according to prescribed wave numbers and period (*n*, *m*, and *T* in equation (45)).

Initial density wave phase ϕ_q is randomly selected from a uniform distribution, with values ranging between 0 and 2π. Wave phase for pressure is shifted by an amount required to yield appropriate pressure-density cross correlation, and wave phase for large-scale perturbation in Eastward wind is shifted by an amount required to yield appropriate density-velocity correlation. Wave phase difference between Northward and Eastward wind components is selected to produce observed amount of cross-correlation (Ruv) between these components. Note that Ruv is observed cross-correlation between total (large-plus-small-scale) perturbations. Required phase shift for the large-scale Northward component is computed from Ruv/(0.02 + 0.98 f_L), where f_L is the large-scale fractional variance (0-1), discussed in section 4.3.4.

Initial large-scale temperature perturbation is computed by the first-order perfect gas law, from the initial large-scale pressure and density perturbations. This initial large-scale temperature perturbation is then rescaled so that it reproduces the appropriate large-scale temperature variance. Finally, large-scale pressure perturbation is recomputed from the 2^{nd}-order perfect gas law.

3.0 SAMPLE OUTPUT

This section examines the output generated by Earth-GRAM. Section 2 described the various data sources and features of Earth-GRAM, this section highlights output generated from Earth-GRAM to demonstrate its capabilities.

Figure 6 displays a profile of the mean and dispersed east-west wind for the month of January. Earth-GRAM output means and standard deviations, as well as dispersions about the mean, at any point in the atmosphere. The dispersions are generated by the perturbation model detailed in section 2.12.

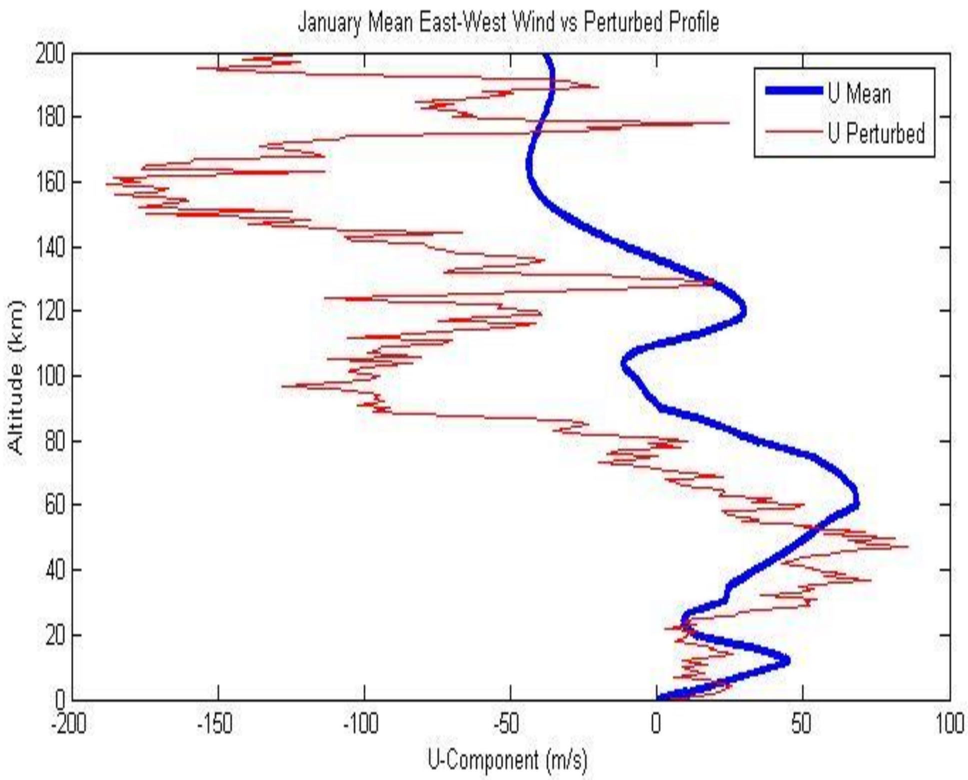

Figure 6. January Mean and Dispersed Profile of East-West Wind.

Figure 7 displays 1000 Monte Carlo dispersions of January east-west wind with the mean and 3-sigma overlaid. Earth-GRAM has the ability to generate several random dispersions about the mean in the form of Monte Carlos. Figure 8 displays the cumulative probability for east-west wind dispersions with a Gaussian distribution fit. Figure 7 and 8 provide evidence of the ability of Earth-GRAM to produce approximately Gaussian distributed dispersions. This process in the perturbation model is described in detail in section 2.12.

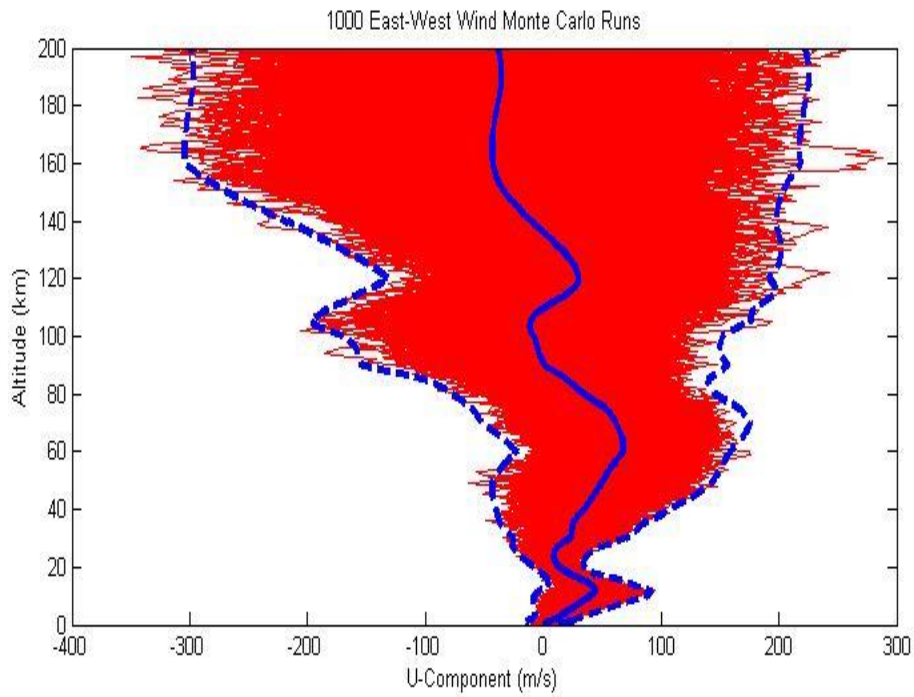

Figure 7. 1000 January East-West Wind Monte Carlo Dispersions with Mean and 3-sigma.

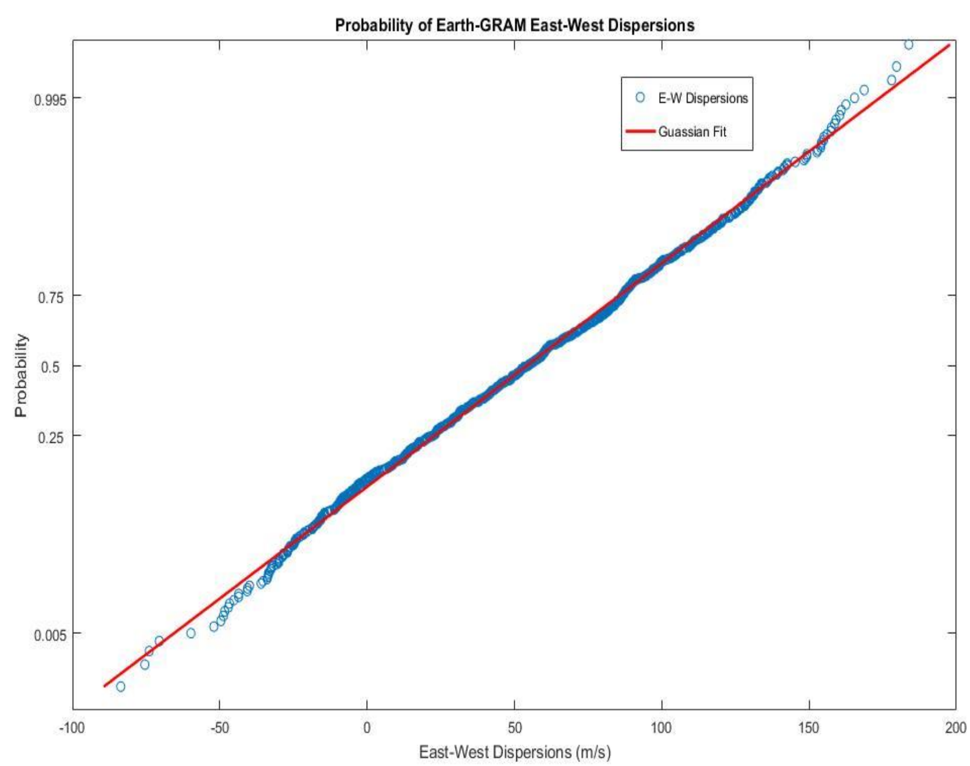

Figure 8. Cumulative Probability of East-West Wind Dispersion with a Gaussian distribution fit.

Figure 9 displays 1000 3-hour CorrMonte east-west dispersions and displays a 3-hour dispersion about a random profile generated in Earth-GRAM. CorrMonte is a tool in Earth-GRAM that produces cross-correlated hourly dispersions detailed in section 2.7.

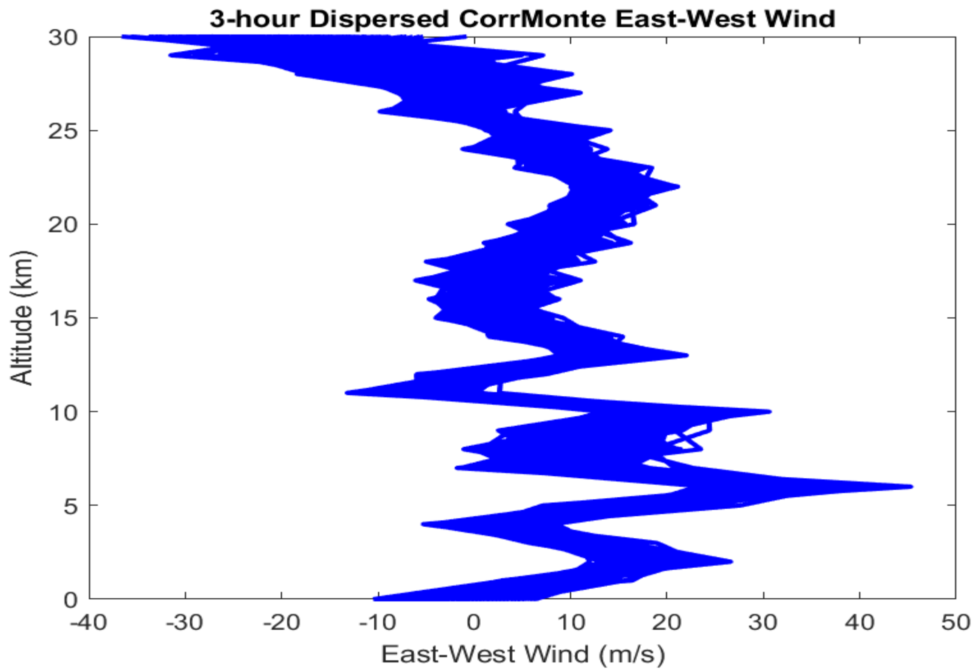

Figure 9. 1000 3-hour East-West Wind Dispersions about a Dispersed Profile Generated by CorrMonte.

