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Space environment (natural and artificial) — Guide to reference and standard atmosphere models

Environnement spatial (naturel et artificiel) — Guide pour les modèles d'atmosphère standard et de référence

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Foreword

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Draft Guides adopted by the responsible Committee or Group are circulated to the member bodies for voting. Publication as a Guide requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO Guide was prepared by Technical Committee ISO/TC 20, Aircraft and space vehicles, Subcommittee 14, Space systems and operations.

Introduction

Since the mid 19th century there has been considerable effort devoted to the development of standards and reference atmosphere models. The first “Standard Atmospheres” were established by international agreement in the 1920s. Later some countries, notably the United States, also developed and published Standard Atmospheres. The term *reference atmospheres* is generally used to identify atmosphere models for specific geographical locations or globally.

The proliferation of atmospheric models and the lack of documentation have hindered general knowledge of their availability as well as information on their relative strengths, weaknesses, and limitations. The intent of this guide is to compile in one reference practical information about some of the known historical and available atmospheric models—those which describe the physical properties and chemical composition of the atmosphere as a function of altitude. The inclusion in this Guide of information on the various reference and standard atmosphere models is not meant to imply endorsement by ISO of the respective model. Also, inputs provided on the models were based on the information available at the time the entry was originally prepared.

The included Earth and other planetary models are those intended for general purpose or aerospace applications. The information provided, while deemed current at time of inclusion in the summary write-ups, may or may not still be current at the time of this version of the Guide is published. Therefore, the reader should further research the information before making decisions on usage of the model(s) of interest. The models extend to heights ranging from as low as the surface to as high as 4000 km. Models describing exclusively low altitude phenomena are not included. Possible examples of the latter are particulate aerosols or pollutants in the boundary layer and cloud properties as a function of altitude in the troposphere. Dynamical models such as the Earth Troposphere-Stratosphere General Circulation Models (GCM), the Thermosphere-Ionosphere-Mesosphere-Electrodynamics General Circulation Model (TIME-GCM), and research reports on measurements made by satellite, aircraft, and ground systems of the atmosphere are also not included in this guide.

Space environment (natural and artificial) — Guide to reference and standard atmosphere models

1 Scope

This standard provides guidelines for selected reference and standard atmospheric models for use in engineering design or scientific research. The guide describes the content of the models, uncertainties and limitations, technical basis, databases from which the models are formed, publication references, and sources of computer code where available for over seventy (70) Earth and planetary atmospheric models, for altitudes from surface to 4000 kilometers, which are generally recognized in the aerospace sciences. This standard is intended to assist aircraft and space vehicle designers and developers, geophysicists, meteorologists, and climatologists in understanding available models, comparing sources of data, and interpreting engineering and scientific results based on different atmospheric models.

The guide summarizes the principal features of the models to the extent the information is available:

- Model content
- Model uncertainties and limitations
- Basis of the model
- Publication references
- Dates of development, authors and sponsors
- Model codes and sources

The models are listed in the table of contents according to whether they are primarily global, middle atmosphere, thermosphere, range, or regional (i.e., applying only to a s pecific geographic location). This division is admittedly somewhat arbitrary because many of the models embody elements of several of the categories listed.

With few exceptions, there is no information on standard deviations from the mean values or frequencies of occurrence of the variables described by these models. This lack of information prohibits quantitative assessments of uncertainties, and is a serious deficiency in nearly all reference and standard atmospheric models.

Recommendations for models to include in subsequent revisions will be welcomed.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 5878:1982, *Reference atmospheres for aerospace use*

ISO 5878:1982/Addendum 1:1983, *Reference atmospheres for aerospace use, Addendum 1: W ind supplement*

ISO 5878:1982/Addendum 2:1983, *Reference atmospheres for aerospace use, Addendum 2: Air humidity in the Northern Hemisphere*

ISO 5878:1982/Amendment 1:1990, *Reference atmospheres for aerospace use, Amendment 1*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1
reference atmospheres
vertical temperature profiles for each latitutde and season; atmosphere models for specific geographical locations or globally

3.2
mean sea level
reference point for both geopotential and geometric altitudes

3.3
geopotential altitude
point in atmosphere expressed in terms of its potential energy per unit mass (geopotential) at this altitude relative to sea level

4 COSPAR International Reference Atmosphere (CIRA), 1986

4.1. Model content

The COSPAR International Reference Atmosphere (CIRA) provides empirical models of atmospheric temperature and density from 0 km to 2000 km as recommended by the Committee on Space Research (COSPAR). Since the early sixties different editions of CIRA have been published: CIRA 1961, CIRA 1965, CIRA 1972, and CIRA 1986.

The Committee on Space Research's *CIRA 1986 Model Atmosphere* consists of three parts: Part I: Models of the Thermosphere, Part II: Models of the Middle Atmosphere, and Part III: Models of Trace constituents. Part II is similar in many respects to the *NASA/GSFC Monthly Mean Climatology of Temperature, Wind, Geopotential Height and Pressure for 0-120 km*. This model is described later in this volume. Part III (published in 1996) gives model information on ozone, water vapor, methane and nitrous oxide, nitric acid, nitrogen dioxide, carbon dioxide and halogenated hydrocarbons, nitric oxide, stratospheric aerosols, atomic oxygen, and atomic hydrogen.

Chapter 1 of Part I (ref 5.1) describes the empirical thermospheric model which is based on the *Mass Spectrometer-Incoherent Scatter (MSIS) 1986* model of Hedin (ref 5.6, 5.8). Like Hedin's model, the altitude range is 90-2000 km, however, the models presented in Part I should be used exclusively for applications above 120 km; Part II should be exclusively used below 90 km while the "merging models" contained in Part II should be used for applications between 90 and 120 km. The atmospheric parameters yielded by the model are temperature, density, and composition, but not neutral winds. A large number of representative tables, coefficients, and the FORTRAN program are listed in the appendices of this referenced volume. With the aid of the program and the coefficients, representative thermospheric parameters can be generated for all locations, Universal Time and seasons, and for a very wide range of solar and geomagnetic activity.

Chapter 2 presents theoretical thermospheric models attributed to Rees and Fuller-Rowell (ref 5.7). These models reveal the detailed interrelationships between thermospheric structure (i.e., temperature and density), chemistry, and dynamics for simplified models of solar and geomagnetic forcing. A set of initial case studies using a c oupled polar ionosphere/global thermosphere model is also presented, which demonstrates the major interactions between the thermosphere and ionosphere.

Part I also contains five specialized chapters which review the major empirical contributions to our current understanding of the thermosphere. T hese sections discuss in situ mass spectrometer measurements of composition, temperature and winds; incoherent scatter radar measurements, satellite and gr ound-based measurements of thermospheric temperatures and winds, the thermospheric storm-like response to high levels of geomagnetic activities; and our understanding of the variance of solar EUV radiation.

Subsequent to publication of the CIRA 1986 model, several related developments have occurred. They include: (1) the characterization of the mean behavior of the Earth's atmosphere from 0 to 120 km altitude on the basis of the CIRA 1986 model (ref 5.4) as an annual zonal mean for 30 deg N to derive single profiles for the pressure, height, temperature, and zonal wind, and (2) a new zonal mean CIRA-1986 of temperature, zonal wind, and geopotential / geometric height as a function of altitude or pressure extending from the ground to approximately 120 km in the 80 deg S – 80 deg N latitudes (ref. 5.5).

The COSPAR committee responsible for updating the CIRA, 1986 Model met in July 2008 to address the updating of the CIRA, 1986 Model. The CIRA 2008 Model was adopted by COSPAR.

4.2 Model uncertainties and limitations

4.2.1 The quality of the database describing some observables is variable. The experimental global scale database for the lower thermosphere is still extremely limited.

4.2.2 The models are not reliable for large atmospheric disturbances. However, the causes of atmospheric variability are discussed in great detail.

Standard deviations from mean values of atmospheric parameters are not provided.

4.3 Basis of the model

As stated previously, the empirical thermosphere model is based on the MSIS-86 model of Hedin (ref. 5.7). The empirical model is complemented by theoretical models of Rees and Fuller-Rowell that show the relationships between thermospheric structure, chemistry and dynamics for simplified models of solar and geomagnetic forcing.

4.4 Databases

The principal publications which present the thermosphere database are listed in the MSIS-86 model description (ref. 5.6). Hedin (1988) also wrote a specially-commissioned section within 5.1 relating to the suitability and use of MSIS as the selected semi-empirical model for CIRA 1986-Part I.

4.5 Publication references

4.5.1 Rees, D., Editor, (1988): "COSPAR International Reference Atmosphere 1986 Part I. Thermospheric Models, "Advances in Space Research, Vol. 8, No. 5/6, Pergamon Press, Oxford and NY.

4.5.2 Rees, D., J. J. Bernett, and K. Labitzke, editors (1990): "CIRA 1986, COSPAR International Reference Atmosphere, Part II: Middle Atmosphere Models," *Advances in Space Research*, Vol. 10, No. 12, Pergamon Press, Oxford and NY.

4.5.3 Keating, G. M., editor (1996): COSPAR International Reference Atmosphere (CIRA), Part III: Trace Constituent Reference Models," *Advances in Space Research*, Vol. 18, No. 9/10, Pergamon Press, Oxford and NY.

4.5.4 Barnett, J. J. and S. Chandra (1990): "COSPAR International Reference Atmosphere Grand Mean," *Advances in Space Research,* Vol. 10, No. 12, Pergamon Press, Oxford and NY.

4.5.5 Fleming, Eric L., Sushil Chandra, J. J. Barnett, and M. Corney (1990): “Zonal Mean Temperature, Pressure, Zonal Wind, and Geopotential Height as Functions of Latitude,” *Advances in Space Research,* Vol 10, No. 12, Pergamon Press, Oxford and NY.

4.5.6 Hedin, A. E. (1987): “MSIS-86 Thermospheric Model.” J. Geophys. Res., Vol 92, Pages 4649-4662.

4.5.7 Rees, D., and T. J. Fuller-Rowell (1988): The CIRA Theoretical Thermosphere Model, “ pages (5) 25-(5) 106, Advances in Space Research, Vol. 8, No. 5/6, Pergamon Press, Oxford and NY.

4.5.8 Hedin, A. E. (1087): The Atmospheric Model in the Region 90 to 2000 km,” Pages (5) 9-(5) 25, Advances in Space Research, Vol. 8, No. 5/6, Pergamon Press, Oxford and NY

4.5.9 Hedin, A. E., J. E. Salah, J. V. Evans, C. A. Reber, G. P. Newton, N. W. Spencer, D. C. Kayser, D. Alcayde, Pl Bauer, L. Cogger, and J. Pl McClure, (1977) “A Global Thermospheric Model Based on Mass Spectrometer and Incoherent Scatter Data”, MSIS 1, N2 Density and Temperature, J. Geophys. Res. 82, 2139-2147, 1977.

4.5.10 Hedin, A. E., G. A. Reber, G. P. Newton, N. W. Spencer, H. C. Brinton, H. G. Mayr, and W. E. Potter (1977): A Global Thermospheric Model Based on Mass Spectrometer and Incoherent Scatter Data”, MSIS 2, Composition, J. Geophys. Res., 82, 2148-2156, 1977.

4.6 Dates of development, authors, and sponsors

4.6.1 Dates:

Original model	1961
Revised model	1965
Revised model	1972
Revised model	1986
Trace constituent model	1996
Zonal mean model	1990

4.6.2 Many scientists made contributions to the three parts of the CIRA models. They are identified in references 5.1, 5.2, and 5.3.

4.6.3 Co-Sponsors: Committee on Space Research (COSPAR) of the International Council of Scientific Unions (ICSU) and the International Union of Radio Science (URSI).

4.7 Model codes and sources

The thermosphere model is published in the form of tables and figures with a FORTRAN computer code included in an Appendix, describing the semi-empirical models of Part I, Chapter 1 (Ref 4.5.1). This program, and the program from which the results of the theoretical and numerical model results can be generated (Part I, Chapter 2) are available in computer-compatible form (tape or disk). They may also be obtained from certain electronic databases. See Reference 4.5.1 for thermosphere model, Reference 4.5.2 for middle atmosphere model, Reference 4.5.3 for trace constituent model, Reference 4.5.1 for grand mean model, and Reference 4.5.5 for new zonal mean CIRA, 1986 model.

NOTE At the time of preparation of this document, plans were being made by the COSPAR to produce an updated and revised version (CIRA08) of the COSPAR International Reference Atmosphere (CIRA), 1986. It is anticipated that the CIRA08 will be published in 2009 as a Special Issue of Advances in Space Research. Therefore, when planning to use CIRA, 1986 the availability of the new CIRA, 2008 should first be ascertained.

5 COSPAR International Reference Atmosphere (CIRA), 2008

5.1 CIRA-08

The COSPAR International Reference Atmosphere (CIRA) provides empirical models of atmospheric temperature and density from 0 km to 4000 km as recommended and adopted by the Committee on Space Research (COSPAR) and by the International Union of Radio Science (URSI). Since the early sixties, several distinct editions of CIRA have been published: CIRA 1961, CIRA 1965, CIRA 1972 CIRA 1986 and most recently, CIRA-08 (or CIRA-2008), which is currently in preparation by the CIRA Working Group.

5.2 Model content

The Committee on Space Research's *CIRA 2008 Model Atmosphere* will contain the following major contributions, in terms of recommended atmospheric models for use:

For Total Mass Density above 120 km:

- Jacchia-Bowman 2008 and GRAM-07

For the Structure and Composition of the Atmosphere (ground-level upward):

- NRLMSISE-00

For Neutral Winds in the Atmosphere (all levels):

- Horizontal Wind Model-07 (HWM-07)

For Neutral Wind up to 120 km altitude:

- Global Wind Empirical Model (GWEM)

There will also be chapters discussing the current state of knowledge and application of the Solar and Geomagnetic Indices that are used to drive the new empirical models such as JB-2008; Metal Chemistry of the Mesosphere and Lower Thermosphere, and expert advice regarding the limitations of the models and the best use of the models for specific applications.

5.3 Model availability

CIRA-08 is currently in preparation, and is expected to be published in early 2009 as a Special Edition of Advances in Space Research. The recommended Models within CIRA-08 are expected to be Web based, along with guides to the best use of the Models.

5.4 Sponsors

Co-Sponsors: Committee on Space Research (COSPAR) of the International Council of Scientific Unions (ICSU) and the International Union of Radio Science (URSI).

6 ISO reference atmospheres for aerospace use, 1982

6.1 Model content

The International Organization for Standardization (ISO) *Reference Atmospheres for Aerospace Use, 1982* consists of three documents containing tables and some figures. They present information on the seasonal, latitudinal, longitudinal, and day-to-day variability of atmospheric properties at levels between the surface and 80 km.

ISO International Standard 5878-1982 contains values of temperature, pressure and density as a function of geometric and geopotential altitude up to 80 km. Specific models include: (1) an annual model for 15 deg N latitude; (2) seasonal models for 30 deg, 45 deg, 60 deg and 80 deg N latitude; (3) cold and warm stratospheric and mesospheric regimes for 60 deg and 80 deg N latitude in December and January; and (4) seasonal and latitudinal variations of temperatures and density for medium, high and low percentile values.

Addendum 2-1983 to this document contains parameters (means and standard deviations) of Northern Hemisphere observed wind distributions in January and July up to 25 km for (1) four latitude zones plus calculated values of the scalar mean wind speed and of high and low percentile values of wind speed; (2) four stations (Dakar, Kagoshima, New York and Jan Mayen) with strong winds; (3) (Ajan, Clyde, Guam, and Muharrag) with light winds; and (4) four meridians plus high and low values of wind speeds.

The Addendum contains values (mixing ratio, vapor pressure and dew point temperatures) of the Northern Hemisphere air humidity in January and July to 10 km for (1) median values at 10 deg, 30 deg, 50 deg, and 70 deg N latitude; (2) median values along 0 deg, 80 deg E and 180 deg, 80 deg W meridians; (3) percentiles (20 percent, 10 percent, 5 percent and 1 percent) in extremely dry and moist areas and seasons, and (4) mean values for four stations representative of dry and moist regions (Tammaurrasset, North Africa; Xhigawsk, East Siberia; Calcutta, India, and Turk, Pacific Islands).

6.2 Model uncertainties and limitations

6.2.1 The temperature, pressure and density models are subject to the uncertainties associated with errors (about 1 deg C) in the standard radiosonde instruments used by the various countries to measure temperature profiles to altitudes near 30 km. Meteorological Rocketsonde temperature errors are about 2 deg C in the 30 to 50 km altitude range and increase to about 8 deg C at 80 km. For the meteorological rocket measurements, the thermistor measurements of temperature are subject to large corrections and uncertainties with increasing altitude. Therefore, the measurements above 50 km were not used. Measurements above 30 km, and especially above 50 km, were very limited. The warm and cold models for 60 deg and 80 deg N latitude are based on so few measurements that they are, at best, only rough estimates. Confidence in their distribution decreases rapidly above 50 km where data are relatively sparse and instrumentation errors relatively large.

6.2.2 The rawinsonde observations of wind velocity have uncertainties of about 5 percent of the vector wind for 0.6 km mean layers. For tracking angles within 6 deg of the horizontal, which occurs under strong jet stream conditions, the wind velocities are unreliable. According to the authors, their analysis of the scalar mean speed derived from observations, and calculated from the circular normal distribution may be used to calculate the values of wind speed with an accuracy sufficient for most practical purposes.

6.2.3 Reasonably reliable radiosonde measurements of humidity are available up to 10 km above sea level. Relative error varies with temperature from about 5 percent at +40 deg C to 15 percent at -40 deg C and are unreliable below -40 deg C. The tabulated humidity values above 8 km should be regarded as approximate because the quantity of data is insufficient.

6.2.4 Other model limitations due to the analytical and statistical fractions used as well as sample sizes are discussed in the text of the documents. The reference atmospheres are considered applicable to the northern hemisphere only.

6.3 Basis of the model

The numerical values of the various thermodynamic and physical parameters used in the comparisons of atmospheric properties are the same as those used in the ISO International Standard 2533-1975, *Standard Atmosphere* with the exception of surface conditions and the acceleration of gravity. Mean sea level is taken as the reference for both geopotential and geometric altitudes. The reference atmospheres are defined by the vertical temperature profiles for each latitude and season. The vertical gradients of temperature are constant with respect to geopotential altitude within each of a number of layers. Air is assumed to be a perfect gas, free from moisture or dust. The reference atmosphere upper stratosphere and mesosphere temperature observations for the southern hemisphere were phase adjusted by six months to conform to northern hemisphere seasons.

The wind parameters are based on observations and use of the circular normal distribution functions, which the authors consider acceptable for most practical purposes.

The humidity parameters are based on relative humidity and temperature measurements from radiosonde observations. The humidity-mixing ratio is used as the main humidity characteristic.

6.4 Databases

The vertical pressure and density distributions were calculated from the temperature-altitude profiles using the hydrostatic equation, the perfect gas law and appropriate mean sea-level values of pressure. The temperature distributions for levels below 30 km were derived from routine radiosonde observations from the 1955-1966 time period as contained in Monthly Climatic Data of the World by the World Meteorological Organization. The temperature field between 30 and 50 km is based on meteorological rocket measurements (bead thermistor or resistance wires) made at 17 locations primarily during the 1964-1970 time period. The temperature distributions between 50 and 80 km are based primarily on grenade, falling sphere, and pressure gauge experiments made at 12 locations during the 1957-1971 time period.

The values of the quantities describing the wind fields were obtained for the altitude range 0 to 25 km from actual observations made by balloon borne instruments and by estimation using the circular normal distribution. The measurements were primarily in the 1950 to 1970 time period.

The values of humidity were derived from radiosonde measurements for the altitude range 0 to 25 km. These measurements were also made primarily during the 1950 to 1970 time period.

6.5 Publication references

6.5.1 ISO International Standard 5878-1982, *Reference Atmospheres for Aerospace Use,* First Edition - 1982-04-14, Technical Committee ISO/TC 20, Aircraft and Space Vehicles.

6.5.2 ISO International Standard 5878-1982 / Addendum 1-1983, *Reference Atmospheres, Addendum 1: Wind Supplement,* Technical Committee ISO TC 20, Aircraft and Space Vehicles.

6.5.3 ISO International Standard 5878-1982 / Addendum 2-1983, *Reference Atmospheres for Aerospace Use, Addendum 2: Air Humidity in the Northern Hemisphere,* Technical Committee ISO/TC 20, Aircraft and Space Vehicles.

6.5.4 ISO International Standard 5878 -1982/ Amendment 1-1990, Reference Atmospheres for Aerospace Use, Amendment 1, Technical Committee ISO/TC, Aircraft and Space Vehicles.

6.6 Dates of development, authors and sponsors

6.6.1 Dates: ISO 5878-1982 circulated in November 1978, published in 1982

ISO 5878-1982/Addendum 1-1983 circulated in March 1979, published in 1983

ISO 5878/1982/Addendum 2-1983 circulated in April 1982, published in 1983

6.6.2 Authors: Members of Subcommittee 6 (Standard Atmospheres) of the International Organization for Standardization Technical Committee 20 (Aircraft and Space Vehicles).

6.6.3 Sponsors: International Organization for Standardization, Geneva, Switzerland, under the direction of Technical Committee 20 - Secretariat, Aerospace Industries Association of America, Inc., 1250 Eye Street, N.W., Washington, DC 20005.

6.7 Model codes and sources

The models are published in the form of tables and figures only. They are available from: American National Standards Institute, 25 West 43 Street, New York, NY 10036. http://www.ansi.org

NOTE At the time this document was prepared, the SC 6 "Standard Atmosphere" of technical committee ISO/TC20 "Aircraft and Space Vehicles" was in the process of updating and revising ISO 5878 "ISO Reference Atmospheres for Aerospace Use". This new version of ISO 5878 was published in draft form for review April 12, 2004 as ISO/WD 213-3 "Global Reference Atmosphere for Altitude 0-120 km for Aerospace Use" based on the work by ISO/TC 20/SC 6 "Standard Atmosphere" during the period 1998–2003. It is the intent that it be published as ISO Standard "Global Reference Atmosphere for Altitude 0-120 km for Aerospace Use".

This planned new ISO standard will present a set of models of vertical profiles of zonal (for 10 degree latitudinal belts) and seasonal mean temperatures, pressures, densities, and meridian and zonal wind speeds, as well as the space and temporal variability of these parameters in terms of standard deviations, for the altitude from 0 up to 120 km. The models of atmospheric parameters will be presented in graphic and tabular form in terms of geometric and componential altitudes and nearly pole-to-pole coverage (80 degrees N–80 degrees S) of both hemispheres for four central months of the seasons—January, April, July and O ctober. The algorithms and recommendations for the atmospheric parameters probability characteristics, which are the most useful for aviation and space practice, will also be given. ISO 213 is being developed to serve as an i nformational basis for international air-space practice as well as to unify the atmospheric models, which have to be used for design, production, exploitation and navigation of aircraft and space vehicles and their equipment.