Figure 10 displays a 1000 3-hour CorrMonte east-west dispersions about the Earth-GRAM climatological mean. CorrMonte offers the ability to produce hourly dispersions about a mean or dispersed profile.

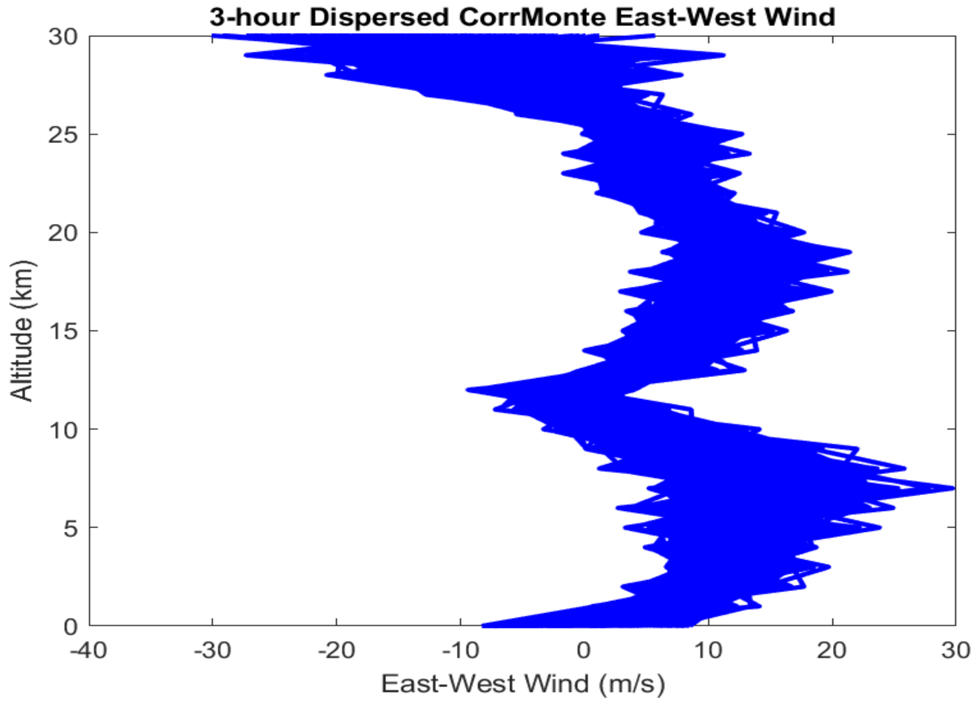

Figure 10. 1000 3-hour East-West Wind Dispersions about the Mean Generated by CorrMonte.

Figure 11 displays the ability of Earth-GRAM to correlate a ballistic trajectory. The plot on the left demonstrates a normal dispersion for an up-down trajectory. The plot on the right demonstrates a correlated dispersion for an up-down trajectory. In previous versions, due to the method of calculating perturbations, Earth-GRAM could not correlate dispersions during an up-down trajectory. Due to the ballistic trajectory feature, Earth-GRAM can now correlate dispersions during an up-down trajectory in the atmosphere.

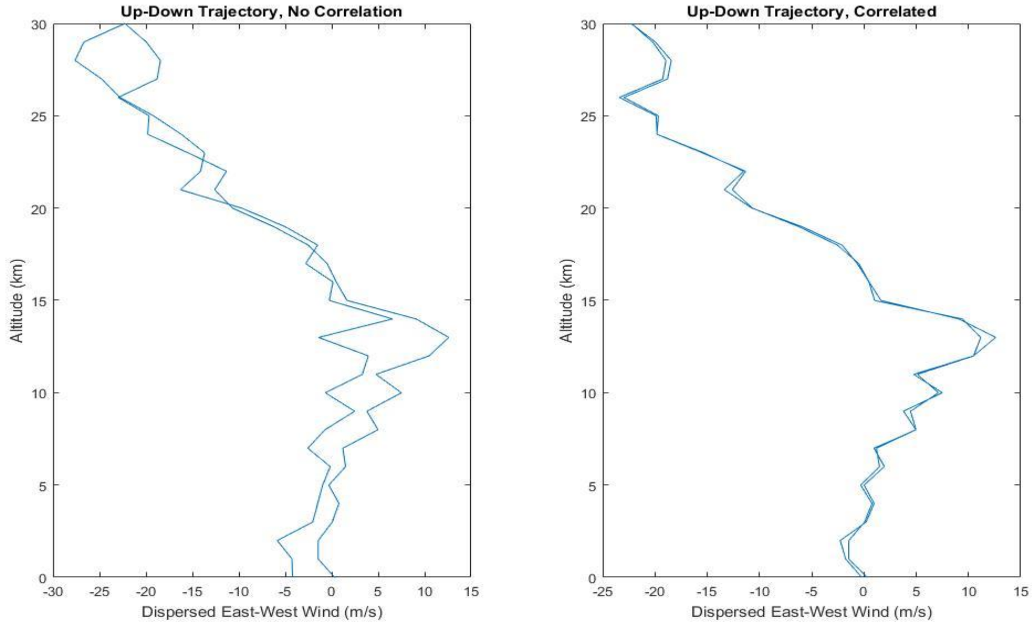

Figure 11. East-West Wind Dispersions Generated by Earth-GRAM (left) and the Ballistic Trajectory Feature (right).

Figure 12 displays a case for two objects with different trajectories through the atmosphere. This case is used to demonstrate the earth correlator feature that is detailed in section 2.11.

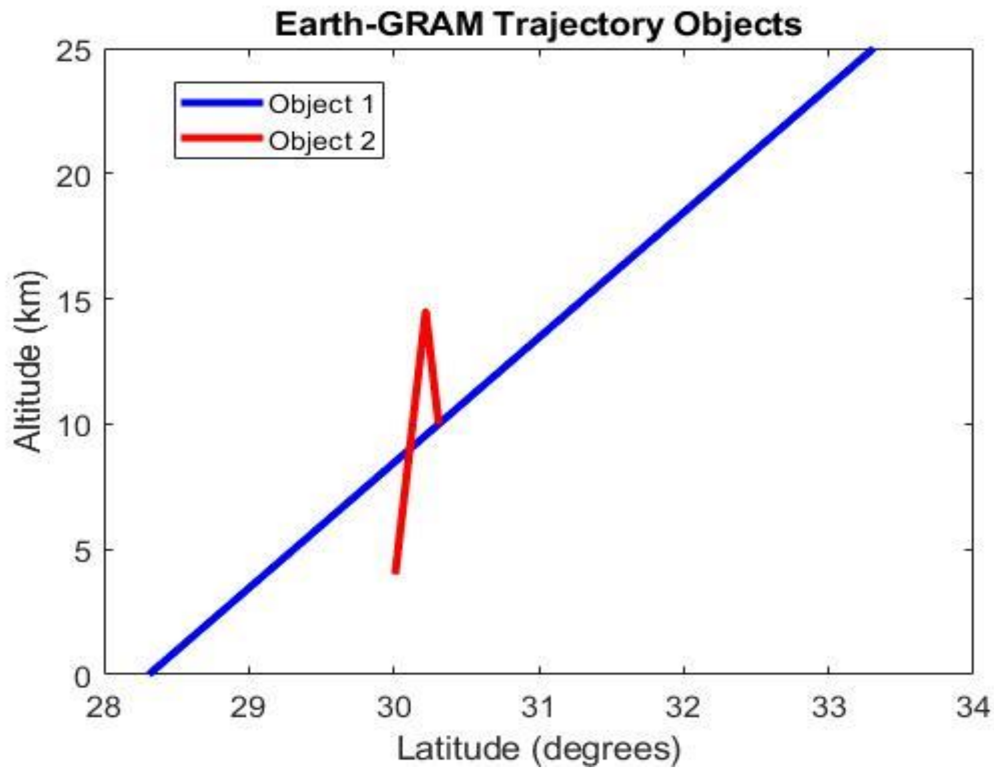

Figure 12. Positional Information Regarding Two Trajectory Objects Generated by Earth-GRAM.

Figure 13 displays the east-west wind dispersions for object 1, object 2 without correlation, and object 2 with correlation. The dispersion with correlation uses the earth correlator feature in Earth-GRAM.

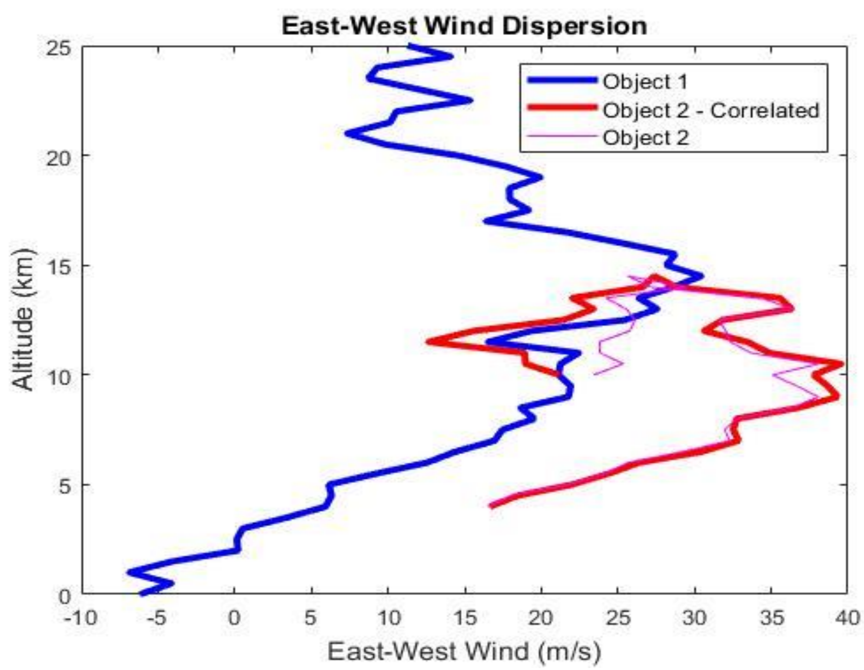

Figure 13. East-West Wind Dispersions Generated from Two Trajectory Objects Generated by Earth-GRAM.

Figure 14 displays the north-south wind dispersions for object 1, object 2 without correlation, and object 2 with correlation.

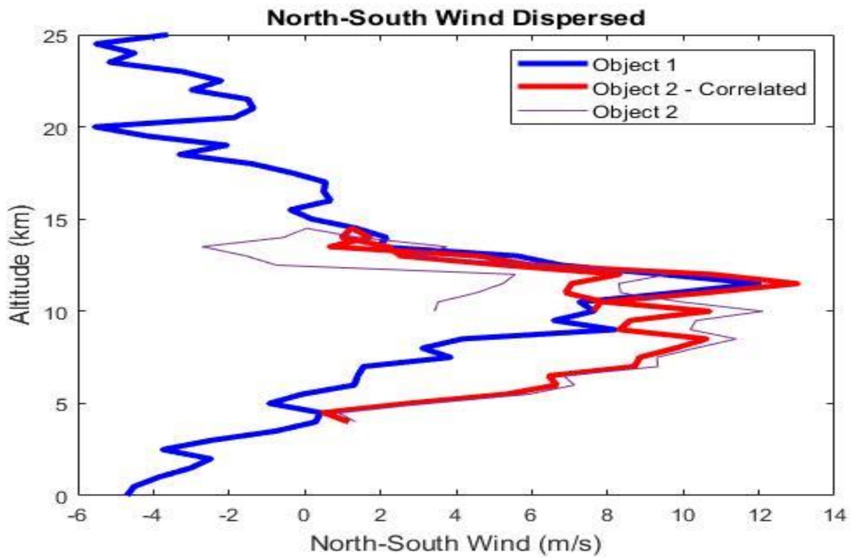

Figure 14. North-South Wind Dispersions Generated from Two Trajectory Objects Generated by Earth-GRAM.