Accordingly, it is recommended that those consulting this document for information on ISO 5878 investigate to see if the new ISO standard "Global Reference Atmosphere for Altitude 0-120 km for Aerospace Use" has been published by the ISO/TC 20/SC 6 "Standard Atmospheres" and obtain a copy for use in lieu of ISO 5878. At the time of the preparation of this document the Draft Standard "Global Reference Atmosphere for Altitude 0-120 km for Aerospace Use" was in a process of approval as a National Russia and Commonwealth of Independent States (CIS) Countries Standard.

7 ISO standard atmosphere, 1975

7.1 Model content

The International Organization for Standardization (ISO) *Standard Atmosphere* consists of a document containing tables of atmospheric characteristics as functions of geometric and geopotential altitudes to 80 km. They define the ISO Standard Atmosphere for the altitudes to 50 km. The data are identical to the ICAO and WMO Standard Atmospheres to 32 km and are based on the standard atmospheres of ICAO 1964 and US Standard 1962. The authors considered these models to be the most representative when comparing current national and international standards and recommendations relative to the atmosphere based on the results of recent research. Data from this recent research have been used for calculation of the atmospheric characteristics for altitudes 50 km to 80 km that represent the ISO Interim Standard Atmosphere for this altitude range. Data in the tables are given in SI units except that temperature is also given in degrees Celsius and pressures are given in millibars and millimeters of mercury.

ISO International Standard 2544:1975 contains values of temperature, pressure, density, acceleration of gravity, speed of sound, dynamic viscosity, kinematic viscosity, thermal conductivity, pressure scale height, specific weight, air number density, mean air-particle collision frequency, and mean free path as a function of geometric and geopotential altitude up to 80 km.

7.2 Model uncertainties and limitations

7.2.1 The tables have been calculated assuming the air to be a perfect gas free from moisture and dust and based on conventional initial values of temperature, pressure and density.

7.2.2 The model approximates the annual nominal atmosphere for 45 degrees north latitude. As such, large variations in monthly mean or even annual mean atmospheres for the other latitudes and longitudes around the globe, relative to the values given in the ISO Standard Atmosphere, may be expected. Thus, while providing a common frame of reference for comparing engineering designs, instrumentation calibrations and processing of data, the model may exhibit significant deviations from the nominal annual, and especially monthly, profiles of atmospheric parameters for given latitude and longitude locations. These are, however, the same limitations found in the models used as a basis for the ISO Standard Atmosphere. The user should be aware of these uncertainties and limitations of the model.

7.3 Basis of the model

The numerical values in the table for altitudes to 50 km are based on the *ICAO Standard Atmosphere 1964,* the *US Standard Atmosphere, 1962,* and the *COSPAR International Reference Atmosphere, 1965 (CIRA 1965)*; results of recent research as noted in the references were used for the 50 to 80 km altitude region. For the altitudes to 32 km the tables are identical to the *ICAO Standard Atmosphere, 1964.*

7.4 Databases

Mean sea level is taken as the reference point for both the geopotential and geometric altitudes. The perfect gas law is used for the calculations that assume a well-mixed atmosphere. The temperature of each atmospheric layer is taken as a linear function of the geopotential altitude. The constants, coefficients, equations and data were selected from these references:

7.4.1 COSPAR Working Group IV. COSPAR International Reference Atmosphere, 1965 (CIRA 1965), North Holland Publishing Co., Amsterdam, 1965.

7.4.2 Comitet Standartov USSR: G OST 4401.64 "Tabblitsa Standartnoy Atmosfery," Izdatelstvo Standartov, Moskva, 1964

7.4.3 Deutscher Normenausschuss: DIN 5450 "Norm Atmosphere," 1968.

7.4.4 Doc. 7486/2. Manual of the ICAO Standard Atmosphere extended to 32 kilometers, second edition, 1964, International Civil Aviation Organization, Montreal, 1964.

7.4.5 List, R. J., editor: Smithsonian Meteorological Tables, Sixth Revised Edition, Washington, DC, 1963.

7.4.6 U.S. Committee on Extension to the Standard Atmosphere: U.S. Standard Atmosphere, 1962, U.S. Government Printing Office, Washington, DC, 1962.

7.4.7 U.S. Committee on Extension to the Standard Atmosphere: U.S. Standard Atmosphere Supplements, 1966. U.S. Government Printing Office, Washington, DC, 1966.

7.5 Publication references

ISO International Standard 2533-1975 "Standard Atmosphere First Edition, "Corrigendum 1, 1978, ISO, Geneva, Switzerland

7.6 Dates of development, authors and sponsors

7.6.1 Dates: Published 1975; corrected and updated 1978

7.6.2 Authors: Members of ISO TC20/SC6 (Aircraft and Space Vehicles / Standard Atmospheres)

7.6.3 Sponsors: International Organization for Standardization, Geneva, Switzerland

7.7 Model codes and sources

The model is published in the form of tables only. It is available from American National Standards Institute, 25 West 43 Street, New York, NY 10036. http://www.ansi.org

8 NASA/GSFC monthly mean global climatology of temperature, wind, geopotential height and pressure for 0–120 KM, 1988

8.1 Model content

This climatological model, the National Aeronautics and Space Administration's *NASA GSFC Monthly Mean Global Climatology of Temperature, Wind, Geopotential Height and Pressure for 0-120 km,* consists of a NASA report and a floppy diskette to be used with a PC, and contains figures and tables which present profiles of temperature, winds, and geopotential height as functions of altitude and pressure in the height range 0-120 km. These atmospheric properties, which are presented in a climatological format, are monthly mean values with nearly pole-to-pole coverage (80 deg S to 80 deg N). The model is intended for various research and analysis activities such as the numerical simulation of atmospheric properties and the design and development of satellite instruments for measuring Atmospheric parameters. The climatological data and the related text will also form the basis of the new COSPAR International Reference Atmosphere (CIRA 86) for the altitude range 0-120 km (Part II).

Section 4 of the report presents various zonal mean cross sectional plots of the temperature and zonal wind climatology in latitude-height, month-height, month-latitude, and global average. Harmonic analyses (amplitude and phase) of the data are also presented and discussed. Similar analyses are done for the mean geopotential height and the mean pressure. The zonal wind climatology is also compared with climatological zonal wind measurements from various radar stations around the globe, and with the CIRA-72 zonal wind model.

Longitudinal variations of these atmospheric properties in the stratosphere and mesosphere are also presented and, finally, a comparison is made between this climatology data from the National Meteorological Center (NMC).

8.2 Model uncertainties and limitations

Since the model is based upon a statistical analysis of the available atmospheric data, the model uncertainties depend upon the quantity and quality of these data and the degree to which they represent the real atmosphere at a given time and place. No quantitative assessments of uncertainty are provided with the model.

8.3 Basis of the model

The model, which is entirely empirical in nature, is based upon analyses of satellite and ground-based atmospheric data obtained since the publication of the CIRA 1972 model atmosphere. The zonal mean temperature and wind values for the troposphere (0-10 km) were obtained from the climatology of Oort (Ref. 8.5.5). Temperatures, geopotential heights, and pressures were taken from the climatology of Barnett and Corney (Ref. 8.5.1) for the stratosphere and mesosphere (10-80 km), and the MSIS-83 and MSIS-86 empirical models (Ref. 8.5.3, 8.5.4) for the lower thermosphere (86-120 km).

Zonally averaged zonal wind speed $\langle Y \rangle$ for the altitude range 10-120 km were derived from the geopotential height climatology using the zonally averaged zonal momentum equation,

$$\frac{\langle U \rangle^2 \tan\theta}{a} + 2\Omega \langle U \rangle \sin\theta = - g_0 \frac{\partial \langle Z \rangle}{\partial y} \tag{1}$$

where a is the earth's radius, Ω is the angular speed of rotation of the earth, g_o is the gravitational acceleration at sea level, θ is latitude and $\langle Z \rangle$ is the zonally averaged geopotential height. At the equator, the authors have used the following expression for the zonal wind speed:

$$\langle U_{eq} \rangle = - \frac{g_0}{ß} \frac{\partial^2 \langle Z \rangle}{\partial y^2} \quad (2)$$

where ß is the meridional gradient of the Coriolis parameter. At latitudes of 10 deg N and 10 deg S, the zonal winds were computed by linearly interpolating between the zonal wind at 15 deg N and 15 deg S computed from Eq. (1) and the wind at the equator [Eq. (2)]. At latitudes of 80 deg N and 80 deg S, the wind speeds were derived from the relation

$$\langle U \rangle_{80} = \langle U \rangle_{70} \frac{\cos (80 \text{ deg})}{\cos (70 \text{ deg})} \quad (3)$$

thus assuming that the relative angular velocity, $\langle m \rangle = \langle U \rangle$ a $\cos\theta$, remains constant poleward of 70 deg N (or S).

8.4 Databases

8.4.1 The *Global Atmospheric Circulation Statistics 1958-1973,* compiled by Oort (ref. 5.5) provides the zonally averaged climatological monthly mean temperature and zonal wind values for 80 deg S to 80 deg N at 5 deg resolution for the 1000-50 mb pressure levels. These values are based upon data for 1963-1973 derived from the National Meteorological Center (NMC, Washington, DC), the National Center for Atmospheric Research (NCAR, Boulder, CO), Ocean Station Vessels (OSV), the British Meteorological Office (Bracknell, United Kingdom) and the National Climatic Center (Asheville, NC).

8.4.2 The *Middle Atmosphere Reference Model Derived from Satellite Data,* (Ref. 8.5.1) contains global zonal mean climatological data sets of temperature, zonal geostrophic wind, geopotential height, and pressure for the stratosphere and mesosphere for 80 deg S-80 N (20 deg N-70 deg N and 20 deg S-70 deg S) at 10 deg resolution. The data are based on measurements from the Nimbus 5 Selective Chopper Radiometer (SCR) and the Nimbus 6 Pressure Modulator Radiometer (PMR) for 1973-1978.

8.4.3 Temperature and composition data for the lower thermosphere (86-120 km) were provided by the MSIS-86 and MSIS-83 empirical models of Hedin (Ref. 8.5.3, 8.5.4), described elsewhere in this report.

8.5 Publication references

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8.5.2 Fleming, E. L., S. Chandra, M. R. Schoeberl, and J. J. Barnett (1988), "Monthly mean global climatology of temperature, wind, geopotential height, and pressure for 0-120 km," NASA TM-100697, NASA Scientific and Technical Information Facility, Linthicum, MD 21240. <http://trs.nasa.gov/archive/>

8.5.3 Hedin, A. E. (1983) "A revised thermospheric model based on mass spectrometer and incoherent scatter data," MSIS-83, *J. Geophys. Res., 88,* 10,170-10, 185.

8.5.4 Hedin, A. E. (1987) "MSIS-86 thermospheric model," *J. Geophys. Res., 92*, 4649-4662.

8.5.5 Oort, A. H. (1983) *Global Atmospheric Circulation Statistics, 1958-1983* National Oceanic and Atmospheric Administration (NOAA) Professional Paper 14, U.S. Government Printing Office.

8.6 Dates of development, authors, and sponsors

8.6.1 Dates: 1988

8.6.2 Authors: E. L. Fleming (principal):

8.6.3 Sponsors: National Aeronautics and Space Administration, Goddard Space Flight Center.

8.7 Model codes and sources

The climatological data are portrayed in figures and tables in NASA TM- 100697 (Ref. 8.5.2). A copy of NASA TM-100697 with these figures and tables can be obtained electronically from http://ntrs.nasa.gov.

9 NASA/MSFC global reference atmosphere model (GRAM-99), 1999

9.1 Model content

The National Aeronautics and Space Administration's NASA/MSFC Global Reference Atmospheric Model (GRAM-99; Justus and Johnson, 1999) is a product of the Environments Group, NASA Marshall Space Flight Center, and is used by several NASA centers, numerous other government agencies, industries and universities, in such projects as Space Shuttle, International Space Station, X-37, Hyper-X, Space Launch Initiative, Space Plane, High Speed Civil Transport, and Stardust. GRAM applications include scientific studies, orbital mechanics and lifetime studies, vehicle design and performance criteria, attitude control analysis problems, analysis of effects of short-term density variation caused by geomagnetic storms, aero braking and aero capture analyses, and dynamic response to turbulence or density shears.

In addition to evaluating the mean density, temperature, pressure, and wind components at any height (0-2500 km), latitude, longitude and monthly period, GRAM also allows for the simulation of “random perturbation” profiles about the mean conditions. This feature permits the simulation of a large number of realistic density, temperature and wind profile realizations along the same trajectory through the atmosphere, with realistic values of the scales of variation and peak perturbation values (e.g., the random perturbation profiles produce values which exceed the three standard deviation values approximately 0.1 percent of the time).

Wind fields in the height range above 90 km are computed from the pressure fields by use of geostrophic wind relations. Wind shears in the same height ranges are evaluated from the thermal wind equations. Below 90 km, winds and shears are evaluated from observed upper atmospheric winds. Mean vertical velocities are computed from the slopes of isentropic surfaces (surfaces of constant potential temperature).

In order to use the model, appropriate input parameters must be supplied, consisting of: (1) values of the program options, the initial position, the profile increments, and other information required before calculations are begun; (2) a data base containing parameter values for the zonal mean model, the stationary perturbations (deviations from zonal mean model, to produce longitude-dependent monthly means), and random perturbation parameters; and (3) the data bases with one data file (pressure, temperature, density) for each month and the parameter variances from the surface to 27 km for the entire globe. If it is desired to compute atmospheric properties along any trajectory other than a linear profile, then a fourth type of data -- the trajectory positions -- must be supplied. All the statistically different profiles of random perturbations desired can be evaluated by computing along the same trajectory with different input starting conditions for the random perturbation values.

Output consists of monthly mean pressure, density, temperature, wind velocity and wind shear components, and random perturbation values of pressure, density, temperature and wind components. GRAM-99 also includes water vapor and several atmospheric constituents.

9.2 Model uncertainties and limitations

9.2.1 The model does not predict any parameters in the sense of a forecast model. It only provides estimates of the monthly mean values and statistically realistic deviations from the mean.

9.2.2 The model does not take account of episodic high latitude thermospheric perturbations associated with auroral activity, high latitude stratospheric warming perturbations, El Niño / Southern Oscillation events, etc. However, values of the normal magnitudes of the random perturbations can be scaled up (or down) to simulate unusually disturbed (or unusually quiescent) conditions.

9.2.3 Above 90 km, predicted winds are geostrophic, computed from mean pressure values. Predicted wind shears are computed from the thermal wind using mean temperature fields.

9.2.4 Water vapor estimates include standard deviations. Only mean values are given for other constituents.

9.3 Basis of the model

9.3.1 Marshall Engineering Thermosphere (MET) model (1988/1999) (Range: 120–2500 km)

9.3.1.1 Temperature and density variation (solar and geomagnetic activity, diurnal variations, seasonal and latitudinal variations including the winter helium bulge)

9.3.1.2 Uniformly mixed composition up to 105 km, diffusive equilibrium for all constituents (N_2, O_2, O, A, He, H) above 105 km

9.3.1.3 Fixed boundary conditions for temperature and density at 90 km

9.3.1.4 Geostrophic winds evaluated by computing horizontal pressure gradients with successive evaluations of the MET model at different latitudes and longitudes

9.3.2 Middle Atmosphere Program (MAP) model (1971) for heights of 20 to 120 km

9.3.2.1 Zonal means for from an amalgamation of six data sources, primarily MAP data. Complete references are available in Justus, et al., 1991c.

9.3.2.2 Longitudinal variations are introduced as perturbations (see Justus et al., 1974) on the zonal mean model, which is latitude and time dependent (in one month increments) only. These data are from global satellite observations. (Dartt et al., 1988, and other references in Justus, et al., 1991a).

9.3.2.3 Middle atmosphere data are supplied at altitude intervals of 5 km.

9.3.3 Global Upper Air Climatic Atlas (GUACA) (1993) data for heights from surface to 27 km

The GUACA data base (Ruth et al., 1993) as produced by the U.S. Navy and U.S. National Climatic Data Center.

9.3.3.1 Altitude intervals are interpolated from pressure level down to, 0-27 km.

9.3.3.2 Data are empirically determined atmospheric parameter profiles as quality controlled, gridded and smoothed for use as initial conditions in the European Centre for Medium-Range Weather Forecasts (ECMWF) global circulation model. Coverage is global.

9.3.4 Altitude interval 20 to 27 km and 90 to 120 km: A “fairing” technique (Justus et al, 1974) is used to ensure a smooth transition between GUACA and MAP data (20 to 27 km) and the MAP data and the MET model (90 to 120 km).

9.3.5 Atmospheric Constituents

Water vapor and several other atmospheric constituents are included in GRAM-99. Below the 300-millibar level, water vapor means and standard deviations are based on the GUACA database. Above this level, water vapor is based on data from NASA Langley, the MAP program and from Air Force Geophysics Lab (see complete references in NASA TM-4715, reference 5.10 below). Other constituents (ozone, nitrous oxide, carbon monoxide, methane, etc.) are also included (mean values only).

9.4 Databases

9.4.1 Jacchia, L. G. (1970) New static models of the thermosphere and exosphere with empirical temperature profiles, Smithsonian Astrophysical Observatory Special Report 313, May.

9.4.2 Jacchia, L. G. (1971) Revised static models of the thermosphere and exosphere with empirical temperature profiles, Smithsonian Astrophysical Observatory Special Report 332, May.

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9.5.8 Justus, C. G., F. N. Alyea, D. M. Cunnold, W. R. Jeffries, III, and D. L. Johnson (1991a), “The NASA/MSFC Global Reference Atmospheric Model - 1990 Version (GRAM-90): Part 1, Technical Users Manual” NASA TM 4268.

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9.5.10 Justus, C. G., W. R. Jeffries III, S. P. Yung and D. L. Johnson (1995), "The NASA/MSFC Global Reference Atmospheric Model - 1995 Version (GRAM-95)," NASA TM-4715.

9.5.11 Hickey, M. P. (1988a), “The NASA Marshall Engineering Thermosphere Model,” NASA CR-179359.

9.5.12 Hickey, M. P. (1988b), “An Improvement in the Numerical Integration Procedure Used in the NASA Marshall Engineering Thermosphere Model,” NASA CR-179389.

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9.6 Dates of development, authors, and sponsors

9.6.1 **Dates:**

	original model	1974–1975
Revised model	1976 (mod. 2)	1980 (mod. 3)
GRAM-86	1986	
GRAM-88	1988	
GRAM-90	1990	
GRAM-95	1995	
GRAM-99	1999	

9.6.2 Principal author: C. G. Justus

9.6.3 Sponsors: National Aeronautics and Space Administration, Marshall Space Flight Center

9.7 Model codes and sources

The monthly Marshall Solar Activity Future Estimation (MSAFE) report provides expected 13-month Zurich smoothed solar and geomagnetic activity based on the most recent monthly mean data for use in the GRAM-99. It can be downloaded from http://sail.msfc.nasa.gov

A description and user's manual for GRAM-99 is provided in NASA TM-1999-209630 (Ref. 9.5.13). GRAM-99 program code is available from NASA Marshall Space Flight Center. It is available in PC-compatible and UNIX forms. Contact: NASA Marshall Space Flight Center, Natural Environments Branch, Marshall Space Flight Center, AL 35812 or jere.Justus@msfc.nasa.gov or barry.c.roberts@nasa.gov for further information.

10 NASA/MSFC Earth global reference atmosphere model (Earth GRAM-07), 2007

10.1 Model content

The National Aeronautics and Space Administration's NASA/MSFC Earth Global Reference Atmospheric Model version 2007 (Earth GRAM-07) is a product of the Natural Environments Branch, NASA Marshal Space Flight Center. (Ref. 10.4.1) Like the previous versions of Earth GRAM, the model provides estimates of means and standard deviations for atmospheric parameters such as density, temperature, and winds, for any month, at any altitude and location within the Earth's atmosphere. Earth GRAM can also provide profiles of statistically-realistic variations (i.e., with Dryden energy spectral density) for any of these parameters along computed or specified trajectory. This perturbation feature makes Earth GRAM especially useful for Monte-Carlo dispersion analyses of guidance and control systems, thermal protection systems, and similar applications. Earth GRAM has found many uses, both inside and outside the NASA community. Most of these applications rely on Earth GRAM's perturbation modeling capability for Monte-Carlo dispersion analyses. Some of these applications have included operational support for Shuttle entry, flight simulation software for X-33 and other vehicles, entry trajectory and landing dispersion analyses for the Stardust and Genesis missions, planning for aerocapture and aerobraking for Earth-return from lunar and Mars missions, six-degree-of-freedom entry dispersion analysis for the Multiple Experiment Transporter to Earth Orbit and Return (METEOR) system, and more recently the Crew Exploration Vehicle (CEV). Earth GRAM-07 retains the capability of the previous version but also contains several new features:

10.1.1 Revised Range Reference Atmosphere (RRA) data

In 2006, the Air Force Combat Climatology Center (AFCCC) developed a set of revised Range Reference Atmosphere (RRA) data including several new sites. Earth GRAM-07 has the option of using either the 2006 revised RRA data, or the earlier (1983) RRA data, as a replacement for conventional Earth GRAM climatology.

10.1.2 Optional auxiliary profile input

In addition to RRA options, an "auxiliary profile" feature has been implemented. This allows the user to input a data profile of pressure, density, temperature, and/or winds versus altitude, with the auxiliary profile values used in place of conventional climatology values. This option is controlled by setting parameters in the input file. Parameters control the latitude-longitude radius within which the weight for the auxiliary profile varies from 0 to 1. Mean conditions are given by the profile if the desired point is within a prescribed radius of influence and are otherwise given by Earth GRAM climatology.

10.1.3 Updated thermosphere models

10.1.3.1 Earth GRAM-07 includes several updates to the Marshall Engineering Thermosphere (MET-2007) model (Ref. 10.4.6) which include:

10.1.3.1a Corrections for inconsistency between constituent number density and mass density.
10.1.3.1b Representation of gravity above an oblate spheroid Earth shape, rather than using a spherical Earth approximation.
10.1.3.1c Treatment of day-of-year as a continuous variable in the semi-annual term, rather than as an integer day.
10.1.3.1d Treatment of year as either 365 or 366 days in length (as appropriate), rather than all years having length 365.2422 days.
10.1.3.1e Allows continuous variation of time input, rather than limiting time increments to integer minutes.

10.1.3.2 The Naval Research Labs Mass Spectrometer, Incoherent Scatter Radar Extended Model for the thermosphere (NRL MSIS E-00) and the associated Harmonic Wind Model (HWM-93) are now an optional thermospheric model in Earth GRAM-07.

10.1.3.3 The Jacchia-Bowman 2006 thermosphere model (JB2006) is another optional thermospheric model in Earth GRAM-07 (Ref. 10.4.2).