4.0 HOW TO RUN EARTH-GRAM

4.1 How to Obtain the Program

Earth-GRAM is available through the NASA Software Catalog: https://software.nasa.gov . The software is offered free of charge. See appendices D and E for summaries of the program and data files available in the downloaded package.

4.2 Running the Program

The Earth-GRAM installation includes a set of Windows and Linux 64-bit executable libraries located in the GRAM/Windows and GRAM/Linux folders. The Earth-GRAM programs in these folders may be relocated to any folder on the appropriate operating system. For those wishing to build their own executables or those running on another operating system, build instructions are provided in appendix E.

Before running Earth-GRAM, the NAIF SPICE data files must be downloaded. These data are available via FTP from ftp://naif.jpl.nasa.gov/pub/naif/generic_kernels. Information about the SPICE data is available from https://naif.jpl.nasa.gov/naif/data.html and help downloading is available from https://naif.jpl.nasa.gov/naif/download_tip.html. NAIF recommends that the entire collection be downloaded, but these files can be rather large. The files required by Earth-GRAM are listed in boldface below. They should be downloaded using the same folder structure as on the NAIF site.

```
/spice    (FTP source folder is /generic_kernels)
 └──────/lsk    (entire folder, less than 100KB)
         └──────/naif0012.tls    (time data, all GRAMs)
 └──────/pck  (entire folder except for a_old_versions, about 27MB)
         └──────/pck00010.tpc    (planetary size/shape data, all GRAMs)
 └──────/spk  (massive, consider getting subfolders only)
         └──────/planets    (entire folder except for a_old_versions, about
                              3.3GB)
                  └──────/de430.bsp    (Earth-GRAM, Venus-GRAM)
         └──────/satellites    (entire folder except for a_old_versions, about
                                 5.8GB)
                  └──────/jup310.bsp    (Jupiter-GRAM)
                  └──────/mar097.bsp    (Mars-GRAM)
                  └──────/nep081.bsp    (Neptune-GRAM)
                  └──────/sat375.bsp    (Saturn-GRAM, Titan-GRAM)
                  └──────/ura111.bsp    (Uranus-GRAM)
```

The default location of the SPICE data files is in the root folder, /spice, on the current disk. If another location is desired, then be certain to set the *SpicePath* input parameter in the NAMELIST file to the desired location.

To run Earth-GRAM, simply double-click the EarthGRAM.exe file or enter 'EarthGRAM.exe' from a command prompt. The program will prompt for the path to an input parameter file in NAMELIST format (see section 3.3). The path may be entered as an absolute path or relative to the current folder. Sample input parameter files, ref_input.txt, traj_input.txt, and more can be found in the /GRAM/Earth/sample_inputs folder. These files are plain text and can be viewed in a text editor, such as WordPad, with no word wrapping. On exit, the program will name the output files generated. In this case, they will be myref_LIST.md and myref_OUTPUT.csv.   The myref_OUTPUT.csv file is best viewed using a spreadsheet program such as Microsoft Excel. See appendix C for optional methods for viewing the myref_LIST.md markdown file. Appendix C also shows examples of the myref_LIST.md output. The input parameter file may also be specified on the Earth-GRAM command line. The format of this option is 'EarthGRAM.exe –file ref_input.txt'. The sample_inputs folder contains pregenerated outputs ref_LIST.md and ref_OUTPUT.csv. These files are provided so that users may compare their output with the expected output.

4.3 Program Input

Earth-GRAM requires an input file in the format of a Fortran NAMELIST file. Appendix B gives a sample of the NAMELIST format input file for Earth-GRAM. All input parameter names are case insensitive. Input parameters whose values are supplied in the input file are given in Table 3. (The legacy GRAM input parameters names are still supported and appear in parentheses.)

Table 3. Earth-GRAM input parameters.

Input Parameter	**Description**	**Default**
	File Path and Names	
SpicePath or SpiceDir	The location of the NAIF SPICE data files. Absolute paths are recommended. Relative paths are acceptable.	/spice
DataPath	The location of the standard Earth-GRAM data folder. This folder is assumed to contain subfolders modeldata, NCEPdata, and RRAdata.	<empty>
AtmPath	Optional override of the default atmosphere data location. If not supplied, *DataPath*/modeldata is used.	<empty>
RRAPath	Optional override of the default Range Reference Atmosphere (RRA) data location. If not supplied, *DataPath*/RRAdata is used.	<empty>
NCEPPath	Optional override of the default NCEP data location. If not supplied, *DataPath*/NCEPdata is used.	<empty>
ListFileName	Name of list formatted file with no file extension. The appropriate file extension will be appended to this name. An example of a LIST file is given in appendix C.	LIST
ColumnFileName (PRTPATH)	Name of the column formatted file with no file extension. The appropriate file extension will be appended to this name. A complete description of this file is contained in appendix A.	OUTPUT

TrajectoryFileName (TRAPATH)	(Optional) The trajectory input file name. This file contains time (seconds) relative to start time, height (km), latitude (degrees), and longitude (degrees, see below).	<empty>
Time Parameters		
Year (IYR)	Integer year for the start time. Typically, a 4-digit year. Alternately, years 1970 - 2069 can be input as a 2-digit number.	2000
Month (MN)	Integer month (1 through 12) for the start time.	1
Day (IDA)	Integer day of month for the start time.	1
Hour (IHRO)	Integer hour (0 through 23) for the start time in the UTC time scale.	0
Minute (MINO)	Integer minute (0 through 59) for the start time in the UTC time scale.	0
Seconds (SECO)	Real seconds (less than 60.0) for the start time in the UTC time scale.	0.0
Model Parameters		
NCEPYear (NCEPYR)	y1y2 to use NCEP climatology for period-of-record (POR) from year y1 through year y2 (e.g. NCEPyr=9008 for POR = 1990 through 2008). NCEP monthly climatology is determined by input value of *Month* in initial time input.	9715
NCEPHour (NCEPHR)	Code for UT hour of day if NCEP climatology is used: 1=00 UT, 2=06UT, 3=12UT, 4=18UT, 5=all times of day combined, or 0 to use NCEP time-of-day based on input UTC hour.	5
Patchy	Patchiness in perturbation model (0 = no patchiness, 1 = patchiness).	0
SurfaceRoughness (Z0IN)	Surface roughness (z0) for sigma-w model. < 0 to use 1-by-1 deg lat-lon surface data, = 0 for speed-dependent z0 over water, > 0 for user-specified z0 value (between 1.0e-5 and 3)	9.9999
Thermosphere Parameters		
ThermosphereModel (ITHERM)	1 for MET (Jacchia), 2 for MSIS, 3 for JB2008 thermosphere	1
AP	Geomagnetic index (Note: Valid ap must be used if JB2008 selected, for use in HWM wind model).	16.0
DailyF10 (F10)	Daily 10.7-cm flux.	230.0

MeanF10 (F10B)	Mean 10.7-cm flux.	230.0
DailyS10 (S10)	EUV index (26-34 nm) scaled to F10 units (0.0 → s10 = f10). Used in the JB2008 model.	0.0
MeanS10 (S10B)	EUV 81-day center-averaged index (0.0 → s10b = f10b). Used in the JB2008 model.	0.0
DailyXM10 (XM10)	MG2 index scaled to F10 units (0.0 → xm10 = f10). Used in the JB2008 model.	0.0
MeanXM10 (XM10B)	MG2 81-day center-averaged index (0.0 → xm10b = f10b). Used in the JB2008 model.	0.0
DailyY10 (Y10)	Solar X-Ray & Lya index scaled to F10 units (0.0 → y10 = f10). Used in the JB2008 model.	0.0
MeanY10 (Y10B)	Solar X-Ray & Lya 81-day center-averaged index (0.0 → y10b = f10b). Used in the JB2008 model.	0.0
DSTTemperatureChange (DSTDTC)	Temperature change computed from DST index. Used in the JB2008 model.	0.0
Range Reference Atmosphere Parameters		
UseRRA (IURRA)	Range Reference Atmosphere flag. 0 = do not use RRA data, 1 = use RRA data	0
RRAYear (was IYRRRA)	1983, 2006, 2013, or 2019 RRAs	2019
RRAOuterRadius (SITELIM)	Lat-lon radius (deg) from RRA site, outside which RRA data are NOT used.	0
RRAInnerRadius (SITENEAR)	Lat-lon radius (deg) from RRA site, inside which RRA data is used with full weight of 1. There is a smooth transition of the weight factor from 1 to 0 between *RRAInnerRadius* and *RRAOuterRadius*.	0
Perturbation Parameters		
InitialRandomSeed (NR1)	The integer seed value for the random number generator. The allowable range is 1 to $9*10^8$. Changing the seed will alter the perturbed values in trajectory. In Monte Carlo runs, the first trajectory uses the *InitialRandomSeed*. New seeds are generated automatically for all subsequent trajectories.	1001
RandomPerturbationScale (RPSCALE)	Random perturbation scale factor for density, temperature, and pressure. (0.1 – 2.0, 1.0 = nominal)	1.0
HorizontalWindPerturbationSca le (RUSCALE)	Random perturbation scale factor for east/west and north/south winds. (0.1 – 2.0, 1.0 = nominal)	1.0

VerticalWindPerturbationScale (RWSCALE)	Random perturbation scale factor for vertical winds. (0.1 – 2.0, 1.0 = nominal)	1.0
InitializePerturbations (INITPERT)	User-defined initial perturbations flag. 0 = random initial perturbation values 1 = user-defined initial perturbations using values below	0
InitialDensityPerturbation (RDINIT)	Initial density perturbation value (% of mean).	0.0
InitialTemperaturePerturbation (RTINIT)	Initial temperature perturbation value (% of mean).	0.0
InitialEWWindPerturbation (RUINIT)	Initial eastward velocity perturbation (m/s).	0.0
InitialNSWindPerturbation (RVINIT)	Initial northward velocity perturbation (m/s).	0.0
InitialVerticalWindPerturbation (RWINIT)	Initial upward velocity perturbation (m/s).	0.0
Trajectory Parameters		
EastLongitudePositive	This flag controls the convention for input and output of longitudes. East positive convention if *EastLongitudePositive* = 1. West positive convention if *EastLongitudePositive* = 0.	1
UseTrajectoryFile	Trajectory file option. 0 = no trajectory file, 1 = use trajectory file	0
NumberOfPositions (NMAX)	The number of positions to generate and evaluate, if an automatically-generated profile is to be produced. This parameter is ignored if a *TrajectoryFileName* is provided.	21
InitialHeight (H1)	Height (km) of the initial position.	0.0
InitialLatitude (PHI1)	Latitude (degrees, north positive) of the initial position.	0.0
InitialLongitude (THET1)	Longitude (degrees) of the initial position. The direction of positive longitudes is determined by the *EastLongitudePositive* parameter.	0.0
DeltaHeight (DHGT)	Height increment (km) between successive steps in an automatically generated profile (positive upward).	10.0
DeltaLatitude (DPHI)	Latitude increment (degrees, north positive) between successive steps in an automatically generated profile.	0.0
DeltaLongitude (DTHET)	Longitude increment (degrees) between successive steps in an automatically generated profile. The direction of	0.0

	positive longitudes is determined by the *EastLongitudePositive* parameter.	
DeltaTime (DELT)	Time increment (seconds) between steps in an automatically generated profile.	0.0
Monte Carlo Parameters		
NumberOfMonteCarloRuns (MC)	Number of Monte Carlo runs during one execution of the program. New/different starting random numbers are automatically generated for each of the Monte Carlo profiles or trajectories.	1
Auxiliary Atmosphere Parameters		
UseAuxiliaryAtmosphere (IURRA)	Indicates the use of an auxiliary atmosphere. 0 = No auxiliary atmosphere 1 = Use an auxiliary atmosphere	0
AuxiliaryAtmosphereFileName (PROFILE)	(Optional) Input file name of the profile data for the auxiliary atmosphere.	<empty>
InnerRadius (SITENEAR)	(Optional) Latitude-longitude radius (degrees) within which weight for the auxiliary profile is 1.0 (A value of 0.0 implies no auxiliary atmosphere data is present.)	0.0
OuterRadius (SITELIM)	(Optional) Latitude-longitude radius (degrees) beyond which weight for the auxiliary profile is 0.0.	0.0
Output Parameters		
FastModeOn	Controls the speed and accuracy of ephemeris calculations. 0: More accurate, but slower. 1: Faster, but less accurate.	0
ExtraPrecision	For the new column output format, this parameter adds precision to all outputs.	0