10.1.4 Coordinate system changes and revised earth reference ellipsoid

Equatorial and polar Earth radii for the "sea-level" reference ellipsoid have been updated to World Geodetic System (WGS 84) values. Previous (Earth GRAM-99) radius values were from IAU 76. WGS 84 values are used by the GPS navigation system. These are also equivalent (to 10 significant figures) to the Geodetic

Reference System (GRS 80) values. Other recent values that could be used include the International Earth Rotation & Reference System (IERS 1989) values. Earth radius values are set by parameters values in one of the Earth GRAM-07 subroutines. Input values of altitude greater than 6000 km are treated as geocentric radius values, rather than heights. Both radius and height are now given in the output file. Although all input latitudes are geocentric, Earth GRAM-07 now gives both geocentric and geodetic values on the output file. A new subroutine has also been added which computes horizontal distance from great-circle distance between two input latitude-longitude positions. This subroutine is used to calculate lat-long "radius" of current position from Range Reference Atmosphere site locations, and to compute horizontal step size in the perturbation model.

10.1.5 Perturbation model revisions

Several changes/additions have been made in the perturbation model for Earth GRAM-07. These include:

10.1.5.1 A new feature to update atmospheric mean values without updating perturbation values.

10.1.5.2 The ability to simulate large-scale, partially-correlated perturbations as they progress over time for a few hours to a few days.

10.1.5.3 A multiple-trajectory driver routine that allows multiple trajectories and perturbations to be simulated in one run.

10.1.5.4 A multiple-profile driver routine that allows multiple profiles and perturbations to be simulated in one run, with small-scale correlations maintained between the profiles.

10.2 Model uncertainties and limitations

10.2.1 The model does not predict any parameters in the sense of a forecast model. It provides estimates of the monthly mean values and statistically realistic deviations from the mean.

10.2.2 The model does not take into account the episodic high latitude thermospheric perturbations associated with auroral activity, high latitude stratospheric warming perturbations, El Niño / Southern Oscillation events, etc. However, values of the normal magnitudes of the random perturbations can be scaled up (or down) to simulate unusually disturbed (or quiescent) conditions.

10.2.3 Above 90 km, predicted winds are geostrophic, computed from mean pressure values (unless the MSIS/HWM thermosphere option is used). Predicted geostrophic wind shears are computed from the thermal wind using mean temperature fields.

10.2.4 Water vapor estimates include standard deviations while only mean values are given for other constituents.

10.3. Basis of the model

10.3.1 Marshall Engineering Thermosphere (MET-2007) model (Above 120 km)

10.3.1.1 Temperature and density variation (solar and geomagnetic activity, diurnal variations, seasonal and latitudinal variations including the winter helium bulge).

10.3.1.2 Uniformly mixed composition up to 105 km, diffusive equilibrium for all constituents (N_2, O_2, O, Ar, He, H) above 105 km.

10.3.1.3 Fixed boundary conditions for temperature and density at 90 km.

10.3.1.4 Geostrophic winds evaluated by computing horizontal pressure gradients with successive evaluations of the MET model at different latitudes and longitudes.

10.3.2 The Naval Research Lab Mass Spectrometer, Incoherent Scatter Radar Extended Model (NRL MSIS E-00)

10.3.2.1 Thermospheric winds are evaluated using the NRL 1993 Harmonic Wind Model, HWM-93.

10.3.2.2 Winds are computed from a geostrophic wind model, with modifications for thermospheric effects of molecular viscosity.

10.3.3 The Jacchia-Bowman 2006 thermosphere model (JB2006)

10.3.3.1 Developed using the CIRA72 (Jacchia 71) model as the basis for the diffusion equations.

10.3.3.2 New solar indices have been used for the solar irradiances in the extreme and far ultraviolet wavelengths.

10.3.3.3 New exospheric temperature and semiannual density equations were created to represent the major thermospheric density variations.

10.3.3.4 Temperature correction equations developed for diurnal and latitudinal effects.

10.3.3.5 Density correction factors have been included for model corrections required at high altitudes (1500–4000 km).

10.3.3.6 Model has been validated through comparisons of accurate daily density drag data previously computed for numerous satellites.

10.3.4 Middle Atmosphere Program (MAP) model (1971) for heights between 20 and 120 km

10.3.4.1 Zonal means from six data sources, primarily MAP data. Compete reference are available in Data Base.

10.3.4.2 Longitudinal variations are introduced as perturbations on the zonal mean which is latitude and time dependent (in one month increments) only. These data are from global satellite observations.

10.3.4.3 Middle atmosphere data are supplied at altitude intervals of 5 km.

10.3.5 Global Upper Air Climatic Atlas (GUACA) 1993 data for heights from surface to 27 km

The GUACA data base as produced by the U.S. Navy and the U.S. National Climatic Data Center.

10.3.5.1 Linear interpolation is used horizontally while vertical interpolation for thermal dynamic variables obey the gas law and hydrostatic constraints. A fairing technique is used for overlapping databases.

10.3.5.2 Data are empirically determined atmospheric parameter profiles as quality-controlled, gridded and smoothed for use as initial conditions in the European Centre for Medium-Range Weather Forecasts (ECMWF) global circulation model. Coverage is global and uses monthly averages.

10.3.5.3 The altitude intervals 20 to 27 km and 90 to 120 km use a "fairing" technique to ensure a smooth transition between GUACA and MAP data as well as the transition from MAP data to the thermosphere model.

10.3.6 Atmospheric constituents

Water vapor and several other atmospheric constituents are included in Earth GRAM-07. Below the 300-milibar level, water vapor means and standard deviations are based on the GUACA database. Above this level, water vapor is based on data from NASA Langley, the MAP program, and from the Air Force Geophysics Lab (see complete references in NASA TM-4715, reference 10.5.12). Other constituents (ozone, nitrous oxide, carbon monoxide, methane, etc.) are also included (mean values only).

10.4 Databases

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10.5.12 Justus, C.G., Jeffries III, W.R., Yung, S.P., and Johnson, D.L. (1995), "The NASA/MSFC Global Reference Atmospheric Model – 1995 Version (GRAM-95)", NASA TM-4715.

10.5.13 Justus, C.G., and Johnson, D.L. (1999), "The NASA/MSFC Global Reference Atmospheric Model - 1999 Version (GRAM-99)", NASA/TM--1999-209630.

10.5.14 Justus, C. G., Duvall, A., and Keller, V.W. (2004), "Earth Global Reference Atmospheric Model (GRAM-99) and Trace Constituents", Paper C4.1-0002-04, Presented at 35th COSPAR Scientific Assembly Paris, France July 18-25, 2004.

10.5.15 Norlin, K.A. (1995), “Flight Simulation Software at NASA Dryden Flight Research Center”, NASA Technical Memorandum 104315, October 1995.

10.5.16 Williams, P.S. (2001), “A Monte Carlo Dispersion Analysis of the X-33 Simulation Software”, AIAA 2001-4067, AIAA Atmospheric Flight Mechanics Conference, Montreal, Canada, August 6–9, 2001.

10.6. Dates of development, authors and sponsors

10.6.1

Version	Date
Earth GRAM	1974
Earth GRAM-86	1986
Earth GRAM-88	1988
Earth GRAM-90	1991
Earth GRAM-95	1995
Earth GRAM-97	1997
Earth GRAM-98	1998
Earth GRAM-99	1999
Earth GRAM-07	2007

10.6.2 Principal authors: C. G. Justus

10.6.3 Sponsors: National Aeronautics and Space Administration, Marshall Space Flight Center

10.7. Model codes and sources

The monthly Marshall Solar Activity Future Estimation (MSAFE) report provides expected 13-month Zurich smoothed solar and geomagnetic activity based on the most recent monthly mean data for use in the GRAM-99. It can be downloaded from http://sail.msfc.nasa.gov.

The Earth GRAM-07 program FORTRAN source code is available from NASA Marshall Space Flight Center. Contact NASA Marshall Space Flight Center, Mail Code: EV44, Natural Environments Branch, Marshall Space Flight Center, AL 35812.

NOTE A new version of Earth-GRAM (Earth-GRAM2010) is currently under development and targeted for release in May 2010. This new program will use a more contemporary global database from the National Centers for Environmental Prediction (NCEP) Reanalysis Project. The NCEP region extends from the surface to the 10 millibar level (~27-31 km), with a default period of record from 1990 to 2008. This climatology includes means and standard deviations for four times of day so the user has the option of selecting monthly mean values occurring at times 00Z, 06Z, 12Z, 18Z or the total daily statistics. In addition, Earth-GRAM2010 uses a global climatology of chemical release winds to revise wind perturbation standard deviations in the 90-120 km altitude range. The thermosphere has also been updated with the new Air Force JB2008 model, while the user still has the option to select the NASA Marshall Engineering Thermosphere (MET) model or the Naval Research Laboratory (NRL) Mass Spectrometer, Incoherent Scatter (MSIS) Radar Extended Model.

11 U.S. standard atmosphere, 1962

11.1 Model content

The *U. S. Standard Atmosphere, 1962* consists of a bound volume, containing principally tables, and to a lesser extent, figures. The latter present profiles of temperature, pressure, density, sound speed, kinematic and dynamic viscosity, thermal conductivity, gravitational acceleration, specific weight, pressure scale height, particle speed, collision frequency, and mean free path, with altitude given in both metric and English units. The altitude range is -5 to 700 km, although some of the data presented are terminated at 90 km. NOTE: This information on t he U. S. Standard Atmosphere, 1962 is provided for historical information. The reader is directed to the U. S. Standard Atmosphere, 1976 for use in any applications.

The model is empirical, being based upon temperature measurements by radiosondes, rocketsondes, and satellites, which yield a standard temperature profile extending from below sea level to 700 km altitude. The U. S. Standard Atmosphere, 1962 is divided into four altitude regions: the first, from -5 to 20 km is designated standard; a second region, from 20 to 32 km is designated proposed standard; the region from 32 to 90 km, tentative, and the region from 90 to 700 km, is termed speculative, reflecting the varying degrees of confidence in the data. All region altitudes are both geopotential (up to 90 km) and geometric altitudes. The temperature profile is selected such that it provides a best fit to the measured data. Tables of geopotential altitude (in both meters and feet) as a function of pressure in millibars are included at the end of the volume. While variations (diurnal, seasonal, latitudinal, and solar cyclical) are briefly discussed and formulas for introducing the variations into the model are given, the model is, in fact, an idealized, middle latitude (45 deg) year-round mean over a range of solar activity between sunspot minima and maxima. T his model was subsequently extended by the 1966 Supplement and then superseded by the U.S. Standard Atmosphere, 1976.

11.2 Model uncertainties and limitations

11.2.1 The Standard is an idealized model corresponding to mean global and annual mid-latitude (45 deg) conditions only. However, formulas are presented for calculating corrections to the kinetic temperatures for nocturnal conditions and for varying 10.7 cm solar flux.

11.2.2 Winds are not modeled.

11.2.3 Data for the region between 32 and 90 km are moderately uncertain; and data for the region above 90 km are very unreliable.

11.2.4 The accuracy of the data used as the basis of the Standard varies from on instrument to another and also with altitude.

11.3 Basis of the model

11.3.1 The model is a successor to the U. S. Extension to the ICAO Standard Atmosphere: Tables and Data to 300 Standard Geopotential Kilometers, 1958.

11.3.2. The air is assumed to be dry and homogeneously mixed up to 90 km. At low altitudes where mixing is complete, the hydrostatic equation

$$\mathrm{d} \ln \mathrm{p} = - \frac{\mathrm{gM}}{\mathrm{RT}} \mathrm{dz}$$

is integrated. Here p is pressure, g is the gravitational acceleration at 45 deg latitude, M is the mean molecule weight, T is the absolute temperature, z is geometric altitude, and R is molecular gas constant

11.3.3 The gravitational acceleration, g, is height-dependent with both "inverse-square" and centripetal effects included in the analysis.

11.4 Databases

Thirty-four papers or reports summarizing the rocket data (falling sphere, grenade, pitot-static tube, and thermistor) as well as the satellite data are listed on pages 29-30 of the basic document. Because of the length of the list, they are not reproduced here.

11.5 Publication references

National Aeronautics and Space Administration, U.S. Air Force, and U. S. Weather Bureau, *U. S. Standard Atmosphere, 1962,* U. S. Government Printing Office, Washington, DC, 1962.

11.6 Dates of development, authors and sponsors

11.6.1 Dates: U.S. Extension to the ICAO Standard Atmosphere 1958

U.S. Standard Atmosphere, 1962

11.6.2 Principal authors: M. Dubin, N. Sissenwine, and H. Wexler, Co-chairmen, U.S. Committee on Extension of the Standard Atmosphere (COESA). The editors were K. S. W. Champion, W. J. O'Sullivan, and S. T. Teweles. The model was developed and adopted in consolation with the International Civil Aviation Organization (ICAO)

11.6.3 Sponsors: National Aeronautics and Space Administration, U.S. Air Force, U.S. Weather Bureau.

11.7 Model codes and sources

The model is published in the form of tables and figures only. No computers codes are available. Copies of the U. S. Standard Atmosphere, 1962 should be available from the U. S. Government Printing Office, Washington, DC.

12 U.S. standard atmosphere supplements, 1966

12.1 Model content

The *U. S. Standard Atmosphere Supplements, 1966* extend the *U. S. Standard Atmosphere, 1962* to include seasonal and latitudinal variations. In addition, it extends the altitude domain upward to 1000 km. The principal tables, which present temperature, temperature variation from the 1962 standard, pressure millibars, the ratio of pressure to that of the 1962 standard, density, the ratio of density ratio to that of the 1962 standard, sound speed, coefficient of viscosity, and thermal conductivity, correspond to the following seasonal and latitudinal conditions: 15 deg N, annual mean; 30 deg N, January and July; 45 deg N, January and July; 60 deg N, January (average, cold and warm) and July; and 75 deg N, January (average, cold and warm) and July.

The profiles are listed for both geometric and geopotential altitude as the independent variables and the data are given in both metric and English units. Tables of geopotential altitude (in both meters and feet) as functions of pressure (in mb) are included for essentially the same seasonal and latitudinal conditions. The *Supplements* conclude with three tables of the following parameters in the 120 to 1000 km geometric altitude region: temperature, number densities of O_2, O, N_2, He and H, the mean molecular weight, the pressure scale height, pressure, and total density. The three tables correspond to mean conditions for winter, summer, and spring/fall. Although superceded in part by the *U.S. Standard Atmosphere, 1976,* the variations from the mean contained in the *Supplement* were not addressed in the 1976 revision and for that reason those contained in the *Supplement* are still in use.

12.2 Model uncertainties and limitations

The uncertainties and limitations are similar to those for the *U.S. Standard Atmosphere, 1962* except that the restrictions with respect to latitude and season have been relaxed as discussed in the preceding section. However, phenomena such as the winter helium bulge were not included since they were discovered after this publication was completed.

12.3 Basis of the model

12.3.1 The supplements are based upon the same physical considerations as the *U. S. Standard Atmosphere, 1962*

12.3.2. The variations of the atmospheric parameters with latitude and season were for the most part derived from measured data. However, in some instances, most notably for altitudes between 90 and 120 km where there were few measured data available, interpolation and "educated guesswork" had to be employed.

12.4 Databases

Numerous references to empirical atmospheric data which were used in the analyses are listed on pages 91-93 of the basic document.

12.5 Publication references

Environmental Science Services Administration, National Aeronautics and Space Administration, and U. S. Air Force, *U. S. Standard Atmosphere Supplements, 1966,* U. S. Government Printing Office, 1966.

12.6 Dates of development, authors and sponsors

12.6.1 Dates: U.S. Standard Atmosphere, 1962

U.S. Standard Atmosphere Supplements1966

12.6.2 Principal authors: M. Dubin, N. Sissenwine, and S. Teweles, Co-chairmen, U. S. Committee on Extension of the Standard Atmosphere (COESA). The editors were K. S. W. Champion, W. J. O'Sullivan, and H. M. Woolf.

12.6.3 Sponsors: Environmental Science Services Administration, National Aeronautics and Space Administration, and U. S. Air Force.

12.7 Model codes and sources

The model is published in the form of tables and figures only. No computer codes are available. Copies of the U. S. Standard Atmosphere Supplements, 1966 should be available from the U. S. Government Printing Office, Washington, DC.

13 U.S. standard atmosphere, 1976

13.1. Model content

The *U. S. Standard Atmosphere, 1976*, the successor to the *U. S. Standard Atmosphere, 1962,* consists of a bound volume. It contains principally tables, and to a lesser extent, figures which present profiles of temperature, pressure, density, sound speed, dynamic and kinematic viscosity, and thermal conductivity with altitude given in both metric and English units. The altitude range is -5 to 1000 km. Below 32 km the U.S. Standard Atmosphere is identical with the Standard Atmosphere of the International Civil Aviation Organization (ICO).The model is empirical, being based upon temperature measurements by radiosondes, rocketsondes, rockets and satellites and is defined in terms of a temperature profile extending from -5 to 1000 km. This profile is chosen so that the vertical profiles of pressure, density and composition, derived using one-dimensional physical equations, and the temperatures provide a best fit to the experimental data for the defined standard conditions.

Tables of geopotential altitude (in both meters and feet) as a function of pressure in millibars as well as tables of composition (N_2, O, O_2, Ar, He, H) as functions of altitude from 86 to 1000 km are included at the end of the volume. Seasonal, latitudinal, and solar cycle associated variations of atmospheric parameters are discussed, allowing the reader to at least make estimates of the variations from mean conditions. Discussions of trace constituent distributions (H_2O, O_3, NO_2, NO, HNO_3, H_2S, NH_3, H_2, CH_4, SO_2, CO, CO_2, N_2O) and aerosols together with plots of vertical profiles permit the derivation of semi-quantitative models or these species, at least in the mean.

13.2 Model uncertainties and limitations

13.2.1 The Standard is defined as a vertical distribution of atmospheric temperature, pressure and density that represents mean global and annual mid-latitude (45 deg N) conditions. To this definition are added mean solar and geomagnetic conditions for altitudes above 100 km.

13.2.2 Variations with latitude, season, and solar and geomagnetic activity are discussed in the text.

13.2.3 Wind systems are not modeled.

13.2.4 The geographic coverage of the rocket network is spotty; as a result, the data may not be sufficiently representative of global conditions.

13.2.5 The accuracy of the data used as the basis of the Standard varies from one instrument to another and also with altitude.

13.2.6 There are errors in Table II: the H and Z headings on pages 79, 81-86, 88, and 90-97 should be interchanged.

13.2.7 Some additional errors that have been noted include:

Page 2, Table 2. R^* = 8.31432x10^3 not 8.31432x10^{-3} Nm/(kmol K)
Page 2, Table 2. r_0 = 6.356766x10^3 not 6.356766x10^6 km.
Page 2, Table 2. According to page 19, column 1, line 11, S = 110.4 not 110 K.
Page 2, Table 2. *sigma* = 3.65x10^{-10} not 3.65x10^{-1} m.
Page 4, column 1, line 37. According to page 19, column 1, line 11, S = 110.4 not 110 K.
Page 4, column 1, line 41. *beta* = 1.458x10^{-6} not 1.458x10^6 kg/(s m $K^{½}$);.
Page 11, column 1, line 10. We can also let a = 19.9429 km instead of -19.9429 km.
Page 13, Table 9. $n(He)_7$ = 7.581730x10^{14} not 7.5817x10^{10} m^{-3}.
Page 20, Table 10. $k_{t,0}$ = 2.5326x10^{-2} not 2.5326x10^{-3} W/(m K).
Page 67. From 80 to 86 km, $T = T_M$ instead of being adjusted according to Table 8 on page 9.

13.3 Basis of the model

13.3.1 The model is a major revision of the U.S. Standard Atmosphere, 1962.

13.3.2 The air is assumed to be dry and homogeneously mixed at altitudes below 86 km. At low altitudes where mixing is complete, the hydrostatic equation

$$d \ln p = - \frac{gM}{RT} dz$$

is integrated. Here, p is pressure, g is the gravitational acceleration at 45 deg latitude, M is the mean molecular weight, T is the absolute temperature, and z is geometric altitude.

13.3.3 At altitudes well above 86 km, where diffusive separation governs, it is assumed that the vertical flux of the background atmosphere is zero,

$$n_i v_i + D_i[\frac{dn}{dz_i} + n_i \frac{(1+\alpha_i)}{T}\frac{dT}{dz} + \frac{gM_i}{RT} n_i] + K[\frac{dn}{dz_i} + \frac{n_i}{T}\frac{dT}{dz} + \frac{gM}{RT} n_i] = 0$$

Where

n_i = the concentration of the ith species

v_i = the vertical velocity of the ith species

D_i = the molecular diffusion coefficient of the ith species diffusing through N_2

α_i = the thermal diffusion coefficient of the ith species

M_i = the molecular weight of the ith species

K = the eddy diffusion coefficient

13.3.4 The gravity field is height dependent, the dependence being given approximately by

$$g = g_0 (\frac{r_0}{r_0 + z})^2$$

where g_o is the acceleration at the earth's surface and r_o is the mean Earth radius. In the region where diffusive separation begins (z>86 km), the number densities are given by

$$n_i = n_i^* \frac{T^*}{T} \exp\{- \int_{z^*}^{z} [f(z') + \frac{v_i}{D_i + K}] dz' \}$$

where the asterisk denotes values at 86 km altitude, and

$$f(z) = \frac{g}{RT} (\frac{D_i}{D_i + K})[M_i + \frac{MK}{D_i} + \frac{\alpha_i R}{g} \frac{dT}{dz}]$$

However, the N_2 density is given simply by

$$n(N_2) = n^*(N_2) \frac{T^*}{T} \exp(- \int_{z^*}^{z} \frac{Mg}{RT} dz)$$

13.3.5 The temperature profile is defined by a set of algorithms.

13.4 Databases

Twenty-six papers or reports summarizing the rocket data (i.e., falling sphere, grenade and pitot-static tube) are listed on pages 26 and 27 of the basic document (Ref. 13.5.1). Because of the length of the list, they are not reproduced here.

13.5 Publication references

13.5.1 National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, U. S. Air Force, *U. S. Standard Atmosphere 1976,* U. S. Government Printing Office, Washington, DC, 1976.

13.5.2 Minzner, R. A.,The 1976 Standard Atmosphere and its relationship to earlier standards, *Revs. Geophys. and Space Phys. 15,* 375-384, 1977 gives the history behind the model's development, going back to 1922.

13.5.3 Zuppardo, Joseph C. (1993): Graphical Comparison of U. S. Standard Atmospheres and Military Standard Climatic Extremes, Report Number AD-A264639, ASC-TR-93-5002, Air Force Systems Command, Wright-Patterson AFB, OH.

13.6 Dates of development, authors and sponsors

13.6.1 Dates: U. S. Standard Atmosphere, 1962

U. S. Standard Atmosphere Supplements, 1966

U. S. Standard Atmosphere, 1976

13.6.2 Principal authors: M. Dubin, A. R. Hull, and K. S. W. Champion, Co-chairmen, Committee on Extension for the Standard Atmosphere (COESA) were the editors. The scientific editors were A. J. Kantor, R. A. Minzner and R. Quiroz. The model was developed and adopted in consultation with the International Civil Aviation Organization (ICAO) and the International Standards Organization (ISO).

13.6.3. Sponsors: National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, U.S. Air Force.

13.7 Model codes and sources

Available in hard copy from the National Technical Information Office, Springfield, Virginia (Product Number: ADA-035-6000). The FORTRAN code can be obtained from Public Domain Aeronautical Software. A DOS executable and Turbo-Pascal source code is available from Small World Communications. An added link to PDF file for the U.S. Standard Atmosphere, 1976 has been provided as noted:

U.S. Committee on Extension to the Standard Atmosphere, "U.S. Standard Atmosphere, 1976", National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, U.S. Air Force, Washington DC, 1976. PDF File.

14 International Reference Ionosphere (IRI), 2007

14.1 Model content

The International Reference Ionosphere (IRI) is an international project sponsored by the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI). These organizations formed a Working Group in the late sixties to produce an empirical standard model of the ionosphere, based on all available data sources. Several steadily improved editions of the model have been released. IRI is widely used for the specification of densities and temperatures in Earth's ionosphere. For given location, time and date, IRI describes the electron density, electron temperature, ion temperature, ion composition, and electron content in the altitude range from about 50 km to about 2000 km. It provides monthly averages in the non-auroral ionosphere for magnetically quiet conditions. The IRI is the ionosphere model recommended in technical specification documents that are currently under consideration by the International Standardization Organization (ISO) and by the European Cooperation for Space Standardization (ECSS).

14.2 Model uncertainties and limitation

The model uncertainties and limitations are as described in the database sources noted in item 4 and publication references in item 5.

14.3 Basis of the model

By charter IRI is an empirical model and is based on most of the internationally available ground and space data for the ionosphere.

New features and improvements in IRI-2007 include the following:

(a) Two new options for the topside electron density profile (IRI-2001 correction term and NeQuick) based on topside sounder data that overcome the problem of IRI-2001 at high altitudes and high solar activities;
(b) A NeuralNet model for E-region densities at auroral latitudes based on EISCAT and rocket data that can be adjusted with ground absorption measurements if available.
(c) A new model for the ion composition in the topside ionosphere based on AE-C, -E, and Intercosmos 24 ion data that show much better agreement with ISIS-2 and ISS-b IMS data than the old model;
(d) A model for the plasmaspheric electron temperature based on over a decade of Akebono TED measurements;
(e) For the first time a model for the Spread F probability, based on Brazilian ionosonde observations, describing variations with latitude, local time, month, and solar activity;
(f) The newest version of the IGRF model (IGRF-10) is implemented for the computation of magnetic field coordinates used in IRI;
(g) Many technical corrections noted in the COMMENT sections of the different program files.

14.4 Databases

The major data sources are the worldwide network of ionosondes, the powerful incoherent scatter radars (Jicamarca, Arecibo, Millstone Hill, Malvern, and St. Santin), the ISIS and Alouette topside sounders, and in situ instruments on several satellites and rockets. IRI is updated yearly during special IRI Workshops (e.g., during COSPAR general assembly). An IRI Newsletter is published quarterly and is available from http://www.ted.isas.jaxa.jp/IRI_News/ There is also an electronic mailer with up-to-date IRI-relevant information available at http:modelweb.gsfc.nasa.gov/ionos/in_news.html. The IRI homepage is at http://IRI.gsfc.nasa.gov/

14.5 Publication references

K. Rawer, D. Bilitza, and S. Ramakrishnan, Goals and Status of the International Reference Ionosphere, Rev. Geophys., 16, 177-181, 1978.

K. Rawer, S. Ramakrishnan, and D. Bilitza, International Reference Ionosphere 1978, International Union of Radio Science, URSI Special Report, 75 pp., Bruxelles, Belgium, 1978.

K. Rawer, J. V. Lincoln, and R. O. Conkright, International Reference Ionosphere-IRI 79, World Data Center A for Solar-Terrestrial Physics, Report UAG-82, 245 pp., Boulder, Colorado, 1981.

K. Rawer and C. M. Minnis, Experience with and Proposed Improvements of the International Reference Ionosphere (IRI), World Data Center A for Solar-Terrestrial Physics, Report UAG-90, 235 pp., Boulder, Colorado, 1984.

D. Bilitza (ed.), International Reference Ionosphere 1990, NSSDC 90-22, Greenbelt, Maryland, 1990.

D. Bilitza, K. Rawer, L. Bossy, and T. Gulyaeva, International Reference Ionosphere - Past, Present, Future, Adv. Space Res. 13, #3, 3-23, 1993.

D. Bilitza, International Reference Ionosphere - Status 1995/96, Adv. Space Res. 20, #9, 1751-1754, 1997.

D. Bilitza, International Reference Ionosphere 2000, Radio Science 36, #2, 261-275, 2001.

D. Bilitza, Reinisch, B.W., International Reference Ionosphere 2007: Improvements and new parameters, J. Adv. Space Res. (2008), doi:10.1016/j.asr.2007.07.048

D. Bilitza, B. Reinisch, and J. Lastovicka (2008), Progress in Observation-Based Ionospheric Modeling, Space Weather, 6, S02002, doi:10.1029/2007SW000359.

14.6 Date of development, authors and sponsors

14.6.1 Dates: 2007

14.6.2 Authors: Joint Working Group of the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI)

14.6.3 Sponsors: Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI)

14.7 Model codes and sources

The IRI master copy is held at the National Space Science Data Center (NSSDC) and updated according to the decisions of the Working Group. The software package distributed by NSSDC includes the FORTRAN subroutines, model coefficients (CCIR and URSI), and documentation files. The IRI build-up and formulas described in detail in a 158-page NSSDC report (Bilitza, 1990).

14.7.1 Availability

The latest version of the IRI model, IRI-2007,is available as a FORTRAN Program from the IRI homepage at http://IRI.gsfc.nasa.gov. Please read the 00README.TXT file for important information regarding the IRI program files and the download process. Also note that the program includes several switches (logical array JF (30)) to turn on/off specific options. The details and defaults of these switches are given in the COMMENT section at the beginning of program irisub.for.

15 Exopheric hydrogen model, 1994

15.1 Model content

A Monte Carlo simulation of the terrestrial hydrogen exosphere is used to derive a global model of the exospheric hydrogen density. A third-order spherical harmonic expansion in longitude and colatitudes is used to represent H at a particular radius. The h_exos.dat file provides the harmonic expansion coefficients for 40 radii (between 6640 km and 62126 km) for solstice and equinox conditions, and for four levels of solar activity (F10.7 = 80, 130, 180, 230). Details of the Monte Carlo simulation are explained in Hodges (1994; Ref. 15.5.1).

15.2 Model uncertainties and limitations

The simulation results show significant differences with previous exosphere models, as well as with the H distributions of the MSIS-86 thermosphere model.

15.3. Basis of model

See Reference 15.5.1 for details.

15.4 Databases

See Reference 15.5.1 for details.

15.5 Publication references

15.5.1 Hodges, R. R., Monte Carlo Simulation of the Terrestrial Hydrogen Exosphere, J. Geophys. Res., 99, 23229-23247, 1994

15.6 Dates of development, authors and sponsors

15.6.1 Date: 1994

15.6.2 Author: R. R. Hodges

15.7 Model codes and sources

See Reference 15.5.1 for details.

16 SHARC/SAMM atmosphere generator, SAG-2 (0-300 KM)

16.1 Model content

The SHARC Atmosphere Generator (SAG) is a stand-alone, interactive program that utilizes a combination of empirical models to generate atmospheric profiles for Air Force infrared (IR) radiation codes that account for systematic variability of the atmosphere, including solar terminator effects. Using information on the day of the year, local time, solar and geomagnetic activity indices, etc., SAG reasonably models the variabilities in temperature and CO_2, O_3, OH, NO, H_2O and O densities. For other species, diurnally averaged profiles are derived from recent climatology database or other standard tabulations. The SAG output files support the Air Force Strategic High-Altitude Radiance Code (SHARC) and the SAMM (SHARC And MODTRAN Merged) code which have been developed to address the strategic requirements for modeling IR background radiation and structure in the upper atmosphere. One of their most critical applications is in modeling radiance variations, which can occur over a wide range of spatial and temporal scales. Short-term and small-scale variations associated with random processes can be characterized and predicted statistically. On the other hand, systematic variations, which can be predicted deterministically, may be quite large and thus play an important role in setting the overall background radiance level for a given band pass. In particular, at the solar terminator, large radiance variations can occur over a small (several-degree) range of solar zenith angle due to photochemical processes in the atmosphere.

The SHARC Atmosphere Generator (SAG) has been designed to allow the major known, systematic variabilities in the atmosphere, including terminator and other diurnal effects, to be practically incorporated in strategic IR radiance calculations. SAG is presently implemented as a FORTRAN subroutine, which may be run via the supplied or user furnished driver program. This allows SAG to be run interactively or in a batch processing mode by looping over atmospheric dependencies in the driver program. SAG may be used to generate an atmosphere file for use with MODTRAN and a file of species and kinetic temperature profiles compatible with SHARC and SAMM. The profiles are customized for the geophysical and geographic information input by the user.

Using information on the day of the year, local time, solar activity indices, etc., SAG reasonably models the systematic variabilities in CO_2, O_3, OH, NO, H_2O, and O atom densities. For other species, diurnally averaged profiles are taken from recent databases. To facilitate use without detailed inputs, defaults are provided so that simple designators, such as day/night, season, and latitude region (low, mid or high), can be specified as desired.

16.2 Model uncertainties and limitations

16.2.1 The model does not have any predictive capabilities. It only provides estimates of the dependence of the mean values of atmospheric temperature, major atmospheric species, and infrared active species densities on geographical location, season, time of day, solar and geomagnetic activity. No estimates of the local variability, which can be substantial, are available. The species profiles are derived a combination of measurements and models and are not necessarily self-consistent.

16.2.2 The NRLMSISE-00 and MSISE-90 databases, supplemented by the AFGL Atmospheric Constituent Profiles model, the UARS NO and SNOE H_2O databases, form the basis of SAG-2 and thus inherit the uncertainties and limitations of these databases.

16.3 Basis of the model

SAG draws on several existing empirical atmosphere models. Either MSISE-90 [4.1] or NRLMSISE-00 [4.2] may be used for the temperature and major species profiles. They provide profiles for species including N_2, O_2, O, and H as a function of altitude, latitude, longitude, universal time (UT), local solar time (LST), daily average Ap index, and the F10.7 (previous day) and F10.7A (81 day centered average) solar flux indices. The second atmosphere model is the NRL climatology database [4.3] for altitudes up to 120 km. This database is used for the SHARC and SAMM species CH_4 and CO, and for lower portions of the O_3 and O profiles, as well as for the additional species N_2O, NO_2, and HNO_3 used in SAMM. The NRL database [4.3] contains mean monthly mixing ratios at 1 to 5 km altitude increments and 10° latitude increments. SAG interpolates between these values and converts to number densities using the MSISE-90 or NRLMSISE-00 total densities.

New water vapor climatology has been introduced into SAG 2.0. The new climatology was developed by the UARS Reference Atmosphere Project (URAP), whose aim is to provide a comprehensive reference description of the stratosphere based on the data recorded by instruments on the NASA Upper Atmosphere Research Satellite (UARS) [4.4]. The URAP water vapor climatology was constructed from the HALOE (HALogen Occulation Experiment) [4.5], MLS (Microwave Limb Sounder Experiment) [4.6], and SAGE II (Stratospheric Aerosol and Gas Experiment) [4.7] data and presented as monthly zonal means, where the zones are designated by latitude and pressure [4.8]. The new climatology is a substantial improvement on CIRA-1996 [4.9], which is based on pre-URAP data.

The Student Nitric Oxide Explorer (SNOE) database has been introduced to provide nitric oxide profiles between 97 km and 150 k m [4.10]. The database consists of measurements of nitric oxide density in the thermosphere for the period March 11, 1998 to September 30, 2000. The data covers the latitude range of 80° S to 80° N at 5° intervals and the longitude range 180° W to 180° E at 24° intervals.

The remaining species profiles, including those for CO_2, OH, SO_2, and NH_3 are derived from a combination of standard concentrations [4.11] used in MODTRAN, photochemical or empirical models based on inputs or outputs (CO_2), or some combination of these (OH), as described in this report.

16.4 Databases

16.4.1 Hedin, A. E., "Extension of the MSIS Thermospheric Model into the Middle and Lower Atmosphere," *J. Geophys. Res.*, 96, 1159, 1991.

16.4.2 Picone, J.M., A. E. Hedin, D. P. Drob, and A. C. Aikin (2002), NRLMSISE-00 empirical model of the atmosphere: Statistical comparisons and scientific issues, *J. Geophys. Res.*, 107 (A12), 1468, doi: 10.1029/2002JA009430.

16.4.3 Summers, M. E., W. J. Sawchuck, and G. P. Anderson, "Model Climatologies of Trace Species in the Atmosphere," Annual Review Conference on Atmospheric Transmission Models, Phillips Laboratory, Hanscom AFB, MA, June 1992.

16.4.4 http://umpgal.gsfc.nasa.gov/uars-science.html

16.4.5 Harries, J. E., J. M. Russel, A. F. Tuck, L. L. Gordley, P. Purcell *et al.*, "Validation of Measurements of Water Vapour from the Halogen Occulation Experiment, HALOE," *J. Geophys. Res.*, 101, 10205, 1996.

16.4.6 Lahoz, W. A., M R. Suttie, L. Froidevaux, R. S. Harwood, C. L. Lau, T. A. Lungu, G. E. Peckham, H. C. Pumphrey, W. G. Read, Z. Shippony, R. A. Suttie, J. W. Waters, G. E. Nedoluha, S. J. Oltmans, J. M. Russel III, and W. Traub, "Validation of UARS Microwave Limb Sounder 183 GHz H_2O Measurements," *J. Geophys. Res.*, 101, 10129, 1996.

16.4.7 Chiou, E. W., M. P. McCormick, and W. P. Chu, "Upper Tropospheric Integrated Water Vapor Distributions Derived from SAGE II Observations," *EOS Transactions,* AGU, 73, 14, 1992.

16.4.8 Pumphrey, H. C., D. Rind, J. M. Russell III, and J. E. Harries, "A Preliminary Zonal Mean Climatology of Water Vapour in the Stratosphere and Mesosphere," *Adv. Space Res.*, 21, 1417, 1998.

16.4.9 Keating, G. M., J. S. Chiou, and N. C. Hsu, "Improved ozone reference models for the COSPAR International Reference Atmosphere," *Adv. Space Res.*, 18, 11, 1996.

16.4.10 http://lasp.colorado.edu/snoe/

16.4.11 G. P. Anderson, G. P., J. H. Chetwynd, S. A. Clough, E. P. Shettle and F. X. Kneizys, "AFGL Atmospheric Constituent Profiles (0-120 km)," AFGL-TR-86-0110, Environmental Research Papers No. 954 (1986), ADA175173.

16.5 Publication references

16.5.1 Adler-Golden, S. M., "Description of the SHARC Atmosphere Generator," PL-TR-93-2123, May 1993.

16.5.2 Shroll, R. M., S. Adler-Golden, J. W. Duff, and J. H. Brown, "Users' Manual for SAG-2, SHARC/SAMM Atmosphere Generator," AFRL-TR-03-1530, October 2003.

16.6 Dates of development, authors and sponsors

16.6.1 Dates: original model 1993
SAG-2 2003

16.6.2 Authors: S. Adler-Golden, R. Shroll, J. W. Duff, and J. H. Brown

16.6.3 Sponsor: Air Force Research Laboratory, Space Vehicles Directorate.

16.7 Model codes and sources

SAG is presently implemented as a FORTRAN subroutine, which may be run via the supplied or user furnished driver program. This allows SAG to be run interactively or in a batch processing mode by looping over atmospheric dependencies in the driver program. The program has been developed for the Windows XP, UNIX, and Linux operating systems.

A description and users' manual for SAG-2 is given in AFRL Report No. AFRL-TR-03-1530 (Ref. 15.5.2). The code is freely available from the Air Force Research Laboratory Space Vehicles Directorate (http://www.kirtland.af.mil/library/factsheets/factsheet.asp?id=7903).

17 Proposed international tropical reference atmosphere, 1987

17.1 Model content

The *Proposed International Tropical Reference Atmosphere* model from India consists of a set of tables of pressure (in millibars and Torr), temperatures, density, sonic velocity, dynamic and kinematic viscosity, thermal conductivity, gravitational acceleration, mean particle speed, mean collision frequency, number density, and mean molecular weight as functions of geometric and geopotential altitude; the last range from -5 to 1000 km in steps of 1 km. In addition, tables of concentrations of atmospheric species (N_2, O_2, O, Ar, and He) are given for altitudes in the range 86 to 1000 km in steps of 1 km. All conditions are specific to the tropics, in particular those which prevail *in the mean* over the whole of the tropical region of the globe from about 30 deg S to 30 deg N latitude. Variations of the important atmospheric parameters are not included.

17.2 Model uncertainties and limitations

17.2.1 The model corresponds to mean conditions only.

17.2.2 The model refers only to tropical conditions.

17.2.3 Not all of the lower mesospheric data on which the model is based are mutually consistent.

17.3 Basis of the model

The model is based upon balloon data up to 20 km and rocket sonde measurements up to about 50 km altitude. At altitudes from 50 to 100 km, falling sphere and grenade data are employed, yielding temperature measurements that are generally consistent with each other, with a claimed accuracy of 2 to 3 K. At altitudes approaching 100 km, Nimbus satellite temperature data obtained from radiance values are somewhat higher than the falling sphere and grenade data. According to the authors, the reason for this disagreement is not clear. At altitudes above 100 km the MSIS-83 model (Hedin, A. E. 1983 -- see section 5) is adopted.

At altitudes below 85 km, the atmosphere is considered to be completely mixed, but above that altitude diffusive separation occurs. At and above 86 km the concentration of the ith species, n_i, is given as a function of altitude z by

$$n_i(z) = n_i(z_0)\frac{T(z_0)}{T(z)} I[\frac{K}{D_i + K}, H]\, I[\frac{D_i}{D_i + K}, H_i] \text{ x}$$
$$I[\alpha_i \frac{d \ln T}{dz} \frac{D_i}{D_i + K}, 1]\, I[\frac{v_i}{D_i + K}, 1]$$

Where

$$I[x, y] = \exp[-\int_{z_0}^{z} (x/y)\, dz]$$

Here z_o is taken to be 86 km, T is the absolute temperature, K is the eddy diffusion coefficient, D_i is the molecular diffusion coefficient for species i, H is the mean scale height, H_i is the scale height of species i, and α_i is the thermal diffusion coefficient of species i. The vertical velocity is given by a simple parametric form:

$$v_i/(D_i + K) = \alpha_i[(120\text{-}z)\,(z\text{-}86)]^2$$

where the α_i are adjustable parameters selected such that predicted species concentrations at 120 km are close to the mean low altitude values obtained from MSIS-83. Above 120 km, the species are assumed to be in diffusive equilibrium.

17.4 Databases

17.4.1 Troposphere and lower stratosphere (balloon sonde data)

17.4.2 Upper stratosphere (rocket sonde data)

17.4.3 Mesosphere (grenade and falling sphere data)

17.4.4 Thermosphere (MSIS-83 Thermospheric Model)

17.5 Publication references

17.5.1 Anathasayanam, M. R., and R. Narasimha, "Proposals for an Indian Standard Tropical Atmosphere up to 50 km," *Adv. Space Res., 3,* 17-20, 1983

17.5.2 Anathasayanam, M. R., and R. Narasimha, "A Proposed International Tropical Reference Atmosphere up to 80 km," *Adv. Space Res.,5,* 145-154, 1985.

17.5.3 Ananthasaynam, M. R., and R. Narasimha, "A Proposed International Tropical Reference Atmosphere up to 1000 km," *Adv. Space Res, 7,* 117-131, 1987.

17.5.4 Hedin, A. E., "A Revised Thermospheric Model Based on Mass Spectrometer and Incoherent Scatter Data: MSIS-83," *J. Geophys. Res., 88,* 10,170-10,188, 1983

17.6 Dates of development, authors and sponsors

17.6.1 Dates: 1983-1987

17.6.2 Authors: M. R. Anathasayanam and R. Narasimha.

17.6.3 Sponsors: Indian Institute of Science, Bangalore, and Aeronautics Research and Development Board, Ministry of Defense, New Delhi

17.7 Model codes and sources

The model is published in the form of tables and figures only. No computer code is available. Contact sponsors for additional information.

18 Referenced atmosphere for Indian equatorial zone from surface to 80 km, 1985

18.1 Model content

The *Reference Atmospheres for Indian Equatorial Zone from Surface to 80 km, 1985* from India, which describes the Indian equatorial zone only, consists of a series of tables of atmospheric temperature (K), pressure (millibars), and density (kg m^{-3}) extending from the surface to 80 km geometric altitude with a resolution of 1 km. These tables give annual mean values together with seasonal dispersions, and monthly values of the three atmospheric properties. The final table in the volume provides a comparison of temperatures at various heights up to 80 km for five other models which include the earlier (1979) version of the model under discussion, the CIRA 1972 model, and the tropical reference atmosphere of Ananthasayanam and Narasimha.

18.2 Model uncertainties and limitations

18.2.1 The temperature values measured by the M-100 rocket payload (a rhenium-tungsten wire in a Wheatstone bridge) contain measurement errors. These errors in the corrected temperatures (which in turn lead to errors in the derived quantities, pressure and density) range from 1 deg C in the 0 to 25 km region to as much as 10 deg C in the 60 to 80 km region. The temperature values of the 1985 model have been improved over the earlier version by using inter-model comparisons as a means of adjustment.

18.2.2 The model is limited to equatorial Indian conditions.

18.3 Basis of the model

The atmospheric data upon which the model is based are meteorological data (balloon sonde) obtained by four India Meteorological Department (IMD) stations for altitudes up to 17 km and M-100B rocket data obtained at Thumba, India for altitudes ranging from 17 to 80 km. It was assumed that the oscillations and the mean temperature are predominantly annual and semi-annual. The twelve monthly mean values of temperature at intervals of one km altitude are used to derive pressure and density from the hydrostatic equation. The time variations of the monthly means are then subjected to harmonic analysis for determining the annual and semiannual cycles of periodic variations. For this analysis the expression

$$X(t) = X_0 + X_1 \sin(\omega t + \phi_1) + X_2 \sin(2\omega t + \phi_2)$$

was used. Here X (t) is the value of the time varying parameter, X_0 is the annual mean value of the parameter, X_1 is the amplitude of the annual oscillation, X_2 is the amplitude of the semiannual oscillation, ϕ_1 and ϕ_2 are the phases of the annual and semiannual oscillations, respectively, $\omega = 2\pi/T$ with T the annual period in months (T=12), and t is the time in months. The amplitude and phases were then obtained from the data with the aid of a least squares fitting technique.

18.4 Databases

18.4.1 Data obtained at Thumba, India, published by the Central Aerological Observatory, Moscow, USSR

18.4.2 Meteorological data from the four IMD stations. The authors do not cite any specific publication with respect to the database.

18.5 Publication references

18.5.1 Sasi, M. N., and K. Sengupta (July 1979), *A Model Equatorial Atmosphere over the Indian Zone from 0 to 80 km*, Indian Space Research Organization (Bangalore), Scientific Report ISRO-VSSC-SR-19-79.