4.4 Program Output

There are two general types of program output provided by Earth-GRAM. The first output file is a listing format with the file name specified by input parameter *ListFileName*. This file contains header and descriptor information which is suitable for printing or viewing by an analyst. The list file is output using a Markdown format. Markdown is a lightweight markup language that is designed to be readable in plain text format and offers improved formatting when converted to other file formats (typically html). Markdown viewer apps are available on all platforms. While not yet natively supported, most web browsers offer an extension/add-on that adds the Markdown capability. Markdown viewing options and an example of the list output file format are given in appendix C.

The second output file is in a CSV format with the file name specified by the input parameter *ColumnFileName*. This file contains one header line and one line per output position and is suitable for reading into another program for additional analysis. The precision of the outputs can be increased using the input parameter *ExtraPrecision*. The CSV format can be easily loaded into most spreadsheet programs. It can also be imported into programs, such as MATLAB®, for analysis. A description of each of the output fields in the CSV file format can be found in appendix A.

4.5 Reference Test Run

The Earth-GRAM distribution includes sample files for application in a reference test run: ref_input.txt, traj_input.txt, aux_input.txt, and rra_input.txt. To verify the Earth-GRAM build, execute *EarthGRAM.exe* using ref_input.txt as the input parameter file. The files myref_LIST.md and myref_OUTPUT.csv, generated during the test run, should be identical to the supplied ref_LIST.md and ref_OUTPUT.csv files.

4.6 How to Run EarthCorrMonte

The EarthCorrMonte program operates in the same fashion as the EarthGRAM program using a NAMELIST file for input and producing markdown and CSV output files. The NAMELIST inputs must include the fields described below in addition to the input parameters listed in table 3.

Table 4. EarthCorrMonte input parameters.

Input Parameter	Description	Default
File Path and Names		
CorrMonte	CorrMonte activation flag 0 = Do not use CorrMonte 1 = Use CorrMonte	0
CorrDeltaHours	Time delta (hours).	0.1
CorrMean	Correlation flag 0 = correlate to a perturbed profile 1 = correlate to the mean profile	0

The distribution contains a sample input file, cm_input.txt, for the EarthCorrMonte program. The nominal run is output to the files Nominal_cm_LIST.md and Nominal_cm_OUTPUT.csv. The correlated profiles are in the files cm_LIST.md and cm_OUTPUT.csv.

4.7 FindDates Utility

Earth-GRAM allows the user to calculate solar longitude (L_s) and Earth local true solar time (LTST) for a given date and time. It also computes the Earth date and time of the next closest occurrence to the initial input date and time of for which L_s and LTST are any desired values. The SPICE data are required for this capability. The FindDates capability is contained within the Earth-GRAM program and controlled via the usual NAMELIST inputs. The use of the utility is controlled by the *FindDates* input parameter (see table 5). The utility will return three dates: the date of the target L_s and the two dates of the target LTST that immediately precede and follow the target L_s date.

Table 5. FindDates input parameters.

Input Parameter	Description	Default
SpicePath or SpiceDir	The location of the NAIF SPICE data files. Absolute paths are recommended. Relative paths are acceptable.	/spice
FindDates	The parameter flags the use of the FindDates auxiliary capability. Use the FindDates capability if *FindDates* = 1. Use Earth-GRAM if *FindDates* = 0.	0
EastLongitudePositive	This flag controls the convention for input and output of longitudes. East positive convention if *EastLongitudePositive* = 1. West positive convention if *EastLongitudePositive* = 0.	1
Time Parameters		
Year	Integer year for the start time. Typically, a 4-digit year. Alternately, years 1970 - 2069 can be input as a 2-digit number.	2000
Month	Integer month (1 through 12) for the start time.	1
Day	Integer day of month for the start time.	1
Hour	Integer hour (0 through 23) for the start time in the UTC time frame.	0
Minute	Integer minute (0 through 59) for the start time in the UTC time frame.	0
Seconds	Real seconds (less than 60.0) for the start time in the UTC time frame.	0.0
Position Parameters		
InitialLongitude	Longitude (degrees) of the initial position. The direction of positive longitudes is determined by the *EastLongitudePositive* parameter.	0.0
FindDates Parameters		
TargetLongitudeSun	The desired longitude of the sun in degrees.	0.0
TargetSolarTime	The desired true local solar time in hours (0 to 24).	0.0

APPENDIX A – HEADERS FOR EARTH-GRAM OUTPUT FILE

Earth-GRAM produces a CSV output file (see table 6) suitable for passing to a data-centric program for plotting and further analysis. The field names purposely lack any special characters other than an underscore separating the units. Thus, for some fields, such as Gravity_ms2, the precise units must be inferred, as in m/s^2.

Table 6. OUTPUT.csv (or as prescribed in the *ColumnFileName* input parameter).

ElapsedTime_s	Seconds past the start time
Height_km	Height above the reference ellipsoid
Latitude_deg	Geocentric latitude
LongitudeE_deg LongitudeW_deg	East (or west) longitude, as controlled by input value *EastLongitudePositive*
TotalRadius_km	Radial distance from planetary center of mass to the current position (latitude radius plus altitude)
LatitudeRadius_km	Planetary radius at current latitude.
Gravity_ms2	Local acceleration of gravity (m/s^2)
Temperature_K	Mean temperature (K)
Pressure_Pa	Mean pressure (Pa)
Density_kgm3	Mean density (kg/m^3)
PressureScaleHeight_km	The height range over which pressure decreases by a factor of *e*
DensityScaleHeight_km	The height range over which density decreases by a factor of *e*
SpeedOfSound_ms	The speed of sound (m/s)
PressureAtSurface_Pa	Pressure at the zero altitude surface (Pa)
SigmaLevel	The ratio of pressure to pressure at the surface.
PressureAltitude_km	Pressure altitude
ReferenceTemperature_K	Temperature of the reference atmosphere
ReferencePressure_Pa	Pressure of the reference atmosphere (Pa)
ReferenceDensity_kgm3	Density of the reference atmosphere (kg/m^3)
ProfileWeight	Weight factor for auxiliary input profile data
LowDensity_kgm3	Mean density - 1 standard deviation (kg/m^3)
HighDensity_kgm3	Mean density + 1 standard deviation (kg/m^3)
PerturbedDensity_kgm3	Mean density + density perturbation (kg/m^3)
DensityPerturbation_pct	Density perturbation (%)
DensityStandardDeviation_kgm3	Standard deviation of the density (kg/m^3)
PerturbedSpeedOfSound_ms	The speed of sound at the current perturbed density (m/s)
RelativeStepSize	Not used in Earth-GRAM
DensityDeviation_pct	Percent deviation of the mean density from the reference density
LowDensityDeviation_pct	Percent deviation of the low density from the reference density
HighDensityDeviation_pct	Percent deviation of the high density from the reference density
PerturbedDensityDeviation_pct	Percent deviation of the perturbed density from the reference density

EWWind_ms	Mean eastward wind component (m/s)
NSWind_ms	Mean northward wind component (m/s)
VerticalWind_ms	Mean upward wind component (m/s)
EWWindPerturbation_ms	Eastward wind perturbation (m/s)
NSWindPerturbation_ms	Northward wind perturbation (m/s)
PerturbedEWWind_ms	Total (mean plus perturbed) eastward wind (m/s)
PerturbedNSWind_ms	Total (mean plus perturbed) northward wind (m/s)
PerturbedVerticalWind_ms	Total (mean plus perturbed) upward wind (m/s)
EWStandardDeviation_ms	Standard deviation of eastward wind perturbations (m/s)
NSStandardDeviation_ms	Standard deviation of northward wind perturbations (m
VerticalStandardDeviation_ms	Standard deviation of upward wind perturbations (m/s)
LongitudeOfTheSun_deg	The planetocentric longitude of the sun, Ls
SubsolarLatitude_deg	The latitude of the sub-solar point at the current time
SubsolarLongitudeE_deg SubsolarLongitudeW_deg	The longitude of the sub-solar point at the current time. East positive or west positive as controlled by the input value *EastLongitudePositive*
LocalSolarTime_hr	The local solar time using 24 “hour” intervals
SolarZenithAngle_deg	The solar zenith angle
OneWayLightTime_min	One way light time to/from Earth and the current position. Always 0 for Earth-GRAM.
OrbitalRadius_AU	The current orbital radius of the planet
SecondsPerSol	The number of seconds in a local sol (planetary day)
TotalNumberDensity_m3	Number density of the atmosphere (#/m^3)
SpecificGasConstant_JkgK	Specific gas constant (J/(kg K))
SpecificHeatRatio	Specific heat ratio of the gas mixture.
AverageMolecularWeight	Average molecular weight of the atmosphere (amu)
CompressibilityFactor	Compressibility factor (or zeta). This quantifies the deviation of a real gas from ideal gas behavior (zeta = 1 for ideal gases).
Arnd_m3	Number density of argon (#/m^3)
Armass_pct	Argon concentration, percent by mass
Armole_pct	Mole fraction (%) of argon concentration (or % by volume)
Aramw	Average molecular weight of argon (amu)
CO2nd_m3	Number density of carbon dioxide (#/m^3)
CO2mass_pct	Carbon dioxide concentration, percent by mass
CO2mole_pct	Mole fraction (%) of carbon dioxide concentration (or % by volume)
CO2amw	Average molecular weight of carbon oxide (amu)
COnd_m3	Number density of carbon monoxide (#/m^3)
COmass_pct	Carbon monoxide concentration, percent by mass
COmole_pct	Mole fraction (%) of carbon monoxide concentration (or % by volume)
COamw	Average molecular weight of carbon monoxide (amu)
N2nd_m3	Number density of molecular nitrogen (#/m^3)
N2mass_pct	Molecular nitrogen concentration, percent by mass