18.5.2 Sasi, M. N., and K. Sengupta (June 1986), *A Reference Atmosphere for Indian Equatorial Zone from Surface to 80 km-1985*, Space Physics Laboratory, Vikram Sarabhai Space Center (Trivandrum) Scientific Report SPL: SR:006:85.

18.6 Dates of development, authors and sponsors

18.6.1 Dates: Original model 1979

Revised model 1985

18.6.2 Authors: M. N. Sasi and K. Sengupta

18.6.3 Sponsors: Indian Space Research Organization

18.7 Model codes and sources

The model is published in the form of tables and figures only. No computer codes are available. Contact sponsors for additional information.

19 Reference model of the middle atmosphere of the southern hemisphere, 1987

19.1 Model content

The *Reference Model of the Middle Atmosphere of the Southern Hemisphere* consists of a paper published in *Advances in Space Research* and subsequent papers (see section 5), containing tables and figures that present monthly mean temperature, pressure, density and zonal wind speed. The altitude range is 20 to 80 km (up to 100 km in the case of the zonal wind) in steps of 5 km while the latitude range is 0 to 70 deg S in steps of 10 deg.

The model is empirical, being based upon temperature and wind measurements near the equator and in the Southern hemisphere. Large differences between the hemispheres (up to 20 deg C in temperature, 30-50 m s^{-1} in wind speed) imply that reference atmospheres such as CIRA should also include southern hemisphere climatology. The model is partly included in the CIRA 1986 (Part II). The principal data used were obtained at Ascension Island; Woomera, Australia; Mar Chiquita, Argentina; Molodezhnaya; Kerguelen Island, and Soviet research vessels. The analysis of temperature includes adjustments in the model to make the new Soviet temperature data optimally compatible with older, more restricted data. Above 50 km all temperature data are also adjusted to the values obtained by means of the grenade technique. All the data were smoothed in time and space. Comparisons between middle atmosphere structure in the northern and southern hemispheres are also made.

19.2 Model uncertainties and limitations

19.2.1 Although the coverage of the southern hemisphere has been greatly improved, it is still much less complete than for the northern hemisphere.

19.2.2 Longitudinal variations are not specified.

19.3 Basis of the model

The model is based principally upon rocketsonde measurements of temperature and wind as discussed in Section 1. However, falling sphere and grenade data were also employed for altitudes of 50 to 80 km for the locations for which they were available. Meteor trail detection and partial reflections techniques were used to determine winds above 80 km. The pressure and density profiles have been integrated using the hydrostatic equation and the temperature data, but the technique is not discussed.

19.4 Databases

The principal published data source is:

(No authors listed), *Bulletins of Results of Rocket Sounding of the Atmosphere*, Gidromtizdat, Moskva, 1960-1981.

Secondary (non-Soviet) sources are:

19.4.1 Briggs, R. S., Meteorological rocket data: McMurdo Station, Antarctica, 1962-1963, *J. Appl. Met.,4*, 238-245, 1965.

19.4.2 Elford, W. G., in *Proc. Intern. Conf. on Structure, Composition and General Circulation of the Upper and Lower Atmosphere, 2*, Toronto, 1965.

19.4.3 Manson, A. H., C. E. Meek, M. Massebeuf, J. L. Fellows, W. G. Elford, R. A. Vincent, R. L. Craig, R. G. Roper, S. Avery, B. B. Balsey, G. J. Fraser, M. J. Smith, R. R. Clark, S. Kato, T. Tsuda, and A. Ebel, Mean winds in the upper middle atmosphere (60-110 km): a global distribution from radar systems (M. F., meteor, VHF), *Handbook for MAP, 16*, 239-268, 1985.

19.4.4 Hind, A. D., Weapons Research Est. Note 988, Australia, 1973.

19.4.5 (No authors listed) *EXAMETNET Data Report Series*, NASA SP-175, 176, 231, Washington, DC, 1968, 1969, 1970.

19.4.6 (No authors listed), *Weapons Research Est. Tech Notes*, Salisbury, Australia, 1962-1974.

19.4.7 World Data Center A. High altitude meteorological data, Asheville, NC. 1965-1978

19.5 Publication references

19.5.1 Koshelkov, Yu. P., Proposal for a r eference model of the middle atmosphere of the southern hemisphere, *Adv. Space Res., 3*, 3-16, 1983.

19.5.2 Koshelkov, Yu. P., Observed wind and temperatures in the southern hemisphere, *Handbook for MAP, 16*, 15-35, 1985

19.5.3 Koshelkov, Yu. P., Southern hemisphere reference middle atmosphere, *Adv. Space Res., 7*, 83-96, 1987.

19.5.4 Koshelkov, Yu. P., "Mean zonal circulation of the southern hemisphere atmosphere in the 20-100 km layer", M-3 Symposium, XIX General Assembly of the IUGG, Vancouver, August 1987 (unpublished).

19.6 Dates of development, authors and sponsors

19.6.1 **Dates**: 1980-1987

19.6.2 **Authors:** Yu. P. Koshelkov

19.6.3 **Sponsors:** State Committee of the USSR for Hydrometeorology, Moscow, USSR

19.7 Model codes and sources

The model is published in the form of tables and figures only. No computer codes are available. Contract sponsors for additional information.

20 China national standard atmosphere, 1980

20.1 Model content

This National Standard provides the properties of the standard atmosphere (below 30km) and shows the standard atmosphere temperature, pressure and density as a function of geometric and geopotential height. It is for use in the calibration of barometers, the design of aircraft and associated calculations. Provided is a table taken from the U.S. Standard Atmosphere, 1976 which presents tabulated values below 1000km of temperature, pressure and density. The part below 30km is the standard for China. The part above 30km is provided for reference.

In China, the usage of atmospheric model for all purposes is all the ISO Standards such as the ISO 2533:1975 and ISO 5878:1982. For aerospace the NASA Global Reference Atmosphere Model (GRAM-99) and NASA Marshall Engineering Thermosphere (MET) models are also used.

20.2 Model uncertainties and limitations

For soundings at 45 degree latitude and under 30km, the result is close to the standard. Above surface to 2km - 3km the difference of temperature is within two degrees and the difference of pressure and density is less than one percent. There is a large difference from the tropical area under 30km with the standard atmosphere. Generally, within the mid and high part of the troposphere the average temperature is higher than the standard atmosphere. In some special cases the difference near 25N can be 18 degrees and the difference in pressure and density 9% and 14 %, respectively. It also may occur in other areas. Therefore, when the standard is used one needs to pay attention to the latitude and season in some cases the parameter of the standard atmosphere can have a large bias.

20.3 Basis of the model

The atmosphere is assumed static and dry ideal gas with values of temperature, pressure and density above sea level obtained by integrating the hydrostatic equation and ideal gas law as function of height.

20.4 Databases

The original reference sources of the atmosphere adopted for use by China is the U. S. Standard Atmosphere, 1976.

20.5 Publication references

China National Standard GB 1920-80 "Standard Atmosphere (Below 30km)"

20.6 Dates of development, authors and sponsors

20.6.1 Dates: Published May 1, 1980

20.6.2 Authors: Members of China National Administration of Meteorology Atmospheric Science Research Center

20.6.3 Sponsors: Standards Administration of China (SAC), Beijing, China

20.7 Model codes and sources

The model is published in the form of tables only. It is available from: Standards Administration of China (SAC), 9 Madian Donglu, Haidian District, Bejing, China 100088. Web site: www.sac.gov.cn

21 ISO middle atmosphere—global model at altitudes between 30 km and 120 km, and wind model at altitudes above 30 km, 1996

21.1 Model content

The International Organization for Standardization (ISO) Technical Report *Middle Atmosphere—Global Model at Altitudes Between 30 km and 120 km, and Wind Model at Altitudes Above 30 km, 1996,* establishes a zonal monthly mean of temperature, pressure, density and zonal wind as a function of 10 deg steps in latitude from 80 deg S to 80 deg N. These data can be used as a function of geopotential/geometric height and has a latitudinal coverage from 80 deg S to 80 deg N, extending from altitudes between 30 km and 120 km. The Technical Report was developed to serve as a m ean basis for the design and operation of vehicles and provides additional information for general scientific purposes. The tables provide in 2 km intervals monthly values of zonal mean temperature, zonal mean pressure, zonal mean density, and zonal mean zonal wind as a function of geometric and geopotential altitude from 30 km to 120 km.

21.2 Model uncertainties and limitations

The model results presented in the extensive tables has the usual uncertainties and limitations associated with the use of ground based, rocketsonde, and satellite measuring systems.

Te computation of monthly mean zonal wind compared accurately with monthly mean radiosonde and rocketsonde wind measurements from various stations.

21.3 Basis of the model

The model is based on ground-based and satellite measurements, especially the large influx of new data since 1975 that has made it possible to encompass the entire globe from the ground to the upper thermosphere and to provide information on the seasonal and latitude variability of the thermodynamic properties of the atmosphere for altitudes between 30 km and 120 km. The detailed information on parameters distribution allows the calculation of mean wind at the middle atmosphere.

21.4 Databases

This Technical Report presents primary thermodynamic parameter tabulations as functions of latitude and time of year for altitudes from 30 km to 120 km. To obtain the global time-space data coverage, the various empirical and theoretical models of middle atmosphere were analyzed and compiled. COSPAR International Reference Atmosphere, 1986, (CIRA-86), has been taken as the basic model.

The wind model is based on CIRA-86 methods of zonal wind values calculation via the gradient of constant pressure level geopotential height.

21.5 Publication references

ISO International Technical Report 14618 “Middle Atmosphere-Global Model at Altitudes Between 30 km and 120 km, and Wind Model at Altitudes Above 30 km, First Edition” ISO, Geneva, Switzerland

21.6 Dates of development, authors and sponsors

21.6.1 Dates: Published January 1, 1996

21.6.2 Authors: Members of ISO TC20/SC6 (Aircraft and Space Vehicles / Standard Atmospheres)

21.6.3 Sponsors: International Organization for Standardization, Geneva, Switzerland

21.7 Model codes and sources

The model is published in the form of tables only. It is available from: American National Standards Institute, 25 West 43 Street, New York, NY 10036. http://www.ansi.org

22 A new reference middle atmosphere program model atmosphere, 1985

22.1 Model content

The New Reference Middle Atmosphere Program Model Atmosphere consists of a bound volume entitled Atmospheric Structure and its Variation in the Region 20 to 120 km: Draft of a New Reference Middle Atmosphere (Ref. 22.5.1). The altitude range spanned by the model introduced in section 2 is 20 to 80 km with a latitude range of 80 deg S to 80 deg N. A model that spans the altitude range 80-120 km is presented in section 3.

Section 2.1 of MAP 16 contains figures and tables which present altitude profiles of temperature data from satellites, of wind data from meteorological rockets, of observed winds and temperatures in the Southern Hemisphere, and of mean winds in the mesosphere.

Section 2.2 outlines an atmospheric model developed by J. J. Barnett and M. Corney (Ref. 22.5.3), giving in the form of tables and figures zonal mean temperature, geopotential height and geostrophic wind for all months of the year. The vertical coordinate is taken first as pressure and in a second set of tables as geometric height.

Atmospheric variability in both time and place is the subject of sections 2.3. Such variability includes planetary waves, gravity waves, atmospheric tides, the quasibiennial oscillation (QBO) and interannual variability. For planetary waves, the influence of wave numbers 1 and 2 on atmospheric properties is given in the form of both figures and tables. An early version of a portion of the Proposed International Tropical Reference Atmosphere (-2 to 80 km) discussed elsewhere in this guide and Interim Reference Ozone Models for the Middle Atmosphere are included as sections 2.4 and 2.5, respectively, of Handbook for MAP 16.

22.2 Model uncertainties and limitations

22.2.1 The model was intended to be a draft version of a new *COSPAR International Reference Atmosphere* for the middle atmosphere. Because of continuing revision, the CIRA-86 middle atmosphere model can be expected to differ, perhaps substantially so, from the finished product published as CIRA-86, Part II, Models of the Middle Atmosphere.

22.2.2 The principal cause of uncertainty in the CIRA-72 model was the sparcity of data in many geographic locations. This has largely been eliminated through greatly expanded worldwide observations of middle atmosphere parameters, allowing hemispherical asymmetries and monthly variations to be satisfactorily modeled. However, variability due to wave motions, etc. lead to substantial departures from the mean values. The variability's are discussed in considerable detail, quantitatively for planetary waves (sections 2.3.1a and b). Standard deviations associated with inter-annual variations as well as trends are discussed in section 2.3.7.

22.3 Basis of the model

The model is strictly empirical, being based upon observational data obtained by satellite (radiometer and limb sounder), meteorological rocketsonde, and medium frequency (partial reflection) radar measurements.

22.4 Databases

The publications which give the data bases used to construct the model are too numerous to list here. Instead, the reader is referred to pp. 11, 22-27, 46, 163, 174, and 227-229 (for the 20-80 km model) and pp. 237-238, 252-253, 276-277 and 287-289 (for the 80-120 km model) of *Handbook for MAP 16*.

22.5 Publication references

22.5.1 Labitzke, K., J. J. Barnett, and B. Edwards, eds., Atmospheric Structure and its Variation in the Region 20 to 120 km: Draft of a New Reference Middle Atmosphere, Handbook for MAP, 16 July 1985

22.5.2 Ananthasaynam, M. R., and R. Narasimha, A proposed international tropical reference atmosphere up to 80 km, *Adv. Space Res.,* 5, 145-154, 1985

22.5.3 Barnett, J. J., and Corney, M., A middle atmosphere temperature reference model from satellite measurements, *Adv. Space Res.,* 5, 125-134, 1985

22.6 Dates of development, authors and sponsors

22.6.1 Dates: 1985

22.6.2 Authors: The New Reference Middle Atmosphere Program Model is the work of numerous authors. It was edited by K. Labitzke, J. J. Barnett and B. Edwards.

22.6.3 Sponsors: International Council of Scientific Unions (ICSU), Scientific Committee on Solar-Terrestrial Physics (SCOSTEP). Address of SCOSTEP Secretariat: University of Illinois, 1406 W. Green Street, Urbana, IL 61801.

22.7 Model codes and sources

The model is published in the form of tables and figures only. No computer codes are available. Contact sponsors for additional information.

23 AFGL atmospheric constituent profiles (0–120 km), 1986

23.1 Model content

The Air Force Geophysics Laboratory's *Atmospheric Constituent Profiles* model, which has been assembled for use with spectral radiance-transmittance models, originally FASCOD2 Fast Atmospheric Signature Code) and LOWTRAN (LOW spectral resolution atmospheric TRANSsmittance Code), and now including MODTRAN® (MODerate spectral resolution atmospheric TRANSsmittance Code), (see section 7), consists of a set of tables of volume mixing fractions for altitudes extending from 0 to 120 km in intervals of 1 km (0 to 25 km), 2.5 km (25 to 50 km), and 5 km (50 to 120 km). The vertical structure including temperature, pressure and density distributions, plus mixing ration profiles of H_2O*, CO_2, O_3, N_2O, CO, and CH_4, were initially taken from *U. S. Standard Atmosphere Supplements, 1966*, tropical, mid-latitude summer, mid-latitude winter, sub-arctic summer and sub-arctic winter; and from the *U. S. Standard Atmosphere, 1976* (both abstracted elsewhere in this guide). However, with the exception of CO (now a photochemical calculation), the associated species profiles are primarily derived from assorted climatologies based on satellite measurements (see data base reference). Altogether, vertical profiles of the number densities of 28 constituents (H_2O, CO_2, O_3, N_2O, CO, CH_4, O_2, NO, SO_2, NO_2, HNO_3, OH, HF, HCl , HBr, HI, ClO, OCS, H_2CO, HOCl , N_2, HCN, CH_3Cl , H_2O_2, C_2H_2, C_2H_6, and PH_3) are listed. An appendix presents graphs of the species mixing fractions as functions of altitude. Over 20 references for species profiles are included in the document.

*(The stratospheric H2O profiles have been updated from those in the 1966 Supplement, because the originals exhibited values that exceeded measurements from the LIMS instrument.

^The CO2 profiles have been maintained at 330 ppmv at the surface. These are readily scalable to current values (~385 ppmv), so the fixed value is kept for backward compatibility and testing.)

A model of lower atmospheric aerosols is presented separately (reference given in 23.5). This model supplies data on parameters and properties which are required for radiative transfer calculations.

23.2 Model uncertainties and limitations

23.2.1 The accuracies of the tabulated mixing fractions vary with species and altitude. At best they offer about 10 to 30% relative consistency for U. S. Standard Atmosphere conditions in the troposphere and stratosphere. Mesospheric and thermospheric profiles are much less certain and are defined only for temperature, pressure, and the mixing fractions of H_2O, CO_2, O_3, CO, CH_4, O_2, NO, SO_2, OH, H_2O_2. Mixing fractions of the other species have been extrapolated using a logarithmically decreasing mixing fraction scale height. Again, H2O variability in the in the troposphere is so large that no climatology can capture the day-to-day fluctuations.

23.2.2 Representative profiles do not necessarily resemble *in situ* environments.

23.2.3 Tropospheric water vapor and anthropologically produced species exhibit factors of 100 or more local variability. Throughout the atmosphere, horizontal gradients on local, latitudinal or seasonal scales often exceed factors of 2 to 10.

23.2.4 In the mesosphere and lower thermosphere excursions brought about by response to dynamic and solar influences can be substantial.

23.2.5 The trace constituent profiles are derived primarily from measurements and therefore are not photochemically self-consistent.

23.3 Basis of the model

23.3.1 U. S. Standard Atmosphere Supplements, 1966.

23.3.2 U. S. Standard Atmosphere, 1976.

23.3.3 COSPAR International Reference Atmosphere (CIRA), 1972.

23.3.4 Compilation of Atmospheric Gas Concentration Profiles from 0-50km, NASA Tech Memorandum 83289, 70 pp, 1982.

23.3.5 The aerosol models were based on a literature review of other models and available measurements (see section 5, papers b and c for references). The vertical profiles are based on extinction and number density vertical distributions. The wavelength dependence of the scattering and absorption are based on Mie scattering calculations, bimodal log-normal size distributions and refractive index data.

23.4 Databases

The origins of the trace constituent profiles are listed in report AFGL-TR-86-0110 (see section 5).

23.5 Publication references

23.5.1 Anderson, G. P., S. A. Clough, F. X. Kneizys, J. H. Chetwynd and E. P. Shettle, AFGL "Atmospheric Constituent Profiles (0-120 km)", Air Force Geophysics Laboratory Report AFGL-TR-86-0-10, Environmental Research paper no. 954, May 1986.

23.5.2 Shettle, E. P., and R. W. Fenn, "Models of the Aerosols of the Lower Atmosphere and the Effects of Humidity Variations on their Optical Properties", Air Force Geophysics Laboratory Report AFGL-TR-79-0214, Environmental Research paper no. 676, September 1979.

23.5.3 Shettle, E. P., and R. W. Fenn, "Models of the Atmospheric Aerosols and their Optical Properties", in AGARD Conference Proceedings No. 183, *Optical Propagation in the Atmosphere*, AGARD-CP-183, available from the U. S. National Technical Information Service (AD-A028-615), 1976.

23.6 Dates of development, authors and sponsors

23.6.1 Dates: Atmospheric profiles 1986

Aerosol properties 1979

23.6.2 Principal authors:

23.6.2.1 Atmospheric Constituent Profiles: G. P. Anderson

23.6.2.2 Optical Properties: E. P. Shettle

23.6.3 Sponsors: Air Force Geophysics Laboratory (now Air Force Research Laboratory)

23.7 Model codes and sources

23.7.1 The model is published in the form of tables and figures. Additionally, computer compatible listings or block data statements are available within all copies of MODTRAN®, MODerate, first released in 1990, the follow-on to LOWTRAN. Separate text listing can be acquired by e-mail. Contact AFRL gail.anderson@hanscom.af.mil for details. For MODTRAN® information, contact AFRL or see the Spectral Sciences, Inc. homepage: http://spectral.com/.

23.7.2 Both the Atmospheric Gas Constituent Profiles and the Aerosol models are included as part of the FASCODE and MODTRAN® computer codes, and also the DOE-funded codes, LBLRTM, RRTM, etc. For MODTRAN® information, contact AFRL at: http://www.kirtland.af.mil/library/factsheet.asp?id=7915 or the Spectral Sciences, Inc. are co-developers of MODTRAN®. For the DOE codes, contact E. Mlawer at emlawer@aer.com, or visit the AER home page: http://www.aer.com/.

23.7.3 Sources are:

23.7.3.1 Clough, S. A., F. X. Kneizys, E. P. Shettle, and G. P. Anderson, Atmospheric radiation of transmittance: FASCOD2, in the Extended Abstracts of the Sixth Conference on Atmospheric Radiation, Williamsburg, VA, 13-16 May, 1986; American Meteorological Society.

23.7.3.2 Kneizys, F. X., E. P. Shettle, W. O. Gallery, J. H. Chetwynd, Jr., L. W. Abreu, J.R., E. A. Selby, S. A. Clough, and R. W. Fenn, Atmospheric transmittance/radiance: computer code LOWTRAN 6, AFGL Report, AFGL-TR-83-0187, Environmental Research Paper 846, August 1983.

23.7.3.3 Anderson, G.P., Alexander Berk, James H. Chetwynd, Jerald Harder, Juan M. Fontenla, Eric P. Shettle, Roger Saunders, Hilary E. Snell, Peter Pilewski, Bruce C. Kindel, James A. Gardner, Michael L. Hoke, Gerald W. Felde, and Ronald B. Lockwood, Prabhat K. Acharya, “Using the MODTRAN®5 radiative transfer algorithm with NASA satellite data: AIRS and SOURCE”, Proc. SPIE, Vol. 6565, 656510 (2007); DOI: 10.1117/12.721184.

24 AFGL extreme envelopes of climatic elements up to 80 km, 1973

24.1 Model content

The Air Force Geophysics Laboratory *Extreme Envelopes of Climatic Elements up to 80 km* provides envelopes for values of extremes (for 16 climatic elements) at each altitude regardless of the location or month in which they occurred. Therefore, the values provided for each altitude do not generally occur at the same time and place for layers greater than a few kilometers, and are not representative of the influence of the entire atmosphere on a vertically rising or descending vehicle. These envelopes are most applicable for determining extreme conditions at specific altitudes of concern for vehicles horizontally traversing the atmosphere, or for determining which altitude may present the most severely adverse effect for each climatic element. For each climatic element information is provided for the recorded extreme (up to an altitude of 30 km), and for the frequency of occurrence during the most severe month in the worst part of the world (excluding areas south of 60 deg S) for that element. Values with a 1-, 5-, 10-, and 20-percent frequency of occurrence are presented.