N2mole_pct	Mole fraction (%) of molecular nitrogen concentration (or % by volume)
N2amw	Average molecular weight of molecular nitrogen (amu)
O2nd_m3	Number density of molecular oxygen (#/m^3)
O2mass_pct	Molecular oxygen concentration, percent by mass
O2mole_pct	Mole fraction (%) of molecular oxygen concentration (or % by volume)
O2amw	Average molecular weight of molecular oxygen (amu)
Hend_m3	Number density of helium (#/m^3)
Hemass_pct	Helium concentration, percent by mass
Hemole_pct	Mole fraction (%) of helium concentration (or % by volume)
Heamw	Average molecular weight of helium (amu)
Hnd_m3	Number density of atomic hydrogen (#/m^3)
Hmass_pct	Atomic hydrogen concentration, percent by mass
Hmole_pct	Mole fraction (%) of atomic hydrogen concentration (or % by volume)
Hamw	Average molecular weight of atomic hydrogen (amu)
CH4nd_m3	Number density of methane (#/m^3)
CH4mass_pct	Methane concentration, percent by mass
CH4mole_pct	Mole fraction (%) of methane concentration (or % by volume)
CH4amw	Average molecular weight of methane (amu)
Nnd_m3	Number density of atomic nitrogen (#/m^3)
Nmass_pct	Atomic nitrogen concentration, percent by mass
Nmole_pct	Mole fraction (%) of atomic nitrogen concentration (or % by volume)
Namw	Average molecular weight of atomic nitrogen (amu)
Ond_m3	Number density of atomic oxygen (#/m^3)
Omass_pct	Atomic oxygen concentration, percent by mass
Omole_pct	Mole fraction (%) of atomic oxygen concentration (or % by volume)
Oamw	Average molecular weight of ozone (amu)
O3nd_m3	Number density of ozone (#/m^3)
O3mass_pct	Ozone concentration, percent by mass
O3mole_pct	Mole fraction (%) of ozone concentration (or % by volume)
O3amw	Average molecular weight of molecular oxygen (amu)
N2Ond_m3	Number density of nitrous oxide (#/m^3)
N2Omass_pct	Nitrous oxide concentration, percent by mass
N2Omole_pct	Mole fraction (%) of nitrous oxide concentration (or % by volume)
N2Oamw	Average molecular weight of nitrous oxide (amu)
H2Ond_m3	Number density of water (#/m^3)
H2Omass_pct	Water concentration, percent by mass

H2Omole_pct	Mole fraction (%) of water concentration (or % by volume)
H2Oamw	Average molecular weight of water (amu)
TemperaturePerturbation_pct	Temperature perturbation (%)
TemperatureStandardDeviation_pct	Temperature standard deviation (%)
PerturbedTemperature_K	Mean temperature + perturbation (K)
PressurePerturbation_pct	Pressure perturbation (%)
PressureStandardDeviation_pct	Pressure standard deviation (%)
PerturbedPressure_Pa	Mean pressure + perturbation (Pa)
PresPertSmall_pct	Small scale pressure perturbation (%)
DensPertSmall_pct	Small scale density perturbation (%)
TempPertSmall_pct	Small scale temperature perturbation (%)
EWWindPertSmall_ms	Small scale east/west wind perturbation (m/s)
NSWindPertSmall_ms	Small scale north/south wind perturbation (m/s)
PresSDSmall_pct	Small scale pressure standard deviation (%)
DensSDSmall_pct	Small scale density standard deviation (%)
TempSDSmall_pct	Small scale temperature standard deviation (%)
EWWindSDSmall_ms	Small scale east/west wind standard deviation (m/s)
NSWindSDSmall_ms	Small scale north/south wind standard deviation (m/s)
PresPertLarge_pct	Large scale pressure perturbation (%)
DensPertLarge_pct	Large scale density perturbation (%)
TempPertLarge_pct	Large scale temperature perturbation (%)
EWWindPertLarge_ms	Large scale east/west wind perturbation (m/s)
NSWindPertLarge_ms	Large scale north/south wind perturbation (m/s)
PresSDLarge_pct	Large scale pressure standard deviation (%)
DensSDLarge_pct	Large scale density standard deviation (%)
TempSDLarge_pct	Large scale temperature standard deviation (%)
EWWindSDLarge_ms	Large scale east/west wind standard deviation (m/s)
NSWindSDLarge_ms	Large scale north/south wind standard deviation (m/s)
DewPoint_K	Mean dewpoint temperature (K)
DewPointSD_pct	Standard deviation of the dewpoint temperature (%)
VaporPressure_Pa	Mean vapor pressure of water (Pa)
VaporPressureSD_pct	Standard deviation of water vapor pressure (%)
VaporDensity_kgm3	Mean water vapor density (kg/m^3)
VaporDensitySD_pct	Standard deviation of the water vapor density (%)
RelativeHumidity_pct	Mean relative humidity (%)
RelativeHumiditySD_pct	Standard deviation of the relative humidity (%)
WindSpeed_ms	Mean wind speed (m/s)
WindSpeedStandardDeviation_pct	Standard deviation of the wind speed (%)
WindCorrelation	Correlation of eastward and northward winds.
WindSpeedAtSurface_ms	Mean wind speed at the surface (m/s)
WindSpeedSDAtSurface_pct	Standard deviation of wind speed at the surface (%)
TemperatureAtSurface_K	Mean temperature at the surface (K)
TemperatureSDAtSurface_pct	Standard deviation of temperature at the surface (%)
PressureSDAtSurface_Pa	Standard deviation of the pressure at the surface (%)
DensitySDAtSurface_pct	Standard deviation of the density at the surface (%)
DensityAtSurface_kgm3	Mean density at the surface (kg/m^3)

EWWindAtSurface_ms	Mean velocity of the east/west winds at the surface (m/s)
NSWindAtSurface_ms	Mean velocity of the north/south winds at the surface (m/s)
EWWindSDAtSurface_pct	Standard deviation of the east/west winds at the surface (%)
NSWindSDAtSurface_pct	Standard deviation of the north/south winds at the surface (%)
WindCorrelationAtSurface_pct	Correlation of eastward and northward winds at the surface.
SurfaceHeight_km	Surface elevation (meters above sea level)
GeodeticLatitude_deg	Latitude in the geodetic reference frame (degrees)
RRAWeight	Fairing weight between RRA and the Earth model. (0 = Earth model, 1 = RRA)
SurfaceRoughness_m	Surface roughness length (m)
NetRadiationIndex	Net radiation index, for stability calculation
Stability	Atmospheric stability category
InverseLength_m	Inverse of Monin-Obukhov scale length (1/m)
FrictionVelocity_ms	Surface friction velocity (m/s)
BVFrequencySquare_s2	Square of Brunt-Vaisala frequency ($1/s^2$)
MetersAboveSurface_m	Current height above surface or height to top of boundary layer (m)
SigmaRatio	Ratio of sigmaW to friction velocity at current height
SigmaW_ms	Vertical wind standard deviation at top of boundary layer (m/s)
BoundaryLayerDepth_m	Current depth of boundary layer (m)
NeutralBoundaryLayerDepth_m	Depth of the neutral boundary layer (m)
PerturbedWindSpeedAtSurface_ms	Surface (10m) wind speed from mean-plus-large-scale-perturbation (m/s)
UnstableBLFactor	Height factor for unstable BL during early daytime
SolarDays	Number of solar days since start time (days)
SolarHourAngle_deg	Angular measure of solar time (degrees)
SolarElevation_deg	The angular height of the sun in the sky (degrees)
ElevationAtMidnight_deg	The solar elevation at midnight (degrees)
ElevationAtNoon_deg	The solar elevation at noon (degrees)
LandCode	Land surface type code
SeverityLevel	Severe turbulence indicator (when patchy = 1). *SeverityLevel* = 1 indicates severe turbulence.

APPENDIX B – EXAMPLE NAMELIST FORMAT INPUT FILE

The following is an example of the NAMELIST format input file required by Earth-GRAM. Input data given here are provided as file ref_input.txt. Values given are the default values assigned by the program. Only values that differ from the defaults actually have to be included in the NAMELIST file.

```
$INPUT
 SpicePath     = '\spice'
 DataPath      = '..\data'
 ListFileName  = 'myref_LIST'
 ColumnFileName = 'myref_OUTPUT'

 Month    = 3
 Day      = 25
 Year     = 2020
 Hour     = 12
 Minute   = 30
 Seconds  = 0.0

 InitialRandomSeed              = 1001
 RandomPerturbationScale        = 1.6
 HorizontalWindPerturbationScale = 1.75
 VerticalWindPerturbationScale  = 2.0
 NumberOfMonteCarloRuns         = 1

 AP        = 16.0
 DailyF10  = 148.0
 MeanF10   = 67.0
 DailyS10  = 0.0
 MeanS10   = 0.0
 DailyXM10 = 0.0
 MeanXM10  = 0.0
 DailyY10  = 0.0
 MeanY10   = 0.0
 DSTTemperatureChange = 0.0

 ThermosphereModel = 1

 NCEPYear = 9715
 NCEPHour = 5

 UseRRA  = 0
 RRAYear = 2019
 RRAOuterRadius = 2.0
 RRAInnerRadius = 1.0

 Patchy = 0
 SurfaceRoughness = -1

 InitializePerturbations         = 0
 InitialDensityPerturbation      = 0.0
 InitialTemperaturePerturbation  = 0.0
 InitialEWWindPerturbation       = 0.0
 InitialNSWindPerturbation       = 0.0
 InitialVerticalWindPerturbation = 0.0

 UseTrajectoryFile    = 0
 TrajectoryFileName   = 'null'
 NumberOfPositions    = 101
```

```
 EastLongitudePositive = 1
 InitialHeight        = 0.0
 InitialLatitude      = 22.0
 InitialLongitude     = 48.0
 DeltaHeight          = 40.0
 DeltaLatitude        = 0.3
 DeltaLongitude       = 0.5
 DeltaTime            = 500.0

 UseAuxiliaryAtmosphere      = 0
 AuxiliaryAtmosphereFileName = 'RRAanfAnn.txt'
 OuterRadius = 0.0
 InnerRadius = 0.0

 FastModeOn        = 0
 ExtraPrecision    = 0
 UseLegacyOutputs  = 0

$END
```

Explanation of variables:

```
 SpicePath      = Path to NAIF Spice data
 DataPath       = Path name for EarthGRAM data folder
 AtmPath        = Optional override of the default atmosphere data location
                  (DataPath/modeldata)
 RRAPath        = Optional override of the default RRA data location
                  (DataPath/RRAdata)
 NCEPPath       = Optional override of the default NCEP data location
                  (DataPath/NCEPdata/FixedBin)
 ListFileName   = List file name
 ColumnFileName = Output file name

 Month     = month of year
 Day       = day of month
 Year      = year (4-digit, or 1970-2069 can be 2-digit)
 Hour      = hour of day (UTC, 0 - 23)
 Minute    = minute of hour (UTC, 0 - 59)
 Seconds   = seconds of minute (UTC, 0.0 - 60.0)

 InitialRandomSeed              = Random number seed for perturbations
                                  (1 through 9 * 10^8)
 RandomPerturbationScale        = Random perturbation scale for density,
                                  temperature, and pressure;
                                  nominal=1.0, max=2.0, min=0.1
 HorizontalWindPerturbationScale = Random perturbation scale for horizontal winds;
                                  nominal=1.0, max=2.0, min=0.1
 VerticalWindPerturbationScale  = Random perturbation scale for vertical winds;
                                  nominal=1.0, max=2.0, min=0.1
 NumberOfMonteCarloRuns = the number of Monte Carlo runs

 AP        = geomagnetic index (Note: Valid ap must be used if JB2008 selected,
             for use in HWM wind model)
 DailyF10  = daily 10.7-cm flux
 MeanF10   = mean 10.7-cm flux
 DailyS10  = EUV index (26-34 nm) scaled to F10 units (0.0 -> s10=f10)
 MeanS10   = EUV 81-day center-averaged index (0.0 -> s10b = f10b)
 DailyXM10 = MG2 index scaled to F10 units (0.0 -> xm10 = f10)
 MeanXM10  = MG2 81-day center-averaged index (0.0 -> xm10b = f10b)
 DailyY10  = Solar X-Ray & Lya index scaled to F10 (0.0 -> y10=f10)
 MeanY10   = Solar X-Ray & Lya 81-day avg. centered index (0.0 -> y10b=f10b)
 DSTTemperatureChange = Temperature change computed from Dst index (for JB2008)
```

ThermosphereModel = 1 for MET (Jacchia), 2 for MSIS, or 3 for JB2008 thermosphere

NCEPYear = y1y2 to use NCEP climatology for period-of-record (POR) from year
y1 through year y2 (e.g. NCEPyr=9008 for POR = 1990 through
2008). NCEP monthly climatology is determined by input value
of Month in initial time input
NCEPHour = Code for UT hour of day if NCEP climatology is used: 1=00 UT,
2=06UT, 3=12UT, 4=18UT, 5=all times of day combined, or 0 to
use NCEP time-of-day based on input UTC hour

UseRRA = Range Reference Atmosphere flag
(0 = do not use RRA data, 1 = use RRA data)
RRAYear = 1983, 2006, 2013, or 2019 RRAs
RRAOuterRadius = lat-lon radius (deg) from RRA site,
outside which RRA data are NOT used.
RRAInnerRadius = lat-lon radius (deg) from RRA site, inside which RRA data is
used with full weight of 1 (smooth transition of weight factor
from 1 to 0 between sitenear and sitelim).
rraSiteList = Optional override of the default RRA sites file name (rrasites.txt)

Patchy = Patchiness in perturbation model (0 = no patchiness, 1 = patchiness)
SurfaceRoughness = surface roughness (z0) for sigma-w model
< 0 to use 1-by-1 deg lat-lon surface data,
= 0 for speed-dependent z0 over water, or
> 0 for user-specified z0 value (between 1.0e-5 and 3)

InitializePerturbations = User-defined initial perturbations
0 = random initial perturbation values
1 = user-defined initial perturbations using values below
InitialDensityPerturbation = initial density perturbation value (% of mean)
InitialTemperaturePerturbation = initial temperature perturbation value
(% of mean).
Note: Initial pressure perturbation is computed from
InitialDensityPerturbation and InitialTemperaturePerturbation
InitialEWWindPerturbation = initial eastward velocity perturbation (m/s)
InitialNSWindPerturbation = initial northward velocity perturbation (m/s)
InitialVerticalWindPerturbation = initial upward velocity perturbation (m/s)

UseTrajectoryFile = Trajectory File option
(0 = no trajectory file, 1 = use trajectory file)
TrajectoryFileName = (Optional) Trajectory input file name
If present, then the values below are ignored

NumberOfPositions = number of positions to evaluate
(0 for trajectory file input)
EastLongitudePositive = 0 for input and output West longitudes positive
1 for East longitudes positive
InitialHeight = initial height (km, upward positive)
InitialLatitude = initial latitude (deg, Northward positive)
InitialLongitude = initial longitude (deg, depends on EastLongitudePositive)
DeltaHeight = height increment (km) between steps
DeltaLatitude = latitude increment (deg) between steps
DeltaLongitude = longitude increment (deg) between steps
(depends on EastLongitudePositive)
DeltaTime = time increment (seconds) between steps.

UseAuxiliaryAtmosphere = Auxiliary profile option
(0 = no auxiliary profile, 1= use auxiliary profile data)
AuxiliaryAtmosphereFileName = (Optional) auxiliary profile input file name
InnerRadius = Lat-lon radius within which weight for auxiliary profile is 1.0
OuterRadius = Lat-lon radius beyond which weight for auxiliary profile is 0.0

FastModeOn = Flags use of faster ephemeris computations (less accurate)
0 Most accurate ephemeris computations are used
1 Faster computations with slight loss in accuracy
ExtraPrecision = For the new column output format, this parameter
adds precision to all outputs.
UseLegacyOutputs = Flags which outputs to generate.
0 Use the new output formats.
1 Use output formats matching those of the legacy EarthGram.

APPENDIX C – SAMPLE OUTPUT LIST FILE

Following is a portion of the list file output produced by the standard input parameters given in appendix B. The output data given below are provided in the file ref_LIST.md. This file allows users to complete a test run after compiling Earth-GRAM on their own computer and to electronically check their output by a file-compare process (e.g. the 'diff' command in UNIX or the 'fc' command from a Windows Command Prompt). Please note that, due to machine-dependent or compiler-dependent rounding differences, some output values may differ slightly from those shown here. These differences are usually no more than one unit in the last significant digit displayed.

Field	Value	Field	Value
Start Date	3/25/2020	Initial Random Seed	1001
Start Time	12:30:00.00	Random Perturbation Scale	1.60
Julian Day	2458934.020833	Hor Wind Perturbation Scale	1.75
Thermosphere Model	MET	Ver Wind Perturbation Scale	2.00
Daily F10.7	148.00	NCEP Global Climatology Data	9715
Mean F10.7	67.00	NCEP Hour	5
AP Index	16.00	Patchy Turbulence Option	Off
Range Reference Atmosphere	not used	RRA Inner, Outer Radii	1.0, 2.0

- NCEP Path: ../data/NCEPdata/FixedBin/

Record #1

Field	Value	Field	Value
Elapsed Time (s)	0.00	Local Solar Time (hrs)	15.58
Height Above Ref. Ellipsoid (km)	0.000	Reference Radius (km)	6375.1
Latitude (deg)	22.000	Geodetic Latitude (deg)	22.134
Longitude E (deg)	48.00	Longitude of the Sun (deg)	5.33
Subsolar Latitude (deg)	2.10	Subsolar Longitude E (deg)	354.32
Pressure Scale Height (km)	8.870	Orbital Radius (AU)	1.00
Density Scale Height (km)	10.217	Solar Zenith Angle (deg)	55.79
Sigma Level	1.079	Gravity (m/s^2)	9.788
Pressure Altitude (km)	-0.676	Speed of Sound (m/s)	347.284
Compressibility Factor (zeta)	0.9994	Perturbed Speed of Sound (m/s)	344.206
Specific Heat Ratio	1.389	Profile Weight	0.000
Specific Gas Constant (J/(kg K))	287.870	RRA Site Name	
Severity Level	0	RRA Weight	0.000
Vapor Pressure (Pa)	9.150e+02	Vapor Pressure SD (%)	562.19
Vapor Density (kg/m^3)	6.574e-03	Vapor Density SD (%)	0.00
Dew Point (K)	276.22	Dew Point SD (%)	9.07
Relative Humidity (%)	23.23	Relative Humidity SD (%)	14.87
Wind Speed (m/s)	3.388e+00	Wind Speed SD (%)	1.94
Wind Speed at Surface (m/s)	5.700e+00	Wind Speed SD at Surface (%)	2.57
Wind Correlation	1.373e-01	Wind Correlation at Surface	0.15

Field	Pressure (Pa)	Density (kg/m^3)	Temperature (K)
Mean	1.013e+05	1.166e+00	301.58
Total Perturbed	1.009e+05	1.184e+00	296.26
Reference Mean (US-76)	1.013e+05	1.225e+00	288.15
At the Surface	9.383e+04	1.095e+00	297.87
Perturbation (%)	-0.31	1.48	-1.76
Deviations (%)	-0.07	-4.79	4.66

Perturbed Deviations (%)	-0.38	-3.38	2.81
Small-Scale Perturbations (%)	-0.02	0.57	-0.56
Small-Scale Std. Devs. (%)	0.04	1.45	1.35
Large-Scale Perturbations (%)	-0.30	0.91	-1.20
Large-Scale Std. Devs. (%)	0.42	3.31	3.09
Standard Deviations (%)	0.42	3.61	3.37
Std. Devs. at the Surface (%)	0.00	0.00	23.19

Field	E/W Wind (m/s)	N/S Wind (m/s)	Vertical Wind (m/s)
Mean	-1.61	-0.43	0.00
Total Perturbed	-4.90	2.91	-1.96
Perturbation	-3.30	3.34	-1.96
At the Surface	-2.87	0.07	
Small-Scale Perturbations	-0.40	3.47	
Small-Scale Std. Devs.	2.66	3.41	
Large-Scale Perturbations	-2.90	-0.14	
Large-Scale Std. Devs.	2.62	3.36	
Standard Deviations	3.73	4.79	1.18
Std. Devs. at the Surface	5.71	7.70	

Gases	Number Density (#/m^3)	Mass (%)	Mole (%)	Avg Mol Wgt
Argon (Ar)	2.2504e+23	1.3	0.9	39.95
Carbon Dioxide (CO2)	9.9022e+21	0.1	0.0	44.01
Carbon Monoxide (CO)	4.9124e+18	0.0	0.0	28.01
Dinitrogen (N2)	1.8813e+25	75.1	77.4	28.01
Dioxygen (O2)	5.0470e+24	23.0	20.8	32.00
Helium (He)	1.2529e+20	0.0	0.0	4.00
Hydrogen (H)	0.0000e+00	0.0	0.0	1.01
Methane (CH4)	6.0753e+19	0.0	0.0	16.04
Nitrogen (N)	0.0000e+00	0.0	0.0	14.01
Oxygen (O)	0.0000e+00	0.0	0.0	16.00
Ozone (O3)	7.6360e+17	0.0	0.0	48.00
Nitrous Oxide (N2O)	8.7963e+18	0.0	0.0	44.01
Water (H2O)	2.2176e+23	0.6	0.9	18.02
Total	2.4317e+25	100.0	100.0	28.87

Field	Value	Field	Value
Land Code	8	Solar Days	25.65
Surface Roughness (m)	0.01500	Solar Hour Angle (deg)	53.68
Net Radiation Index	2.49	Solar Elevation (deg)	34.19
Stability	4.21	Elevation At Midnight (deg)	-65.99
Inverse Length (1/m)	-0.00078	Elevation At Noon (deg)	70.01
BV Frequency Square (1/s^2)	0.00011	Local Solar Time (hours)	15.58
Friction Velocity (m/s)	0.474	Perturbed Wind Speed At Surface (m/s)	7.568
Sigma Ratio	1.250	Meters Above Surface (m)	0.0
Sigma W (m/s)	0.592	Boundary Layer Depth (m)	1164.9
Unstable BL Factor	1.000	Neutral Boundary Layer Depth (m)	1127.8

Record #2

Field	Value	Field	Value
Elapsed Time (s)	500.00	Local Solar Time (hrs)	15.75
Height Above Ref. Ellipsoid (km)	40.000	Reference Radius (km)	6375.0
Latitude (deg)	22.300	Geodetic Latitude (deg)	22.435
Longitude E (deg)	48.50	Longitude of the Sun (deg)	5.34
Subsolar Latitude (deg)	2.11	Subsolar Longitude E (deg)	352.24
Pressure Scale Height (km)	7.689	Orbital Radius (AU)	1.00
Density Scale Height (km)	7.291	Solar Zenith Angle (deg)	58.19
Sigma Level	0.003	Gravity (m/s^2)	9.665
Pressure Altitude (km)	44.295	Speed of Sound (m/s)	322.641
Compressibility Factor (zeta)	1.0006	Perturbed Speed of Sound (m/s)	319.504
Specific Heat Ratio	1.401	Profile Weight	0.000
Specific Gas Constant (J/(kg K))	287.199	RRA Site Name	
Severity Level	0	RRA Weight	0.000
Vapor Pressure (Pa)	2.486e-03	Vapor Pressure SD (%)	0.00
Vapor Density (kg/m^3)	2.082e-08	Vapor Density SD (%)	0.00
Dew Point (K)	172.24	Dew Point SD (%)	0.16
Relative Humidity (%)	0.00	Relative Humidity SD (%)	0.00
Wind Speed (m/s)	4.985e+01	Wind Speed SD (%)	39.93
Wind Speed at Surface (m/s)	4.988e+00	Wind Speed SD at Surface (%)	2.38
Wind Correlation	8.690e-02	Wind Correlation at Surface	0.03