Climatic data up through 30 km (98,425ft) are generally given for both actual (geometric) and pressure altitude. Values above this altitude are provided for geometric altitude only. Actually, the geometric altitudes up to 30 km are geopotential heights, but for de- sign purposes these may be considered geo- metric heights above sea level; for instance, at 30 km, the difference between geopotential and geometric heights is 143 m, and less than that value at lower altitudes. Information at geometric altitude is applicable in missile design whereas information at pressure altitudes is applicable in aircraft design since aircraft generally fly on given pressure surfaces. Pressure altitude is the geopotential height corresponding to a given pressure in the Standard Atmosphere. The heights given by most altimeters are based on the relationship between pressure and height in the Standard Atmosphere. Since atmospheric conditions are seldom standard, aircraft at a given pressure altitude may be at significantly different true altitudes above sea level; an aircraft flying at a constant pressure altitude may be ascending, descending, or flying level.

24.2 Model uncertainties and limitation

Since the model is based upon a statistical analysis of the available atmospheric data, the model uncertainties depend entirely upon the quantity and quality of these data and the degree to which they represent the real atmosphere at a given time and place. Also, see Section 24.4.

24.3 Basis of the model

The model, which is empirical in nature, is based upon analysis of rawinsonde and Meteorological Rocket Network data. Highest / lowest values of recorded parameters and 1-, 5-, 10- and 20-percent extremes are provided. These extremes are based on observed values; they are not extrapolated values obtained by assuming a normal (or any other) distribution for the values of a given element. Because upper atmospheric observations are not routinely taken 24 hours per day, but usually only twice per day, the percent extremes do not strictly represent the number of hours per month that the value of a given element is equaled or exceeded. However, since diurnal cycles in the free air are relatively small, the distributions as obtained from summaries of original sounding data for each kilometer level for the extreme month and location selected are considered as reasonably representative of the extreme values.

A comparison was made between the various locations selected in order to arrive at a final most severe extreme for each level. When it was determined that the extreme condition existed either between two stations having sounding data or displaced from a sounding station, extrapolation through spatial analysis and/or subjective evaluation was accomplished in order to obtain a worldwide extreme value for a given element.

24.4 Databases

24.4.1 For altitudes below 30 km, only about five years of data, with measurements usually taken twice per day, were readily available in an acceptable format (complete period of record, data at a sufficient number of intervals) for summarization of reliable statistics. Only data from standard meteorological pressure levels had been recorded for many overseas stations. With the increased distance between standard levels, especially above 700 mb, "straight line" extrapolating procedures introduces the ever increasing possibility of error if these data were used. In addition, a number of stations had broken periods of record that did not appear to be dependable. In both of these cases the reliability sought for this study could not be obtained from such data. On several occasions substitute stations had to be used. Records to altitudes above approximately 24 km were incomplete so a more thorough evaluation of these data than the data at lower levels was required. This was accomplished by comparison with data from nearby stations to attempt to establish the validity of the extreme based on a station with more complete data, as well as by spatial analysis.

24.4.2 For altitudes above 30 km, observations of climatic elements are very limited. Consequently, estimates of extremes are generally not as accurate as those at lower altitudes, and are limited to frequencies of occurrence of one and ten percent of the worst month for most elements. Estimates of extremes for altitudes between 30 and 55 km, for all elements except humidity, were based upon daily Meteorological Rocket Network (MRN) data available for more than 30 northern hemisphere locations. Values were extrapolated up to 80 km using results from special observation programs.

24.5 Publication references

24.5.1 Department of Defense, "Climatic Information to Determine Design and Test Requirements for Military Systems and Equipment", Report Mil-Std-210C, Naval Publications and Forms Center, 5801 Tabor Avenue, Philadelphia, PA 19120, January 9, 1987.

24.5.2 Sissenwine, N., and R. V. Cormier, "Synopsis of Background Material," MIL-STD-210B, Climatic Extremes for Military Equipment, Report AFGL-TR-74-0052 (AD780508), Air Force Surveys in Geophysics, No. 280, Hanscom AFB, MA 01713, 1974.

24.6 Dates of development, authors and sponsors

24.6.1 Dates: 1967 to 1973

24.6.2 Principal author: N. Sissenwine

24.6.3 Sponsors: U.S. Air Force Geophysics Laboratory (now Air Force Research Laboratory)

24.7 Model codes and sources

The model is presented in the publications listed in section five above. There are no computer codes. Contact sponsors for additional information.

25 AFGL profiles of temperature and density based on 1- and 10-percent extremes in the stratosphere and troposphere, 1984

25.1 Model content

The Air Force Geophysics Laboratory *Profiles of Temperature and Density Based on 1- and 10-Percent Extremes in the Stratosphere and Troposphere* consists of a set of empirically derived profiles of temperature and associated density, and density and associated temperature, based on the 1- and 10-percent high and low temperature and density extremes occurring during the most extreme month at the most severe location in the world (except Antarctica). The 1- and 10-percent high temperature or high-density values exceed 99 and 90 percent of the observations at a specified altitude at the most extreme location, respectively. Conversely, the 1- and 10-percent cold temperature or low-density values are exceeded by 99- and 90-percent of the observations, respectively. These are also referred to as 1- and 10-percent values (cold temperature, high density), and 90- and 99-percent values (high temperature, high density) as obtained from a pl ot of the cumulative frequency distribution of all the monthly temperature (or density observations at a specified altitude).

The profiles from the surface up to 80 km are based on extremes that occur at 5, 10, 20, 30 and 40 km. For example, one of the temperature profiles was based on a 10-percent warm temperature at an altitude of 20 km, so that it represents atmospheric conditions typically associated with this extreme. T en such warm profiles (5 levels by 2 percentiles) and ten cold profiles have been constructed from 14 years of rawinsonde and rocket-sonde observations. I nternally consistent hydrostatic profiles of density associated with these temperature profiles are provided. Twenty analogous density (and associated temperature) profiles also have been developed from extreme densities occurring at the aforementioned altitudes. T hus, a s et of realistic vertical profiles of temperature and density associated with extremes at specified levels in the troposphere and stratosphere are available for altitudes up to 80 km.

Model results are presented at 2-km intervals of geometric altitude from sea level to 80 km. Results are also presented in the form of temperature—altitude profiles for lapse-rate breakpoints in geopotential height (km). They are realistic, hydrostatically consistent representations of the temperature and density structure associated with the extremes that occur at the indicated altitudes.

25.2 Model uncertainties and limitations

The lack of Eurasian, African and Australian data for model development resulted in warm extremes that are less severe than expected at 5 and 10 km. Near-eastern locations, particularly over the Indian subcontinent in summer, undoubtedly would produce warmer 90- and 99-percent temperatures at these levels. S imilarly, winter observations over Siberia would produce somewhat colder 1-percent temperatures at 5 k m. The inclusion of African and Australian densities also would produce more extreme 90-and 99-percent densities at 5, 10, and possibly 20 km.

25.3 Basis of the model

The model profiles from the surface to approximately 25 km were developed using rawinsonde data. Meteorological Rocket Network (MRN) data were used to derive those portions of the profiles from approximately 25 km up to approximately 55 km. The model profiles were extended up to 80 km using inter-level temperature correlations derived from independent rocket grenade and pressure gauge experiments, and the Air Force Reference Atmosphere.

25.4 Databases

25.4.1 Rawinsonde data, provided in National Climatic Data Center (NCDC), Ashville, N. C., Tape Deck 5600, consist of 00 UT and 12 UT observations of temperatures and pressure altitudes for most areas of the world excluding Eurasia, Africa, and Australia. This tape deck contains observations from some 130 locations (U. S., Central and South America, and Oceania) for the years 1969 through 1981, and was in combination with Canadian rawinsonde tapes which also contain twice-daily observations from some 40 Canadian-controlled high-latitude stations for the years 1969 through 1982.

25.4.2 MRN tape deck TDF 5850 provides temperatures and calculated densities at 21 MRN locations for altitudes from approximately 25 km to 65 km for the years 1969 through 1982. They lie mostly in the western hemisphere and are located between latitudes 77 deg N and 38 deg S.

25.5 Publication references

Kantor, A. J., and P. Tattleman, "Profiles of Temperature and Density Based on 1 and 10 Percent Extremes in the Stratosphere and T roposphere", Report AFGL-TR-84-0336, ADA 160552, Air Force Surveys in Geophysics No. 447, December 1984.

25.6 Dates of development, authors, and sponsors

25.6.1 Dates: 1982-1984

25.6.2 Authors: A. J. Kantor and P. Tattleman

25.6.3 Sponsors: U.S. Air Force Geophysics Laboratory (now Air Force Research Laboratory)

25.7 Model codes and sources

The model is published in the form of tables provided in the reference. No computer codes are available. Contact sponsors for additional information.

26 AFGL global reference atmosphere from 18 to 80 km, 1985

26.1 Model content

The *Global Reference Atmosphere from 18 to 80 km* consists of a report published and distributed by the Air Force Geophysics Laboratory. It gives monthly mean values of mean temperature, pressure, density, number density, pressure scale height and geostrophic zonal winds. The altitude range is 18 to 80 km and the latitude range is 80 deg S to 80 deg N in 10 deg intervals. Mo nthly mean longitudinal variations of temperature, pressure and density are tabulated at 30 deg longitude intervals for September to April in the northern hemisphere and April to November in the southern hemisphere at latitudes 20, 30,.80 deg N (or S) over the same range of heights. Formulas by which temperature, pressure and density variations may be computed are also included. An intercomparison of the temperature data from the sources used to develop the model is also made.

26.2 Model uncertainties and limitations

26.2.1 A more extensive set of satellite remote sounding data is required. The lack of data for a longer period of time and from other instruments is limitations to the usefulness of the model.

26.2.2 As the report shows, there are systematic differences between the satellite temperature profiles from the SCR and PMR instruments and t hose obtained with *in situ* instruments. Comparing data from other remote sounding instruments and using different data reduction methods may shed some light on the problem.

26.3 Basis of the model

The zonal mean values are derived from tabulations of temperature and ge opotential height based upon Nimbus 5 s elective chopper radiometer (SCR) and Nimbus 6 pr essure-modulated radiometer (PMR) data during the period 1973 to June 1978, a southern hemisphere reference atmosphere based on rocket sonde data, and on two earlier northern hemisphere rocket-based reference atmospheres (CIRA 1972 and the Air Force Reference Atmospheres 1978).

26.4 Databases

The model databases are contained in the following documents

26.4.1 Barnett, J. J., Plots and Tables of Temperature and Geopotential Height Based on Nimbus 5 SCR and Nimbus 6 PMR, Working Group 4 Document, XXV COSPAR Meeting, Graz, Austria, 1984.

26.4.2 Barnett, J. J., and M. Corney, "A Middle Atmosphere Temperature Reference Model from Satellite Measurements," Adv. Space Res., 5, 125-134, 1985.

26.4.3 Koshelkov, Yu. P., Climatology of the Middle Atmosphere of the Southern Hemisphere, Preprint of the XVIII General Assembly of the IUGG, Hamburg, Germany, 1983.

26.4.4 Koshelkov, Yu. P., "Proposals for a R eference Model of the Middle Atmosphere of the Southern Hemisphere," Adv. Space Res., 3, 3, 1983.

26.4.5 Koshelkov, Yu. P., Reference Middle Atmospheres for the Southern Hemisphere, Preprint to XXV COSPAR Meeting, Graz, Austria, 1984.

26.5 Publication references

Groves, G. V., *A Global Reference Atmosphere from 18 to 80 km,* Air Force Surveys in Geophysics No. 448, AFGL-TR-85-0129, Air Force Geophysics Laboratory, 1985.

26.6 Dates of development, authors and sponsors

26.6.1 Dates: 1985

26.6.2 Authors: G. V. Groves

26.6.3 Sponsors: Air Force Geophysics Laboratory (now Air Force Research Laboratory)

26.7 Model codes and sources

The model is published in the form of tables and figures only. No computer codes are available. Contact sponsors for additional information.

27 Extensions to the CIRA reference models for middle atmosphere ozone, 1993

27.1 Model content

The recent ozone reference models generated for the new COSPAR CIRA include ozone vertical structure from 25 to 90 km as a function of month and latitude based on five satellite experiments. This new model extends the ozone vertical structure climatology from 20 mb (about 25 km) to 70 mb (about 18 km) based on three years of recently reprocessed AEM-2 SAGE I (sunset) data. In addition, model refinements are made at altitudes above 25 km based on the reprocessed data. Comparisons are made between the ozone reference models and non-satellite data sets. The model extensions to lower altitudes are in excellent agreement with in situ measurements both at mid latitudes and in the tropics. Annual mean models of ozone are also provided as a function of latitude from 100 mb (about 16 km) to 0.003 mb (about 90 km).

27.2 Model uncertainties and limitations

See reference 27.5 for model comparisons with non-satellite data. The model extensions to lower altitudes are in excellent agreement with in situ measurements both at mid latitudes and in the tropics.

27.3 Basis of the model

The model is based on three years of processed AEM-2 SAGE I (sunset) data.

27.4 Databases

AEM-2 SAGE I (sunset) reprocessed data. See reference 27.5.

27.5 Publication references

Keating, G. M. and C. Chen (1993): Extensions to the CIRA Reference Models for Middle Atmosphere Ozone, Advances *in Space Research,* Vol. 13, No. 1.

27.6 Dates of development, authors and sponsors

27.6.1 Dates: 1993

27.6.2 Authors: G. M. Keating and C. Chen

27.6.3 Sponsors: National Aeronautics and Space Administration (Langley Research Center)

27.7 Model codes and sources

See Reference 27.5.

NOTE. Users may want to consult the current scientific literature regarding ozone climatological publications of a more recent date.

28 Update to the stratospheric nitric acid reference atmosphere, 1998

28.1 Model content

This model provides the zonal mean distribution of HNO3 characterized by a stratospheric layer with largest mixing ratios near 30 hPa in Polar Regions, with areas of very low concentration within the Antarctic vortex. These data extend to 80 deg S, which is within the Antarctic vortex during southern winter. An evaluation is presented of the resolution of HNO3 global distribution.

28.2 Model uncertainties and limitations

See referenced publication (28.5).

28.3 Basis of the model

The model is based on measurements obtained with the Upper Atmosphere Research Satellite's Cryogenic Limb Array Etalon Spectrometer instrument.

28.4 Databases

See referenced publication (28.5).

28.5 Publication references

Gille, J. C., L. V. Lyjak, A. E. Bailey, A. E. Roche, J. B. Kumer, and J. L. Mergenthaler (1998): Update to the Stratospheric Nitric Acid Reference Atmosphere, *Advances in Space Research,* Vol. 21, No. 10.

28.6 Dates of development, authors and sponsors

28.6.1 Dates: 1998

28.6.2 Authors: J. C. Gille, et al.

28.6.3 Sponsors: National Aeronautics and Space Administration

28.7 Model codes and sources

See Reference 28.5.

29 Reference atmosphere for the atomic sodium layer (CIRA 2008)

29.1 Model content

This reference atmosphere forms part of the COSPAR International Reference Atmosphere (CIRA) 2008. It describes the layer of Na atoms which occurs globally in the mesosphere/lower thermosphere (MLT) region, peaking at a height of about 90 km and extending from 80 to 110 km. The layer is produced by the ablation of the approximately 30 tonnes of interplanetary dust which enters the atmosphere every day (Ref. 29.4.1). The Na layer has been studied since the 1950s, first using ground-based photometry, then by resonance lidar, and most recently by limb-scanning spectroscopy from satellites. The database is now sufficient to produce a near-global reference atmosphere of the layer.

The reference atmosphere consists of zonally averaged data in 10^{o} latitude bins, on a monthly timeframe. Four tables of data are provided: the layer column abundance, the peak height, the peak concentration, and the layer full width at half maximum (FWHM), as a function of latitude and month.

The model is accompanied by a discussion of the physical chemistry of meteoric ablation, and the known chemistry (both neutral and ionic) which sodium undergoes in the MLT, giving rise to the characteristic features of the layer. The techniques that have been used to observe the layer are then reviewed, along with a description of the phenomenon of sporadic Na layers. Finally, the Na layer is compared with the smaller databases of Fe, Ca and K observations.

29.2 Basis of the model

The reference atmosphere has been constructed from several data-sets. The recent satellite measurements using the OSIRIS spectrometer on the Odin provides a near-global data set (Ref. 29.4.2). Because the data is self-consistent and ground-truthed to lidar observations (Ref. 29.4.3), it forms the backbone of the reference atmosphere. However, there are some limitations. First, the data covers only two complete years, 2003 and 2004. Second, the sun-synchronous orbit of Odin provided measurements only at ~0600 and 1800 hrs local time. Since the Na layer is subject to photochemical and tidally-driven diurnal variations (Ref. 29.4.2, 29.4.4), the data from both local times has been averaged. Third, the dayglow spectroscopic measurements are restricted to periods when the mesosphere is illuminated (solar zenith angle < 92^{o}), and so there is no data at mid- to high latitudes during winter. In order to partly overcome these limitations, lidar data from the South Pole for the years 1995-1997 (Ref. 29.4.5), from São José dos Campos (23°S) for the years 1972-1986 (Ref. 29.4.6, 29.4.7, 29.4.8), and Urbana-Champaign (40^{o}N) and Ft. Collins (41^{o}N) for the years 1991-1999 (Ref. 29.4.9, 29.4.10, 29.4.11) has been included.

29.3 Model uncertainties and limitations

The uncertainty in the absolute Na density near the layer peak retrieved from OSIRIS/Odin is about $\pm$ 10% (Ref. 29.4.3), similar to modern ground-based lidars. However, the natural variability of the Na layer means that the average monthly column abundance and peak density values in some of the 10^{o} latitude bins have a larger uncertainty (up to $\pm$30%), depending on the number of profiles in the average (Ref. 29.4.2). Although these data-sets are taken from different decades and phases of the solar cycle, a long-term study of the Na layer (Ref. 29.4.6, 29.4.8) shows that, at least at low latitudes (23^{o}S), the effects of changing climate and the solar cycle on the Na layer are small. The centroid of the layer moves down only 0.17 $\pm$ 0.11 km between solar min and max. This downward trend is probably due to changes in the diurnal tide (Ref 29.4.6) and chemistry. Measurements made at Urbana-Champaign, Illinois (40^{o}N) between 1991-94 (Ref. 29.4.9) and 1996-98 (Ref 29.4.10), which correspond to periods at and shortly after solar max and min, respectively, show that the Na column abundance was about 20% higher at solar max.

29.4 Publication references

29.4.1 Plane, J. M. C. (2003): "Atmospheric chemistry of meteoric metals", Chemical Reviews 103, 4963-4984.

29.4.2 Fan, Z. Y., J. M. C. Plane, J. Gumbel, J. Stegman and E. J. Llewellyn (2007): "Satellite measurements of the global mesospheric sodium layer", Atmos. Chem. Phys. 7, 4107-4115.

29.4.3 Gumbel, J., Z. Y. Fan, T. Waldemarsson, J. Stegman, G. Witt, E. J. Llewellyn, C. Y. She and J. M. C. Plane (2007): "Retrieval of global mesospheric sodium densities from the Odin satellite", Geophys. Res. Lett. 34, article no.: L04813

29.4.4 Clemesha, B. R., D. M. Simonich, P. P. Batista and V. Kirchhoff (1982): "The Diurnal-Variation of Atmospheric Sodium", J. Geophys. Res. 87, 181-186.

29.4.5 Gardner, C. S., J. M. C. Plane, W. L. Pan, T. Vondrak, B. J. Murray and X. Z. Chu (2005): "Seasonal variations of the Na and Fe layers at the South Pole and their implications for the chemistry and general circulation of the polar mesosphere", J. Geophys. Res. 110, article no.: D1030210.

29.4.6 Clemesha, B. R., D. M. Simonich, H. Takahashi, P. P. Batista and Y. Sahai (1992): "The Annual Variation of the Height of the Atmospheric Sodium Layer at 23^{o}S - Possible Evidence for Convective-Transport", J. Geophys. Res. 97, 5981-5985.

29.4.7 Clemesha, B. R., D. M. Simonich, H. Takahashi, P. P. Batista and Y. Sahai (1992): "The Annual Variation of the Height of the Atmospheric Sodium Layer at 23^{o} S - Possible Evidence for Convective-Transport", J. Geophys. Res. 97, 5981-5985.

29.4.8 Clemesha, B. R., D. M. Simonich, P. P. Batista, T. Vondrak and J. M. C. Plane (2004): "Negligible long-term temperature trend in the upper atmosphere at 23^{o} S", J. Geophys. Res. 109, article no. D0503.

29.4.9 Plane, J. M. C., C. S. Gardner, J. R. Yu, C. Y. She, R. R. Garcia and H. C. Pumphrey (1999): "Mesospheric Na layer at 40^{o} N: Modelling and observations", J. Geophys. Res. 104, 3773-3788.

29.4.10 States, R. J. and C. S. Gardner (1999): "Structure of the mesospheric Na layer at 40^{o} N latitude: Seasonal and diurnal variations", J. Geophys. Res. 104, 11783-11798.

29.4.11 She, C. Y., S.S. Chen, Z.L. Hu, J. Sherman, J.D. Vance, V. Vasoli, M.A. White, J.R. Yu, and D.A. Krueger (2000): "Eight-year climatology of nocturnal temperature and sodium density in the mesopause region (80 to 105 km) over Fort Collins, CO (41^{o} N, 105^{o} W)", Geophys. Res. Lett. 27 3289-3292.

29.5 Dates of development, authors and sponsors

29.5.1 Dates: Original model 2008

29.5.2 Authors: J. M. C. Plane, University of Leeds, United Kingdom

29.5.3 Sponsors: Committee on Space Research (COSPAR) of the International Council of Scientific Unions.

NOTE At the time of preparation of AIAA G-003C-2009, plans were being made by the COSPAR to produce an updated and revised version (CIRA08) of the COSPAR International Reference Atmosphere (CIRA). It is anticipated that the CIRA08 will be published in 2009 as a Special Issue of Advances in Space Research. It will contain this Reference Atmosphere for the Atomic Sodium Layer.

30 Drag temperature model (DTM)-2000, thermospheric model, 2001

30.1 Model content

The Drag Temperature Model (DTM) is a semi-empirical model describing the temperature, density and composition of the thermosphere in the altitude range [120 - 1,500] km. The DTM–2000 model was inferred from the following data: 1) total mass density from orbit determination (including the Jacchia data) and satellite accelerometers, (2) direct measurements of exospheric temperature, (3) mass spectrometers, (4) relative density variations derived from wind measurements, and (5) incoherent scatter radar. The model predicts total and partial densities, as well as temperature and exospheric temperature, as a function of the user-provided values of date, location, solar flux and geomagnetic activity.

The differences relative to the DTM-94 model mainly concern (1) the modeling of the temperature and its gradient at 120 km, (2) assimilation of Atmosphere Explorer data, and (3) using the Mg II index (instead of the radio flux at 10.7 cm) as a proxy for solar activity.

30.2 Model uncertainties and limitations

30.2.1 The model was compared to the Jacchia data set, which densities are predicted unbiased with a standard deviation of 19% on average in the in the altitude range [250 - 900] km.

30.2.2 The data used to constrain the model in the altitude range [120 - 250] km and [900-1,500] km is sparse and their spatial-temporal resolution is low. The model uncertainty for these two altitude ranges is significantly larger than the average for the (250-900) km range: i.e. approximately 25-35% (1□).

30.2.3 Longitudinal variations are not modeled.

30.2.4 Wave-like perturbations with horizontal scales of less than 3,000 km cannot be reproduced by the model, which causes a large part of the model uncertainty of 19% on average.

30.3 Basis of the model

30.3.1 The DTM-2000 model is a revision and update of the DTM-94 model, which itself was an update of the first DTM model, DTM-78. These models are empirical, based upon total density, mass spectrometer, and temperature measurements by satellite, and upon ground-based incoherent scatter radar observations.

30.3.2. Variations incorporated into the model: solar activity, magnetic activity, latitude, and solar local time; annual, semiannual, diurnal, semidiurnal, and terdiurnal.

30.4 Databases

The most important ingested data sets are described in the following documents:

30.4.1 Barlier, F., Berger, C., Falin, J.L., Kockarts, G., Thuillier, G., 1978. A thermospheric model based on satellite drag data, Ann. Geophys, 34, 9-24.

30.4.2 Thuillier, G., Falin, J.L., Barlier, F., 1977. Global experimental model of the exospheric temperature using optical and incoherent scatter measurements, J. Atmos. Terr. Phys., 39, 1195-1202.

30.4.3 Carignan, G.R., Block, B.P., Maurer, J.C., Hedin, A.E., Reber, C.A., Spencer N.W., 1981. The neutral mass spectrometer on Dynamics Explorer, Space Sci. Instrum., 5, 429-441.

30.4.4 Spencer, N.W., Wharton, L.E., Niemann, H.B., Hedin, A.E., Carignan, G.R., Maurer, J.C., 1981. The Dynamics Explorer wind and temperature spectrometer, Space Sci. Instrum., 5, 417-428.

30.4.5 Villain, J.P., 1980. Traitement des données brutes de l 'accéléromètre CACTUS. Etude des perturbations de moyenne échelle de la densité thermosphérique, Ann. Geophys., 36, 41-49.

30.4.6 Nier, A.O., Potter, W.E., Hickman, D.R., Mauersberger, K., 1973. The open-source neutral-mass spectrometer on Atmosphere Explorer-C, -D, -E, Radio Sci., 8, 271-276.

30.4.7 Pelz, D.T., Reber, C.A., Hedin, A.E., Carignan, G.C., 1973. A neutral-atmosphere composition experiment for the Atmosphere Explorer-C, -D, -E, Radio Sci., 8, 277-283.

30.4.8 Bruinsma, S., Vial, F., Thuillier, G. 2002. Relative density variations at 120 km derived from tidal wind observations made by the UARS/WINDII instrument, Journal of Atmospheric and Solar-Terrestrial Physics, 64, 13-20.

30.5 Publication references

30.5.1 Barlier, F., Berger, C., Falin, J.L., Kockarts, G., Thuillier, G., 1978. A thermospheric model based on satellite drag data, Ann. Geophys, 34, 9-24.

30.5.2 Berger, C., Biancale, R., Ill, M., Barlier, F., 1998. Improvement of the empirical thermospheric model DTM: DTM-94- comparative review on various temporal variations and prospects in space geodesy applications, Journal. of Geodesy, 72, 161- 178.

30.5.3 Bruinsma, S.L., Thuillier, G., Barlier, F., 2003. The DTM-2000 empirical thermosphere model with new data assimilation and constraints at lower boundary: accuracy and properties, Journal of Atmospheric and Solar-Terrestrial Physics, 65, 1053-1070.

30.6 Dates of development, authors and sponsors

30.6.1 Dates:	OGO 6 model	1977
	DTM-78	1977 -1978
	DTM-94	1993 - 1996
	DTM-2000	2000 - 2002
30.6.2 Authors:	S.L. Bruinsma, G. Thuillier, and F. Barlier	
30.6.3 Sponsor:	Centre National d'Etudes Spatials, France	

30.7 Model codes and sources

The model (F77 source codes, test run results, and a file containing the model coefficients) may be obtained upon request to the author (sean.bruinsma@cnes.fr .

31 Earth's upper atmosphere density model for ballistics support of flights of artificial Earth satellites, 1985

31.1 Model content

The Earth's Upper Atmosphere Density (EUAD) Model is the reference atmosphere model of Russia. The model was a State Standard of the former Soviet Union. The model was developed from density data derived from the calculation of atmospheric drag on satellites during the period from 1964 until 1982.

The model computes atmospheric density from 0 to 1500 km altitude. For altitudes under 120 km, the density is dependent on altitude. This region is divided into four altitude layers with density determined by an exponential fit using coefficients for each layer. For altitudes of 120 km and higher, the model determines density based on computations that utilize coefficients for three altitude layers and six levels of solar flux activity. The computations consider the relationship of density to daily solar flux, geomagnetic activity, and the change in density distribution due to daily and semi-annual effects is accounted for in the model.

The model inputs are the desired position vector, altitude, Moscow time, Greenwich Sidereal time, day of year, Sun right ascension and declination, geomagnetic index (Ap or Kp), daily solar flux value, and 135 day average solar flux value.

31.2 Model uncertainties and limitations

The report listed in 31.5.2 provides some information on the models accuracy. "The results of the calculations over a great number of real data indicate that at the heights 200-500 km root mean-square relative errors of determining density according to the model GOST 25645.115-84 don't exceed 10% in quiet periods and can exceed 30% during strong geomagnetic storms.

31.3 Basis of the model

The model was developed from density that derived from the calculation of atmospheric drag on satellites during the period from 1964 till 1982.

31.4 Databases

Information on the observations used in development of the model is not currently available.

31.5 Publication references

31.5.1 State Standard of the USSR: GOST 25645.115-84, "Earth Upper Atmosphere Density Model for Ballistics Support of Flights of Artificial Earth Satellites."Bazhkov, N. V., et al., 24 August 1984. All Russian Research Institute of Standardization, Moscow, Russia.

31.5.2 "Determination and Prediction of Satellite Motion at the End of the Lifetime," Nazarenk, A.I. Computer Center "COSMOS", USSR. Proc. Internet. Workshop on Reentry of Slyut-7/Kosmos 1686 Reentry, ESA SP-345, Darnstadt (D), August 1991.

31.5.3 Nazarenko, A. I., et al., "The Space-Temporal Variations of the Upper Atmosphere Density During the Period of June-September 1989 Derived from the Satellite Drag Data," Adv. Space Research, vol. 11, no. 6, pp. 155-160, 1991.

31.5.4 Vlasov, M. N. "Upper Atmosphere Model for the Prediction of he Position of Satellites," American Geophysical Union/International Union of Geodesy and Geophysics, 1993, pages 151-156. Washington, D.C.

31.6 Dates of development, authors and sponsors

31.6.1 The model is authored by N. K. Bazhkov, et al., and was approved August 24, 1984, by the USSR State Standardization Committee. Effective as of July 1, 1985, by decree of the USSR State Standardization Committee.

31.7 Model codes and sources

Reference 31.5.1 contains in an appendix the mathematical description of the model, the coefficient tables, and FORTRAN listing of the computer code.

32 Russian Earth's upper atmosphere density model for ballistic support of the flight of artificial Earth satellites, 2004

32.1 Model content

The Russian Earth's Upper Atmosphere Density Model For Ballistic Support Of The Flight Of Artificial Earth Satellites, 2004, (Ref. 32.5.1) is a product of the State Committee on Standardization and Metrology of the Russian Federation, Moscow. It was developed by the 4th Central Scientific Research Institute of the Ministry of Defense of the Russian Federation and adopted by the Russian Gosstandart on March 9, 2004. This standard defines the Earth's upper atmosphere density model including a technique for calculation. The values of the parameters for the density of the Earth's atmosphere in a range of altitudes from 120 km up to 1500 km for various levels of the solar activity are given. It describes an altitude profile of density and its basic space-temporal variations depending on the position of an artificial satellite in near-Earth space environment, the position of the Sun, the season and day, and also the solar and geomagnetic activities. The model is focused on the practical applications of (1) design calculations of aerodynamic drag and (2) ballistic-navigation support of operational control of an artificial satellite.

32.2 Model uncertainties and limitation

Data from satellite drag calculations were used to formulate the empirical functions used to derive the atmospheric parameters. The calculation error of aerodynamic drag coefficient for Artificial Earth Satellite by the described technique generally does not exceed 30%. For an Artificial Earth Satellite of near spherical shape, the error in the determination of the aerodynamic drag coefficient is estimated by 7%.

All drag-based models are deficient in the way in which they represent the large variations in total density that are associated with short term (hourly-daily time periods) geomagnetic disturbances. The major source of uncertainty for future thermospheric neutral density calculations is the uncertainty in the estimation of future solar EUV heat input as represented by the solar flux index used as input to the model. (Ref. 32.5.2) Some thermosphere models are based on data from satellite-borne mass spectrometers, accelerometers, and other sensors represent composition and changes in composition more accurately than do models based upon drag data. However, they are for the most part, not significantly better in their representation of the total neutral density.

A comparison of the NASA Marshall Engineering Thermosphere and some earlier Russian Upper Atmosphere Density Models is provided in Reference 32.5.3. The paper by I.I. Volkov and V. Suevalov "Estimation of long-Term Density Variations in the Upper Atmosphere of the Earth at Minimums of Solar Activity from Evolution of the Orbital Parameters of the Earth's Artificial Satellites" (Ref. 32.5.4) further discusses the determination of density variations associated with solar activity parameters, solar radio flux and level of geomagnetic disturbance, from long-term satellite drag data.

32.3 Basis of the model

The GOST 2004 model is based on Artificial Earth Satellite drag data over the period 1964 to 2000. The model defines an atmosphere density in a range of heights from 120km up to 1500 km. The model of density of the atmosphere is presented as a simple analytical formula with the factors in the formula representing the:

- Secular change in the night atmosphere density over the 11-year solar cycle,
- Amplitude of the diurnal effect,
- Influence of the semi-annual effect,
- Short-period effect due to the daily variation in solar activity, and
- Short-period effect due to the geomagnetic index.

Each of these factors is modified by a polynomial function of the altitude. The coefficients in these polynomials are given by tables. The coefficient values are presented for two altitude ranges in table form. Each of the two tables gives the coefficients as a function of the reference level of solar radiation flux with wavelength of 10.7 cm (of frequency 2800 MHz) expressed in Solar Flux Units 10^{-22} $watt \cdot m^{-2} Hz^{-1}$. Tables are constructed for seven fixed levels of solar activity: F_0 = *75, 100, 125, 150, 175, 200 and 250.* To calculate the atmosphere density, the values of the coefficients for the F_0 level nearest to the current F_{81} value are used. The quantity F_{81} is the weighted average of the daily values of the solar flux $F_{10.7}$ over three previous rotations of the Sun.

Recommendations are given on use of the density model of the upper atmosphere for ballistic maintenance of artificial satellite flights. The technique for calculation of the aerodynamic drag coefficient is also given.

The Russian Federation standards noted in References 32.5.5 and 32.5.6 were used in the preparation of this standard.

Future modifications to the density model given in this standard may involve:

- Modified numerical values for the polynominal coefficients,
- Modifications to the degree of the several polynomials, and
- Modifications to the scope of the physical terms for which corrections are introduced.

32.4 Databases

The density model of the Earth's upper atmosphere is constructed using Artificial Earth Satellite drag data over the period 1964 to 2000. No specific database references are given in the GOST-2004 model standard (Ref. 32.5.1).

32.5 Publication references

32.5.1 Anon.: "Earth's Upper Atmosphere Density Model for Ballistic Support of the Flight of Artificial Earth Satellites", National Standard of the Russian Federation, Document number GOST R 25645.166-2004, Gosstandart of Russia, Moscow, 2004 (English translation accomplished by Vasiliy S. Yurasov in 2006 and edited by Paul J. Cefola in 2007. Contact Paul J. Cefola, Consultancy in Aerospace Systems, Spaceflight Mechanics, & Astrodynamics, Sudbury, MA 01776 Cefola@mit.edu)

32.5.2 Vaughan, W. W., J. K. Owens, K. O. Niehuss, and M. A. Shea: "The NASA Marshall Solar Activity Model For Use In Predicting Satellite Lifetime," *Advances in Space Research,* Vol. 23, No. 4, 1999.

32.5.3 Pavelitz, Steven and B. Jeffrey Anderson: "Comparison of the NASA Marshall Engineering Thermosphere and the Russian Upper Atmosphere Density Models", AIAA Paper Number 95-0554, January 1995, 33rd Aerospace Sciences Meeting and Exhibit, Reno, NV. American Institute of Aeronautics and Astronautics.

32.5.4 Volkov, I. I. And V. V. Suevlov: "Estimation of Long-Term Density Variations in the Upper Atmosphere of the Earth at Minimums of Solar Activity from Evolution of the Orbital Parameters of the Earth's Artificial Satellites", Solar System Research, Vol. 39, No. 2, 2005, pp. 157-162. Translated from Astronomicheskii Vesnik, Vol. 39, No. 2, 2005, pp.177-183.

32.5.5 Anon.: "Ballistic Calculations of the Earth's Artificial Satellites. Calculation Technique of Indexes of Solar Activity", National Standard of the Russian Federation, Document number GOST 25645.302-83, Gosstandart of Russia, Moscow, 1983.

32.5.6 Anon.: "Standard Atmosphere. Parameters" National Standard of the Russian Federation, Document number GOST 4401-81, Gosstandart of Russia, Moscow, 1981.

32.6 Dates of development, authors and sponsors

32.6.1 Dates: 2004, based upon work done during previous years

32.6.2 Authors: 4th Central Scientific Research Institute of the Ministry of Defense of the Russian Federation

32.6.3 Sponsors: State Committee on Standardization and Metrology of the Russian Federation

32.7 Model codes and sources

Contact the State Committee on Standardization and Metrology of the Russian Federation, (Gosstandart of Russia), Moscow, Russia. See Reference 32.5.1.

33 Jacchia J70 static models of the thermosphere and exosphere with empirical temperature profiles, 1970

33.1 Model content

The Jacchia J70 Static Models of the Thermosphere and Exosphere with Empirical Temperature Profiles consists of a document with tables of temperature, composition, density, and pressure scale height as a function of height for exospheric temperatures ranging from 600 to 2000 K, at 100 K intervals, and for heights extending from 90 to 2500 km. Also, functions are given which enable the user to program the model for computer outputs. A summary table in the document gives total density for the same range of height and temperatures, but at 50 K intervals in the exospheric temperature. A set of auxiliary tables is provided to help in the evaluation of the diurnal, geomagnetic, semiannual, and seasonal-latitudinal effects.

33.2 Model uncertainties and limitations

A comparison was made of the ten-day means of the residuals in $\log_{10}$ (density) for five satellites (Explorers 1, 8, and 19, Injun 3, and Echo 2) in the 270 to 1130 km range. The mean systematic error was very close to zero for all satellites. Slowly varying systematic deviations from the model were all within 12 percent in density. Larger variations in the residuals of two satellites (Echo 2 Explorer 19) were attributed to imperfect knowledge of the seasonal migration of helium (the winter helium bulge) and the associated semiannual helium variation. Available data on average total densities obtained from mass spectrometer data are approximately 10 percent lower. This discrepancy is believed by some authors (Cook, 1966) to result from the use of a C_D=2.2 rather than C_D=2.4 in the satellite drag derivations. Variations occurring on time scales of less than the diurnal period are not modeled.

A recent analysis by Bowman, 2004, (Ref. 33.5.4) addresses the semi-annual thermospheric density variation from 1970 to 2002 between 200-1100 km and concludes that errors in the semi-annual component of density variations of over 100% across the years of the solar cycle are possible in current thermospheric models if the semi-annual density variation is not modeled on a yearly basis. This analysis illustrates a high correlation of semi-annual density variation with solar activity. It involved the analysis of daily temperature corrections to a modified Jacchia 1970 Model, which is part of the U.S. Air Force's High Accuracy Satellite Drag Model, 2002.

33.3 Basis of the model

The Jacchia J70 model is based upon satellite-drag data derived from ground-based tracking of selected satellites. An earlier (1965) model by Jacchia was used as the basis for this successor model. All the available observational material up to that time, including the then most recent measurements of density and composition, has been taken into account in the construction of this model. It should be understood that no good observational data existed above 1100 km at the time this model was prepared, so that all of the model data output above that height must be considered as unconfirmed extrapolation.

The atmosphere is assumed to be well mixed up to 105 km and in diffusive equilibrium above this height. Oxygen dissociation is assumed to be the cause of any change in mean molecular weight below 105 km. All temperature profiles start from a constant value T_0=183 K at the height z_0 =90 km. Changes in an index of geomagnetic activity have been related to changes in the exospheric temperature T_∞.

33.4 Databases

The models are based upon satellite-drag data obtained from ground-based tracking of various satellites by the Smithsonian Astrophysical Observatory.

33.5 Publication references

33.5.1 Cook, G. E., "Drag Coefficients of Spherical Satellites," *Ann. Geophys.*, *22*, 33-64, 1966.

33.5.2 Jacchia, L. G., "New Static Models of the Thermosphere and Exosphere with Empirical Temperature Models", Smithsonian Astrophysical Observatory Special Report 313, Cambridge, Massachusetts, May 1970.

33.5.3 Lear, William M., "A Simple Orbital Density Model for Drag Equations", TRW, Inc, document #JSC-2097, NASA Johnson Space Center, Houston, Texas, August 1966. (This describes revisions made primarily

to correct and improve the calculation of the right Ascension and declination of the Sun in the Jacchia J70 model).

33.5.4 Bowman, Bruce R., "The Semi-annual Thermosphere Density Variation from 1970 to 2002 Between 200 - 1100 km". Paper # AAS – 04-174. 14th AAS/AIAA Space Flight Mechanics Meeting. American Astronautical Society, Springfield, VA (info@astronautical.org), February 2004.

33.5.5 Dowd, Douglas L. and B. D. Topple, "Density Models for the Upper Atmosphere." Celestial Mechanics, 20, 271-295, 1979.

33.6 Dates of development, authors and sponsors

33.6.1 Dates: 1970, based upon work during the preceding six years.

33.6.2 Authors: L. G. Jacchia

33.6.3 Sponsors: Smithsonian Astrophysical Observatory

33.7 Model codes and sources

The monthly Marshall Solar Activity Future Estimation (MSAFE) report provides expected 13-month Zurich smoothed solar and geomagnetic activity based on the most recent monthly mean data for use in the J70 model. It can be downloaded from http://sail.msfc.nasa.gov.

The J70 model output is contained in tables within the Smithsonian Astrophysical Observatory Special Report 313. The Jacchia J70 model has, however, been prepared for computer output by various groups such as the Smithsonian Astrophysical Observatory (Cambridge, MA), NASA Marshall Space Flight Center (Huntsville, AL), and Air Force Research Laboratory (Hanscom AFB, MA). Copies of the computer code may be available from these groups upon request.

34 Jacchia J71 revised static models of the thermosphere and exosphere with empirical temperature profiles, 1971

34.1 Model content

The *Jacchia J71 Revised Static Models of the Thermosphere and Exosphere with Empirical Temperature Profiles* consists of a document with tables of temperature, composition, density, and pressure scale height as a function of height for exospheric temperatures ranging from 600 to 2000 K, at 10 K intervals, and for heights from 90 to 2500 km. Also, functions are given which enable the user to program the model for computer outputs. A summary table in the document gives total density for the same range of height and temperatures, but at 50 K intervals in the exospheric temperature. A set of auxiliary tables is also provided to help in the evaluation of the diurnal, geomagnetic, semiannual and seasonal-latitudinal effects. The analytical structure of the basic models is identical to that of the Jacchia 70 models. The Jacchia 71 models were incorporated into COSPAR International Reference Atmosphere 1972 model.

34.2 Model uncertainties and limitations

The model has the limitations inherent in the satellite-drag data, namely the smoothing of short-term dynamic variations (of less-than-diurnal period) in the total density, etc. The exact degree of uncertainty resulting from this feature is difficult to ascertain. Based upon information contained in the basic document, this dynamical variation could be on the order of 12 to 50 percent, depending upon altitude, solar activity magnitude variation and time interval. However, the smooth mean total density model values are considered by the author to be very representative of the actual values.

Ref 5.3 provides a comparison of the Jacchia J71 model with several other thermospheric models vs. altitude, latitude, local time, day of year, and solar and geomagnetic conditions.

34.3 Basis of the model

The Jacchia 71 models are revisions of the J70 models published by the author. Although an effort had been made in the J70 models to increase the n (O)/n(O_2) ratios, new observational evidence showed that the increase had not been large enough. The J71 models attempt to meet, as closely as possible, the composition and density data derived for a height of 150 km on the basis of available mass spectrometric and EUV—absorption data. Mixing is assumed to prevail to a height of 100 km, with diffusive separation governing above this height. All recognized variations of model parameters are represented by empirical equations. Some of these equations were revised in the J71 models, not only in their numerical coefficients, but also in their form, as a result of new analyses. While revising the basic variation models, the author reanalyzed the variations. Hence there are substantial changes in the description of some of the individual types of atmospheric variations from that given in the J70 models.

34.4 Databases

The J71 models are based on satellite-drag data obtained from ground-based tracking of various satellites by the Smithsonian Astrophysical Observatory. Available mass spectrometer and EUV—absorption data were also utilized in this update of the J70 models.

34.5 Publication references

34.5.1 Jacchia, L. G., Revised static models of the thermosphere and exosphere with empirical temperature profiles, Smithsonian Astrophysical Observatory Special Report 332, Cambridge, Massachusetts, May 1971.

34.5.2 Dowd, Douglas L. and B. D. Tapley, “Density Models for the Upper Atmosphere.” Celestial Mechanics, 20, 271-295, 1979.

34.5.3 Marcos, Frank A., Bruce R. Bowman, and Robert E. Sheehan, “Accuracy of Earth’s Thermospheric Neutral Density Models.” AIAA Paper Number AIAA 2006-6167. American Institute of Aeronautics & Astronautics, Reston, VA 20006.

34.6 Dates of development, authors and sponsors

34.6.1 Dates: 1971 and preceding year

34.6.2 Authors: L. G. Jacchia

34.6.3 Sponsors: Smithsonian Astrophysical Observatory.

34.7 Model codes and sources

The monthly Marshall Solar Activity Future Estimation (MSAFE) report provides expected 13-month Zurich smoothed solar and geomagnetic activity based on the most recent monthly mean data for use in the J71 model. It can be downloaded from http://sail.msfc.nasa.gov.

The J71 model output is contained in tables in the referenced publication. The Jacchia J71 model has been programmed for computer output by various groups, such as the Smithsonian Astrophysical Observatory (Cambridge, MA), the NASA-Marshall Space Flight Center (Huntsville, AL), and the Air Force Research Laboratory (Hanscom AFB, MA). Copies of the computer code may be available from these groups upon request.