Field	Pressure (Pa)	Density (kg/m^3)	Temperature (K)

Mean	2.996e+02	4.031e-03	258.76
Total Perturbed	2.845e+02	3.904e-03	253.76
Reference Mean (US-76)	2.872e+02	3.996e-03	250.35
At the Surface	9.516e+04	1.112e+00	297.55
Perturbation (%)	-5.02	-3.15	-1.94
Deviations (%)	4.33	0.88	3.36
Perturbed Deviations (%)	-0.91	-2.29	1.36
Small-Scale Perturbations (%)	0.28	0.97	-0.56
Small-Scale Std. Devs. (%)	0.92	2.82	1.74
Large-Scale Perturbations (%)	-5.30	-4.11	-1.38
Large-Scale Std. Devs. (%)	5.72	3.78	2.34
Standard Deviations (%)	5.80	4.72	2.92
Std. Devs. at the Surface (%)	0.00	0.00	865.73

Field	E/W Wind (m/s)	N/S Wind (m/s)	Vertical Wind (m/s)
Mean	6.54	0.13	0.00
Total Perturbed	16.22	-4.45	0.95
Perturbation	9.68	-4.58	0.95
At the Surface	-2.49	-0.31	
Small-Scale Perturbations	15.77	4.08	
Small-Scale Std. Devs.	25.28	8.15	
Large-Scale Perturbations	-6.09	-8.66	
Large-Scale Std. Devs.	23.55	7.60	
Standard Deviations	34.55	11.14	1.50
Std. Devs. at the Surface	4.76	7.11	

Gases	Number Density (#/m^3)	Mass (%)	Mole (%)	Avg Mol Wgt
Argon (Ar)	7.8313e+20	1.3	0.9	39.95
Carbon Dioxide (CO2)	3.4459e+19	0.1	0.0	44.01
Carbon Monoxide (CO)	3.3545e+15	0.0	0.0	28.01
Dinitrogen (N2)	6.5470e+22	75.5	78.1	28.01
Dioxygen (O2)	1.7563e+22	23.1	20.9	32.00
Helium (He)	4.3600e+17	0.0	0.0	4.00
Hydrogen (H)	0.0000e+00	0.0	0.0	1.01
Methane (CH4)	7.5563e+16	0.0	0.0	16.04
Nitrogen (N)	0.0000e+00	0.0	0.0	14.01
Oxygen (O)	5.8338e+14	0.0	0.0	16.00
Ozone (O3)	4.8070e+17	0.0	0.0	48.00
Nitrous Oxide (N2O)	2.3444e+15	0.0	0.0	44.01
Water (H2O)	4.3281e+17	0.0	0.0	18.02
Total	8.3853e+22	100.0	100.0	28.97

(Snipped for brevity)

Record #100

Field	Value	Field	Value
Elapsed Time (s)	49500.00	Local Solar Time (hrs)	8.63
Height Above Ref. Ellipsoid (km)	3960.000	Reference Radius (km)	6364.9
Latitude (deg)	51.700	Geodetic Latitude (deg)	51.815
Longitude E (deg)	97.50	Longitude of the Sun (deg)	5.90
Subsolar Latitude (deg)	2.33	Subsolar Longitude E (deg)	148.03
Pressure Scale Height (km)	1089.172	Orbital Radius (AU)	1.00
Density Scale Height (km)	1089.172	Solar Zenith Angle (deg)	64.90
Sigma Level	0.000	Gravity (m/s^2)	3.716
Pressure Altitude (km)	37116.755	Speed of Sound (m/s)	2597.242
Compressibility Factor (zeta)	1.0000	Perturbed Speed of Sound (m/s)	2434.186
Specific Heat Ratio	1.667	Profile Weight	0.000
Specific Gas Constant (J/(kg K))	4279.942	RRA Site Name	
Severity Level	0	RRA Weight	0.000
Vapor Pressure (Pa)	0.000e+00	Vapor Pressure SD (%)	0.00
Vapor Density (kg/m^3)	0.000e+00	Vapor Density SD (%)	0.00
Dew Point (K)	0.00	Dew Point SD (%)	0.00
Relative Humidity (%)	0.00	Relative Humidity SD (%)	0.00
Wind Speed (m/s)	2.931e+02	Wind Speed SD (%)	236.81
Wind Speed at Surface (m/s)	4.787e+00	Wind Speed SD at Surface (%)	2.78
Wind Correlation	-3.024e-02	Wind Correlation at Surface	-0.01

Field	Pressure (Pa)	Density (kg/m^3)	Temperature (K)
Mean	1.394e-10	3.444e-17	945.66
Total Perturbed	1.394e-10	3.920e-17	830.65
Reference Mean (US-76)	0.000e+00	0.000e+00	0.00

At the Surface	8.793e+04	1.154e+00	265.25
Perturbation (%)	-0.03	13.82	-12.16
Deviations (%)	inf	-99.90	inf
Perturbed Deviations (%)	inf	-99.90	inf
Small-Scale Perturbations (%)	0.89	13.95	-19.10
Small-Scale Std. Devs. (%)	4.54	11.93	15.81
Large-Scale Perturbations (%)	-0.91	-0.13	6.94
Large-Scale Std. Devs. (%)	14.34	4.63	6.14
Standard Deviations (%)	15.04	12.80	16.96
Std. Devs. at the Surface (%)	0.00	0.00	1159.47

Field	E/W Wind (m/s)	N/S Wind (m/s)	Vertical Wind (m/s)
Mean	-0.11	0.20	0.01
Total Perturbed	222.96	64.59	-24.17
Perturbation	223.07	64.39	-24.17
At the Surface	3.17	0.75	
Small-Scale Perturbations	106.17	-39.39	
Small-Scale Std. Devs.	112.19	112.19	
Large-Scale Perturbations	116.90	103.78	
Large-Scale Std. Devs.	102.92	102.92	
Standard Deviations	152.25	152.25	24.02
Std. Devs. at the Surface	5.58	5.28	

Gases	Number Density (#/m^3)	Mass (%)	Mole (%)	Avg Mol Wgt
Argon (Ar)	5.0313e-23	0.0	0.0	39.95
Carbon Dioxide (CO2)	0.0000e+00	0.0	0.0	44.01
Carbon Monoxide (CO)	0.0000e+00	0.0	0.0	28.01
Dinitrogen (N2)	1.1605e-09	0.0	0.0	28.01
Dioxygen (O2)	3.7079e-14	0.0	0.0	32.00
Helium (He)	3.3326e+09	64.3	31.2	4.00
Hydrogen (H)	7.3447e+09	35.7	68.8	1.01
Methane (CH4)	0.0000e+00	0.0	0.0	16.04
Nitrogen (N)	0.0000e+00	0.0	0.0	14.01
Oxygen (O)	4.3488e+01	0.0	0.0	16.00
Ozone (O3)	0.0000e+00	0.0	0.0	48.00
Nitrous Oxide (N2O)	0.0000e+00	0.0	0.0	44.01
Water (H2O)	0.0000e+00	0.0	0.0	18.02
Total	1.0677e+10	100.0	100.0	1.94

Record #101

Field	Value	Field	Value
Elapsed Time (s)	50000.00	Local Solar Time (hrs)	8.80
Height Above Ref. Ellipsoid (km)	4000.000	Reference Radius (km)	6364.8
Latitude (deg)	52.000	Geodetic Latitude (deg)	52.115
Longitude E (deg)	98.00	Longitude of the Sun (deg)	5.90
Subsolar Latitude (deg)	2.33	Subsolar Longitude E (deg)	145.95
Pressure Scale Height (km)	1082.584	Orbital Radius (AU)	1.00
Density Scale Height (km)	1082.583	Solar Zenith Angle (deg)	63.73
Sigma Level	0.000	Gravity (m/s^2)	3.687
Pressure Altitude (km)	36874.476	Speed of Sound (m/s)	2579.415
Compressibility Factor (zeta)	1.0000	Perturbed Speed of Sound (m/s)	2414.106
Specific Heat Ratio	1.667	Profile Weight	0.000
Specific Gas Constant (J/(kg K))	4203.076	RRA Site Name	
Severity Level	0	RRA Weight	0.000
Vapor Pressure (Pa)	0.000e+00	Vapor Pressure SD (%)	0.00
Vapor Density (kg/m^3)	0.000e+00	Vapor Density SD (%)	0.00
Dew Point (K)	0.00	Dew Point SD (%)	0.00
Relative Humidity (%)	0.00	Relative Humidity SD (%)	0.00
Wind Speed (m/s)	2.931e+02	Wind Speed SD (%)	236.81
Wind Speed at Surface (m/s)	5.214e+00	Wind Speed SD at Surface (%)	3.03
Wind Correlation	-3.010e-02	Wind Correlation at Surface	-0.02

Field	Pressure (Pa)	Density (kg/m^3)	Temperature (K)
Mean	1.394e-10	3.492e-17	949.78
Total Perturbed	1.387e-10	3.967e-17	831.94
Reference Mean (US-76)	0.000e+00	0.000e+00	0.00
At the Surface	8.650e+04	1.140e+00	264.35
Perturbation (%)	-0.49	13.61	-12.41
Deviations (%)	inf	-99.90	inf
Perturbed Deviations (%)	inf	-99.90	inf
Small-Scale Perturbations (%)	-1.83	8.55	-15.16
Small-Scale Std. Devs. (%)	4.54	11.93	15.81
Large-Scale Perturbations (%)	1.34	5.06	2.76

```
| Large-Scale Std. Devs. (%)    | 14.34              | 4.63               | 6.14               |
| Standard Deviations (%)       | 15.04              | 12.80              | 16.96              |
| Std. Devs. at the Surface (%) | 0.00               | 0.00               | 1154.55            |

| Field                         | E/W Wind (m/s)     | N/S Wind (m/s)     | Vertical Wind (m/s) |
|-------------------------------|-------------------:|-------------------:|-------------------:|
| Mean                          | -0.24              | 0.20               | 0.01               |
| Total Perturbed               | 30.85              | 207.04             | 11.62              |
| Perturbation                  | 31.08              | 206.84             | 11.61              |
| At the Surface                | 3.71               | 0.49               |                    |
| Small-Scale Perturbations     | 10.57              | 127.45             |                    |
| Small-Scale Std. Devs.        | 112.19             | 112.19             |                    |
| Large-Scale Perturbations     | 20.51              | 79.39              |                    |
| Large-Scale Std. Devs.        | 102.92             | 102.92             |                    |
| Standard Deviations           | 152.25             | 152.25             | 24.02              |
| Std. Devs. at the Surface     | 6.00               | 5.50               |                    |

| Gases                | Number Density (#/m^3) | Mass (%) | Mole (%) | Avg Mol Wgt |
|----------------------|------------------------|----------|----------|-------------|
| Argon (Ar)           | 7.1612e-23             | 0.0      | 0.0      | 39.95       |
| Carbon Dioxide (CO2) | 0.0000e+00             | 0.0      | 0.0      | 44.01       |
| Carbon Monoxide (CO) | 0.0000e+00             | 0.0      | 0.0      | 28.01       |
| Dinitrogen (N2)      | 1.4846e-09             | 0.0      | 0.0      | 28.01       |
| Dioxygen (O2)        | 4.9155e-14             | 0.0      | 0.0      | 32.00       |
| Helium (He)          | 3.4444e+09             | 65.6     | 32.4     | 4.00        |
| Hydrogen (H)         | 7.1870e+09             | 34.4     | 67.6     | 1.01        |
| Methane (CH4)        | 0.0000e+00             | 0.0      | 0.0      | 16.04       |
| Nitrogen (N)         | 0.0000e+00             | 0.0      | 0.0      | 14.01       |
| Oxygen (O)           | 4.9968e+01             | 0.0      | 0.0      | 16.00       |
| Ozone (O3)           | 0.0000e+00             | 0.0      | 0.0      | 48.00       |
| Nitrous Oxide (N2O)  | 0.0000e+00             | 0.0      | 0.0      | 44.01       |
| Water (H2O)          | 0.0000e+00             | 0.0      | 0.0      | 18.02       |
| Total                | 1.0631e+10             | 100.0    | 100.0    | 1.98        |

--------------------
## End of data
--------------------
```

The list file is formatted using the Markdown syntax. The file can also be displayed using a Markdown viewer. A sample of the Markdown output is shown below. Most web browsers support Markdown via extensions/add-ons or through online Markdown editors. The 'Markdown Viewer' extension is suggested for Chrome and the 'Markdown Viewer Webext' works well in Firefox. Installable Markdown viewers are available on all platforms. On Windows, the Notepad++ application has a 'Markdown++' plugin which displays Markdown with exports to html or pdf formats. For command line users, Pandoc will convert Markdown (use –f gfm) to a host of familiar rich text formats. The example below used Pandoc to convert Markdown to Open Document format.

Field	**Value**	**Field**	**Value**
Start Date	3/25/2020	Initial Random Seed	0
Start Time	12:30:00.00	Random Perturbation Scale	1.60
Julian Day	2458934.020833	Hor Wind Perturbation Scale	1.75
Thermosphere Model	MET	Ver Wind Perturbation Scale	2.00
Daily F10.7	148.00	NCEP Global Climatology Data	9715
Mean F10.7	67.00	NCEP Hour	5
AP Index	16.00	Patchy Turbulence Option	Off
Range Reference Atmosphere	not used	RRA Inner, Outer Radii	1.0, 2.0

- NCEP Path: ../data/NCEPdata/FixedBin/

Record #1

Field	Value	Field	Value
Elapsed Time (s)	0.00	Local Solar Time (hrs)	15.58
Height Above Ref. Ellipsoid (km)	0.000	Reference Radius (km)	6375.1
Latitude (deg)	22.000	Geodetic Latitude (deg)	22.134
Longitude E (deg)	48.00	Longitude of the Sun (deg)	5.33
Subsolar Latitude (deg)	2.10	Subsolar Longitude E (deg)	354.32
Pressure Scale Height (km)	8.870	Orbital Radius (AU)	1.00
Density Scale Height (km)	10.217	Solar Zenith Angle (deg)	55.79
Sigma Level	1.079	Gravity (m/s^2)	9.788
Pressure Altitude (km)	-0.676	Speed of Sound (m/s)	347.284
Compressibility Factor (zeta)	0.9994	Perturbed Speed of Sound (m/s)	344.206
Specific Heat Ratio	1.389	Profile Weight	0.000
Specific Gas Constant (J/(kg K))	287.870	RRA Site Name	
Severity Level	0	RRA Weight	0.000
Vapor Pressure (Pa)	9.150e+02	Vapor Pressure SD (%)	562.19
Vapor Density (kg/m^3)	6.574e-03	Vapor Density SD (%)	0.00
Dew Point (K)	276.22	Dew Point SD (%)	9.07
Relative Humidity (%)	23.23	Relative Humidity SD (%)	14.87
Wind Speed (m/s)	3.388e+00	Wind Speed SD (%)	1.94
Wind Speed at Surface (m/s)	5.700e+00	Wind Speed SD at Surface (%)	2.57
Wind Correlation	1.373e-01	Wind Correlation at Surface	0.15

Field	Pressure (Pa)	Density (kg/m^3)	Temperature (K)
Mean	1.013e+05	1.166e+00	301.58
Total Perturbed	1.009e+05	1.184e+00	296.26
Reference Mean (US-76)	1.013e+05	1.225e+00	288.15
At the Surface	9.383e+04	1.095e+00	297.87
Perturbation (%)	-0.31	1.48	-1.76
Deviations (%)	-0.07	-4.79	4.66
Perturbed Deviations (%)	-0.38	-3.38	2.81
Small-Scale Perturbations (%)	-0.02	0.57	-0.56
Small-Scale Std. Devs. (%)	0.04	1.45	1.35
Large-Scale Perturbations (%)	-0.30	0.91	-1.20
Large-Scale Std. Devs. (%)	0.42	3.31	3.09
Standard Deviations (%)	0.42	3.61	3.37
Std. Devs. at the Surface (%)	0.00	0.00	23.19

Field	E/W Wind (m/s)	N/S Wind (m/s)	Vertical Wind (m/s)
Mean	-1.61	-0.43	0.00
Total Perturbed	-4.90	2.91	-1.96
Perturbation	-3.30	3.34	-1.96
At the Surface	-2.87	0.07	
Small-Scale Perturbations	-0.40	3.47	

Small-Scale Std. Devs.	2.66	3.41	
Large-Scale Perturbations	-2.90	-0.14	
Large-Scale Std. Devs.	2.62	3.36	
Standard Deviations	3.73	4.79	1.18
Std. Devs. at the Surface	5.71	7.70	

Gases	**Number Density (#/m^3)**	**Mass (%)**	**Mole (%)**	**Avg Mol Wgt**
Argon (Ar)	2.2504e+23	1.3	0.9	39.95
Carbon Dioxide (CO2)	9.9022e+21	0.1	0.0	44.01
Carbon Monoxide (CO)	4.9124e+18	0.0	0.0	28.01
Dinitrogen (N2)	1.8813e+25	75.1	77.4	28.01
Dioxygen (O2)	5.0470e+24	23.0	20.8	32.00
Helium (He)	1.2529e+20	0.0	0.0	4.00
Hydrogen (H)	0.0000e+00	0.0	0.0	1.01
Methane (CH4)	6.0753e+19	0.0	0.0	16.04
Nitrogen (N)	0.0000e+00	0.0	0.0	14.01
Oxygen (O)	0.0000e+00	0.0	0.0	16.00
Ozone (O3)	7.6360e+17	0.0	0.0	48.00
Nitrous Oxide (N2O)	8.7963e+18	0.0	0.0	44.01
Water (H2O)	2.2176e+23	0.6	0.9	18.02
Total	2.4317e+25	100.0	100.0	28.87

Field	**Value**	**Field**	**Value**
Land Code	8	Solar Days	25.65
Surface Roughness (m)	0.01500	Solar Hour Angle (deg)	53.68
Net Radiation Index	2.49	Solar Elevation (deg)	34.19
Stability	4.21	Elevation At Midnight (deg)	-65.99
Inverse Length (1/m)	-0.00078	Elevation At Noon (deg)	70.01
BV Frequency Square (1/s^2)	0.00011	Local Solar Time (hours)	15.58
Friction Velocity (m/s)	0.474	Perturbed Wind Speed At Surface (m/s)	7.568
Sigma Ratio	1.250	Meters Above Surface (m)	0.0
Sigma W (m/s)	0.592	Boundary Layer Depth (m)	1164.9
Unstable BL Factor	1.000	Neutral Boundary Layer Depth (m)	1127.8

Many of the Markdown viewers allow customization of the table formats using Cascading Style Sheets (CSS). The following CSS snippet will give the table layout a nice look and feel. Search the options of the Markdown viewer for custom CSS.

```
table {
  width: 100%;
  margin-top: 10px;
  border-collapse: collapse; }
table tr {
  border-top: 1px solid silver;
  background-color: white; }
table tr:nth-child(2n) {
```

```
  background-color: whitesmoke; }
table tr th {
  font-weight: bold;
  border: 1px solid silver;
  background-color: lightgray;
  text-align: left;
  padding: 2px 8px; }
table tr td {
  border: 1px solid silver;
  text-align: left;
  padding: 1px 8px;}
```

APPENDIX D – SUMMARY OF FILES PROVIDED WITH EARTH-GRAM

The following are provided with the Earth-GRAM distribution:

- Build: A makefile system for building the GRAM suite.
- MSVS: A Visual Studio solution for building the GRAM suite (no Fortran).
- Documentation: A User Guide, a Programmer's Manual, and a GRAM Suite change log.
- Windows: Binary executables and libraries (64-bit) for Windows.
- Linux: Binary executables and libraries (64-bit) for Linux.
- common: A framework shared by all GRAM models:
  - include: Header files for the model
  - source: Source code for the model
  - examples: Generic example functions
  - unittest: Source code for unit tests
  - cspice: Headers and libraries for the NAIF SPICE toolkit
  - googletest: Headers and source for the unit test framework
- Earth: The model-specific code, examples, and tests for each planet
  - include: Header files for the model
  - source: Source code for the model
  - data: Data files for the model
  - examples: Examples and the GRAM program for this model
  - unittest: Source code for unit tests
  - sample_inputs: Sample input parameter files and resulting outputs
  - md files: Markdown files used to build the Programmer's Manual
- GRAM: Source files for examples that combine all GRAM models.
- Doxyfile and DoxygenLayout.html: Configuration files used to generate the Programmer's Manual

APPENDIX E – BUILDING EARTH-GRAM

The Earth-GRAM distribution contains 64-bit executables and libraries for Windows in the folder /GRAM/Windows. These binaries were compiled with Microsoft Visual Studio 2017 using the solution /GRAM/MSVS/GRAMs.sln. To rebuild these binaries:

(1) Open the solution in MSVS 2017.
(2) Set the Solution Configuration to *Release*.
(3) Set the Solution Platform to *x64*.
(4) From the Build menu, select *Rebuild Solution*.

The resulting binaries will be found in /GRAM/MSVS/x64/Release. It is possible to use MSVS 2015 to build Earth-GRAM. Instructions can be found in the first chapter of the GRAM Programmer's Manual.

To build Earth-GRAM on other operating systems or other compilers, a GNU makefile system is provided in the /GRAM/Build folder. The process for building the executables and libraries is:

(1) Set the build environment in makefile.defs.
(2) Enter the command “make clean”.
(3) Enter the command “make –j”.

The resulting executables will be placed in /GRAM/Build/bin. Libraries will be placed in /GRAM/Build/lib. The makefile system parameters are defined in the file makefile.defs. The current settings work on a Linux platform or under MSYS2 using the GCC compiler suite version 6.3 or later. The key parameters in this file are:

- CXX, CC, FF, LNK
  - The command that invokes the C++ compiler, C compiler, Fortran compiler, and the linker, respectively.
- CXX_FLAGS
  - Must be set to use the C++11 standard.
- C_FLAGS
  - Must be set to use the C99 standard.
- F_FLAGS
  - Must be set to use the Fortran 2003 standard.
- SPICE_LIB
  - Path to the NAIF CSPICE library.

The above processes use pre-built SPICE libraries that were compiled following the cspice instructions (version N0066). These libraries are found in /GRAM/common/cspice/lib. To rebuild these libraries, please refer to the README.txt file that comes with the appropriate CSPICE toolkit. The toolkits can be obtained from https://naif.jpl.nasa.gov/naif/toolkit_C.html.

APPENDIX F – HISTORY OF EARTH-GRAM VERSION REVISIONS

Earth-GRAM version history is documented in “EarthGRAMhist.txt” file in documentation folder.

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