35 Jacchia J77 thermospheric temperature, density and composition: new models, 1977

35.1 Model content

The *Jacchia J77 Thermospheric Temperature, Density, and Composition: New Models* consists of two parts: (1) the basic static models, which give temperature and density profiles for the relevant atmospheric constituents for any specified exospheric temperature, and (2) a set of formulas to compute the exospheric temperature and the expected deviation from the static models resulting from all of the recognized types of thermospheric variation. For the basic static models, the total density for heights in the range 90 to 2500 km and exospheric temperatures in the range 500 K to 2600 K are listed in tables. Number densities of six atmospheric constituents in the height range 90 to 2500 km and in the temperature range 500 K to 2600 K are also listed. The Jacchia J77 models are a complete revision of the earlier J71 models.

35.2 Model uncertainties and limitations

The model is characterized by the limitations inherent in the satellite-drag data, namely the smoothing of short-term dynamical (less than the diurnal period) variations in the total density, etc. For example, the Explorer 32 satellite detected the existence of waves throughout the upper atmosphere in the height range extending from 286 to 570 km. The apparent half-wave lengths of the waves were found to increase with altitude. Their half-amplitudes for density range up to a maximum of about 50 percent of the mean density.

According to the author, L. G. Jacchia, the smoothed mean total density values compare very well with observational values with the same resolution.

35.3 Basis of the model

The Jacchia J77 models are a revision and updating of the Jacchia J71 models published by the author. In revising the basic models, the author endeavored to reproduce the results from the OGO-6 satellite with respect to the relative concentrations of N_2 and O at 450 km, while keeping the total density anchored to satellite-drag data.

All temperature profiles start at a constant value or To=188 K at a height of Zo=90 km. A condition of complete atmospheric mixing is assumed up to 100 km and diffusive separation above this altitude. The J77 model adds independent corrections to the values of n(O) and n(O_2) determined from the mean molecular mass profile derived for the J71 model. These corrections extend across the hoopoes.

35.4 Databases

The J77 models are based upon satellite—drag data obtained from ground-based tracking of various satellites and available mass spectrometric and EUV—absorption data.

35.4 Publication references

35 5.1 Jacchia, L. G., "Thermospheric temperature, density, and composition: new models", Smithsonian Astrophysical Observatory Special Report 375, Cambridge, Massachusetts, March 1977.

35.5.2 Mueller, Alan C., "Jacchia-Lineberry Upper Atmosphere Density Model," Computational Mechanics Services Document No. JSC-18507, NASA - Johnson Space Center, Houston, Texas, October 1982 (In an effort to reduce computation time, use has been made of the assumption that the log of the density may be expressed as a truncated Laurent series in temperature and altitude. The atmosphere is layered into several altitude bands and the series of coefficients of each band are found by point-wise fit of Jacchia's tabular results. A more efficient method of computing the temperature, together with this layered model, significantly reduces the computation time, yet maintains the model accuracy and storage costs. This document also contains cautions for the user on its limitations.)

35.5.3 de Lafontaine, Jean and Peter Hughes, "An Analytic Version of Jacchia's 1977 Model Atmosphere", *Celestial Mechanics, 29,* 3-26, 1983.

35.6 Dates of development, authors, and sponsors

35.6.1 Dates: 1977 and the prior six years

35.6.2 Authors: L. G. Jacchia

35.6.3 Sponsors: Smithsonian Astrophysical Observatory, Smithsonian Research Foundation and the National Aeronautics and Space Administration.

35.7 Model codes and sources

The monthly Marshall Solar Activity Future Estimation (MSAFE) report provides expected 13-month Zurich smoothed solar and geomagnetic activity based on the most recent monthly mean data for use in the J77 model. It can be downloaded from http://sail.msfc.nasa.gov.

The J77 model output is contained in tables within the publication reference (Section 35.5). The model has been modified for computer output by various groups such as the Smithsonian Astrophysical Observatory (SAO) (Cambridge, MA), NASA Johnson Space Center (Houston, TX), NASA Marshall Space Flight Center (Huntsville, AL), Air Force Research Laboratory (Hanscom AFB, MA), and Lincoln Laboratories (MIT) (Lexington, MA). Copies of the computer codes may be available from these groups upon request.

36 Jacchia-Bowman 2006 (JB2006) empirical thermospheric density model

36.1 Model content

A new empirical thermospheric density model is developed using the CIRA72 model as the basis for the diffusion equations. New solar indices based on orbit-based sensor data are used for the solar irradiances in the extreme and far ultraviolet wavelengths. New exospheric temperature and semiannual density equations are employed to represent the major thermospheric density variations. Temperature correction equations are also developed for unmodeled diurnal and latitudinal effects, and finally density correction factors are used for model corrections required at high altitude (1500-4000 km). The new model, Jacchia-Bowman 2006 Empirical Thermospheric Density Model (JB2006), is validated through comparisons of accurate daily density drag data previously computed for numerous satellites.

36.2 Model uncertainties and limitations

Density model errors on the order of 15%-20% one standard deviation have been recognized for all empirical models (Ref. 36.5.1) developed since the mid 1960s. These large density standard deviations correspond to maximum density errors of approximately 40-60% as observed in satellite drag data. There are two main reasons for these consistently large values. One is the result of not modeling the semiannual density variation (Ref. 36.5.2) as a function of solar activity, and the other results from not modeling the full thermospheric heating from solar ultraviolet radiation. Geomagnetic storms provide episodic, and overall smaller, contributions to the standard deviation. All previous empirical atmospheric models have used the F_{10} and 81-day centered average $\overline{F}_{10}$ proxies as representative of the solar ultraviolet (UV) heating. However, the unmodeled errors derived from satellite drag data all show very large density errors with approximately 27-day periods, representing one solar rotation cycle. These errors are the result of not fully modeling the ultraviolet radiation effects on the thermosphere, which have a one solar rotation periodicity.

Density standard deviations were computed from a comparison of historical density values (Ref. 36.5.3) with model density values over the eight-year period of 1997 through 2004. Only low to moderate solar activity (ap < 35) was considered in the evaluations. The resulting decrease, from 16% to 10%, in the standard deviation at 400 km altitude agrees very well with the results from direct orbit fits using the different models. More detailed comparisons using several different neutral density models were undertaken (Ref. 36.5.4) to globally quantify the improved results obtainable when using the new JB2006 model.

Reference 36.5.15 provides a comparison of the JB 2006 model with several other thermosphere models vs. altitude, latitude, local time, day of year, and solar and geomagnetic conditions.

36.3 Basis of the model

The basis of the new Jacchia-Bowman Empirical Thermospheric Density Model (JB2006) is the CIRA72 (Ref. 36.5.5) model atmosphere. The CIRA72 model integrates the diffusion equations using the Jacchia 71 (Ref. 36.5.6) temperature formulation to compute density values for an input geographical location and solar conditions. The CIRA72 model was first converted to a CIRA "70" model by replacing the CIRA72 equations with equations from the Jacchia 70 (Ref. 36.5.7) model. This was done because the model corrections, for altitudes below 1000 km, obtained for temperature and density are based on the Jacchia 70 model, not the Jacchia 71 (CIRA72) model. New semiannual density equations (Ref. 36.5.2) were developed to replace the Jacchia formulation. New global nighttime minimum exospheric temperature equations, using new solar indices, replaced Jacchia's Tc equation. In addition several other equations to correct errors in the diurnal (local solar time) modeling were also incorporated. Finally, new density factors were incorporated to correct model errors at altitudes from 1000 to 4000 km. These model corrections are discussed in the sections that follow.

36.3.1 Global Nighttime Minimum Exospheric Temperature Equation

The variations in the ultraviolet solar radiation that heats the earth's thermosphere consists of two components, one related to solar rotational modulation of active region emission, and the other long-term evolution of the main solar magnetic field. The passage of active regions across the disk during a solar rotation period produces irradiance variations of approximately 27 days, while the main solar magnetic field evolution produces irradiance variations over approximately 11 years. The 10.7-cm solar flux, F_{10}, has in the past been used to represent these effects. However, new solar indices have been recently (Ref. 36.5.8) used to compute better density variation correlations with ultraviolet radiation covering the entire Far UV as well as the

EUV wavelengths. From the previous solar indices analysis (Ref. 36.5.8) the daily indices selected for this model development include F_{10}, S_{10}, and Mg_{10}.

S_{10}: The NASA/ESA Solar and Heliospheric Observatory (SOHO) research satellite operates in a halo orbit at the Lagrange Point 1 (L1) on the Earth-Sun line, approximately 1.5 million km from the Earth. One of the instruments on SOHO is the Solar Extreme-ultraviolet Monitor (SEM) that has been measuring the 26–34 nm solar EUV emission since launch in December 1995. This integrated 26–34 nm emission has been normalized and converted to sfu through linear regression with F_{10}, producing the new index S_{10}. The broadband (wavelength integrated) SEM 26-34 nm irradiances are EUV line emissions dominated by the chromospheric He II line at 30.4 nm with contributions from other chromospheric and coronal lines. This energy principally comes from solar active regions.

Mg_{10}: The NOAA series of operational satellites, e.g., NOAA 16 and NOAA 17, host the Solar Backscatter Ultraviolet (SBUV) spectrometer that has the objective of monitoring ozone in the Earth's lower atmosphere. The chromospheric Mg II *h* and *k* lines at 279.56 and 280.27 nm, respectively, and the weakly varying photospheric wings (or continuum longward and shortward of the core line emission), are operationally observed by the instrument. The Mg II core-to-wing ratio (cwr) is calculated between the variable lines and nearly non-varying wings. The result is a measure of chromospheric and some photospheric solar active region activity independent of instrument sensitivity change through time, and is referred to as the Mg II cwr, which is provided daily by NOAA Space Environment Center. The Mg II cwr have been used in a linear regression with F_{10} to derive the Mg_{10} index in sfu units.

The new *T*c equation is:

$$Tc = 379.0 + 3.353\ \overline{F}_{10} + 0.358\ \Delta F_{10} + 2.094\ \Delta S_{10} + 0.343\ \Delta Mg_{10} \qquad (1)$$

The $\overline{F}_{10}$ represents the 81-day centered average value of the F_{10} index. The delta values (ΔF_{10}, ΔS_{10}, ΔMg_{10}) represent the difference of the daily and 81-day centered average value of each index. The 81-day (3 solar rotation period) centered value was determined (Ref. 5.8) to be the best long-term average to use.

It was also determined that a lag time of 1 day was the best to use for the F_{10} and S_{10} indices. However, for using the Mg_{10} index the analysis initially centered on using an index E_{SRC} representing the FUV solar radiation from the Schumann-Runge continuum. From the analysis it was determined that the Mg_{10} index could be used as an excellent proxy for the real FUV E_{SRC} index. The best time lag determined for both E_{SRC} and Mg_{10} corresponded to a 5-day lag, which was used in determining the new Tc equation above.

36.3.2 Semiannual density variation

The semiannual amplitude (Ref. 36.5.2) is measured from the yearly minimum, normally occurring in July, to the yearly maximum, normally in October. During solar maximum, the semiannual variation can be as small as 30% at 220 km, and as large as 250% near 800 km. During solar minimum, the maximum variation near 800 km is only 60%. Thus, there is a major difference in amplitudes of the yearly variation from solar minimum to solar maximum, unlike the Jacchia models, which maintain constant amplitude from year to year.

Using daily derived density data from 1979 through 2004 for numerous satellites with perigee heights from 200 km to 1100 km, a quadratic polynomial equation in height and $\overline{F}_{10}$ was developed to represent the semiannual amplitude variation from year to year. An equation in terms of $\overline{F}_{10}$ and day of year phase was also developed to represent the semiannual phase within the year. The new semiannual equations now account for the long term density variability due to the 11-year solar cycle.

36.3.3 Diurnal density correction

Daily temperature corrections, ΔTc, to the Jacchia 1970 atmospheric model were obtained (Ref. 36.5.3) on 79 calibration satellites for the period 1994 through 2003, and 35 calibration satellites for the solar maximum period 1989 through 1990. All the "calibration" satellites have moderate to high eccentricity orbits, with perigee heights ranging from 150 to 500 km. The observed errors to Jacchia 1970 showed variations as a function of local solar time, latitude, height, and F_{10}. The resulting temperature correction equations were developed as a function of these parameters.

36.3.4 High altitude density correction

The analysis method was described previously (Ref. 36.5.9) from the long-term orbit perturbation analysis of West Ford needles' orbits. A semi-analytical integrator was developed (Ref. 36.5.10) using the perturbations in the semi-major axis from atmospheric drag, solar radiation pressure, and earth albedo. The atmospheric drag equations required modification due to the variation of the drag coefficient, which changes greatly depending upon altitude and solar conditions. A non-linear least squares program was developed to fit mean semi-major axis (*a*) values. Density factors were obtained for 25 satellites spanning a period of over 30 years. Approximately 500 density factors were obtained from data from all 25 satellites covering more than 30 years of time. The density factors were then fit as a function of height and $\overline{F}_{10}$ to form the basis for the high altitude correction from 1500 km up to 4000 km.

36.4 Databases

The density data used to develop the new model equations are very accurate daily values (Ref. 36.5.3) obtained from drag analysis of numerous satellites with perigee altitudes of 175 km to 1100 k m. D aily temperature corrections to the US Air Force High Accuracy Satellite Drag Model's (HASDM) (Ref. 36.5.12) modified Jacchia 1970 atmospheric model were obtained on the satellites throughout the period 1978 through 2004. Approximately 120,000 daily temperature values were computed using a special energy dissipation rate (EDR) method (Ref. 36.5.3), where radar and optical observations are fit with special orbit perturbations. For each satellite tracked from 1978 through 2004 approximately 100,000 radar and optical observations were available for the special perturbation orbit fitting. A differential orbit correction program was used to fit the observations to obtain the standard 6 Keplerian elements plus the ballistic coefficient. "True" ballistic coefficients (Ref. 36.5.11) were then used with the observed daily temperature corrections to obtain daily density values. T he daily density computation was validated (Ref. 36.5.3) by comparing historical daily density values computed for the last 30 years for over 30 satellites. The accuracy of the density values was determined from comparisons of geographically overlapping perigee location data, with over 8500 pairs of density values used in the comparisons. The density errors were found to be less than 4% overall, with errors on the order of 2% for values covering the latest solar maximum.

36.5 Publication references

36.5.1 Marcos, F.A., "Accuracy of Atmospheric Drag Models at Low Satellite Altitudes," *Advances in Space Research*, 10, p 417, 1990.

36.5.2 Bowman, B.R., "The Semiannual Thermospheric Density Variation From 1970 to 2002 Between 200-1100km," AAS 2004-174, *AAS/AIAA Spaceflight Mechanics Meeting*, Maui, HI, February, 2004.

36.5.3 Bowman, B.R., etc., "A Method for Computing Accurate Daily Atmospheric Density Values from Satellite Drag Data," AAS 2004-179, *AAS/AIAA Spaceflight Mechanics Meeting*, Maui, HI, Feb, 2004.

36.5.4 Marcos, F., etc., "Accuracy of Earth's Thermospheric Neutral Density Models," AIAA 2006-6167, *AIAA/AAS Astrodynamics Specialist Conference*, Keystone, CO, August, 2006.

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36.5.8 Bowman, B.R., etc., "Improvements in Modeling Thermospheric Densities Using New EUV and FUV Solar Indices," AAS 2006-237, *AAS/AIAA Spaceflight Mechanics Meeting*, Tampa, Fl, January, 2006.

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Barbara, CA, February, 2001.

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36.5.12 Storz, M.F., etc., “High Accuracy Satellite Drag Model (HASDM),” AIAA 2002-4886, *AIAA/AAS Astrodynamics Specialist Conference*, Monterey, Ca, August, 2002.

36.5.13 Bowman, B.R., etc., “A New Empirical Thermospheric Density Model JB2006 Using New Solar Indices,” AIAA 2006-6166, *AIAA/AAS Astrodynamics Specialist Conference*, Keystone, CO, August, 2006.

36.5.14 Bowman, Bruce R., W. Kent Tobiska, Frank A. Marcos, and Cesar Valladares, “The JB 2006 Empirical Thermosphere Density Model”, Journal of Atmospheric and Solar-Terrestrial Physics, Elsevier Ltd, 2007.

36.5.15 Marcos, Frank A., Bruce R. Bowman, and Robert E. Sheehan, “Accuracy of Earth’s Thermospheric Neutral Density Models, AIAA Paper Number AIAA 2006-6167, American Institute of Aeronautics and Astronautics, Reston, VA 20006.

36.6 Dates of development, authors and sponsors

36.6.1 Dates: 2006

36.6.2 Authors: Bowman, Bruce R., Tobiska, W. Kent, and Frank A. Marcos

36.6.3 Sponsors: Department of Defense, U. S. Air Force Space Command

36.7 Model codes and sources

A detailed description (Ref. 36.5.13) of the model, Fortran source code, new solar indices and published papers describing the model equations can be obtained at the web site below, or by contacting Bruce R. Bowman, AFSPC/A9A, (719) 556-3710, bruce.bowman@peterson.af.mil.

JB2006 model web site: http://sol.spacenvironment.net/~JB2006/

37 Jacchia-Bowman 2008 (JB2008) empirical thermospheric density model

37.1 Model content

The JB2008 empirical thermospheric density model was developed starting from the improved Jacchia-Bowman 2006 model as the basis for the density modeling improvements. Additional solar indices based on orbit-based sensor data were used for the solar irradiances in the extreme and far ultraviolet wavelengths. A new geomagnetic index Dst was used to replace the older geomagnetic ap index. New exospheric temperature and semiannual density corrections were developed to represent the major thermospheric density variations. The new JB2008 model was validated through comparisons of accurate daily density drag data previously computed for numerous satellites at altitudes of 200-1100 km, and from highly accurate CHAMP and GRACE satellite accelerometer density data.

37.2 Model uncertainties and limitations

Density model errors on the order of 15%-20% one standard deviation have been recognized for all empirical models (Ref. 37.5.1) developed since the mid 1960s. These large density standard deviations correspond to maximum density errors of approximately 40-60% as observed in satellite drag data. There are several main reasons for these consistently large values. One is the result of not modeling the semiannual density variation (Ref. 37.5.2, 37.5.10) as a function of solar activity, another results from not modeling the full thermospheric heating from solar ultraviolet radiation, and finally large short-term density errors result from not correctly modeling geomagnetic storm variations. Except for the Jacchia-Bowman 2006 model (Ref. 37.5.9) all previous empirical atmospheric models have used the F_{10} and 81-day centered average $\overline{F}_{10}$ proxies as representative of the solar ultraviolet (UV) heating. However, the unmodeled errors derived from satellite drag data all show very large density errors with approximately 27-day periods, representing one solar rotation cycle. These errors are the result of not fully modeling the ultraviolet radiation effects on the thermosphere, which have a one solar rotation periodicity.

Figure 1 shows computed density-to-model ratios for the JB2006 and JB2008 models, the Jacchia 70 model, and the NRLMSIS-2000 model. These ratios were obtained by using the computed 3-hour spherical harmonic HASDM (Ref. 5.8) temperature correction coefficients, and computing density values at 10 minute steps along the CHAMP reference orbits obtained for 2001 through 2007. These HASDM-to-Model ratios were then binned by $\overline{F}_{10}$. It can be readily seen that all the previous models using just $\overline{F}_{10}$ for the 11-year cycle variations show a significant decrease in the ratios at solar minimum conditions. The JB2008 model does much better at representing the solar minimum density decrease, although it still does not completely capture the full density variation. Figure 2 shows the density model standard deviations binned again by $\overline{F}_{10}$. The much larger sigma at solar minimum (very low $\overline{F}_{10}$) is a direct result of the model ratio errors at low $\overline{F}_{10}$. The new JB2008 model shows significant improvements over all other models in representing the solar EUV thermospheric heating. Figure 3 shows 1-standard deviation model density errors as a function of geomagnetic storm magnitude. The values were obtained as percent density differences from the calibrated orbit averaged accelerometer data, from both CHAMP and GRACE, and the different model orbit averaged values. The results show that the JB2008 model is a major improvement over modeling density changes during large geomagnetic storms. The HASDM modeling is the best at under a 10% sigma, which is expected since it accounts for real time density changes. The J70 modeling is the worst since it is based on computing a density from a single 3-hour a_p value, while the MSIS model uses a history of a_p values for 57 hours prior to the time of interest.

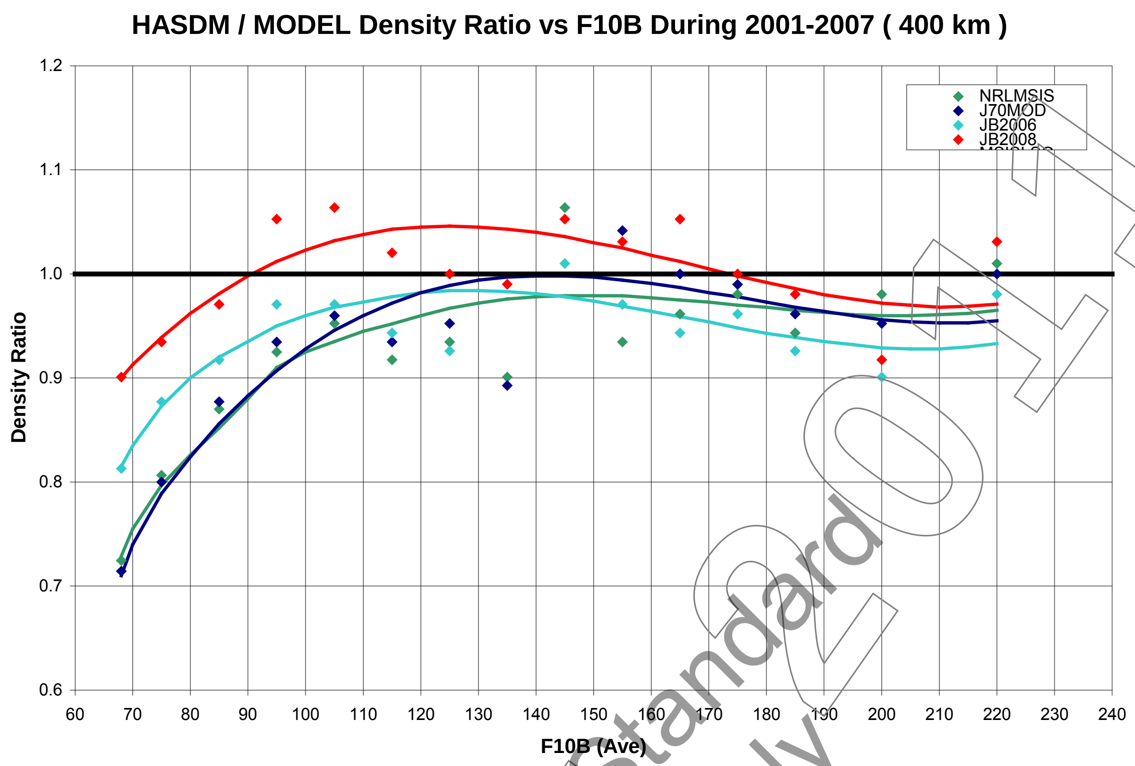

Figure 1 — HASDM-to-Model density ratios at 400km altitude as a function of $\overline{F}_{10}$ (F10B)

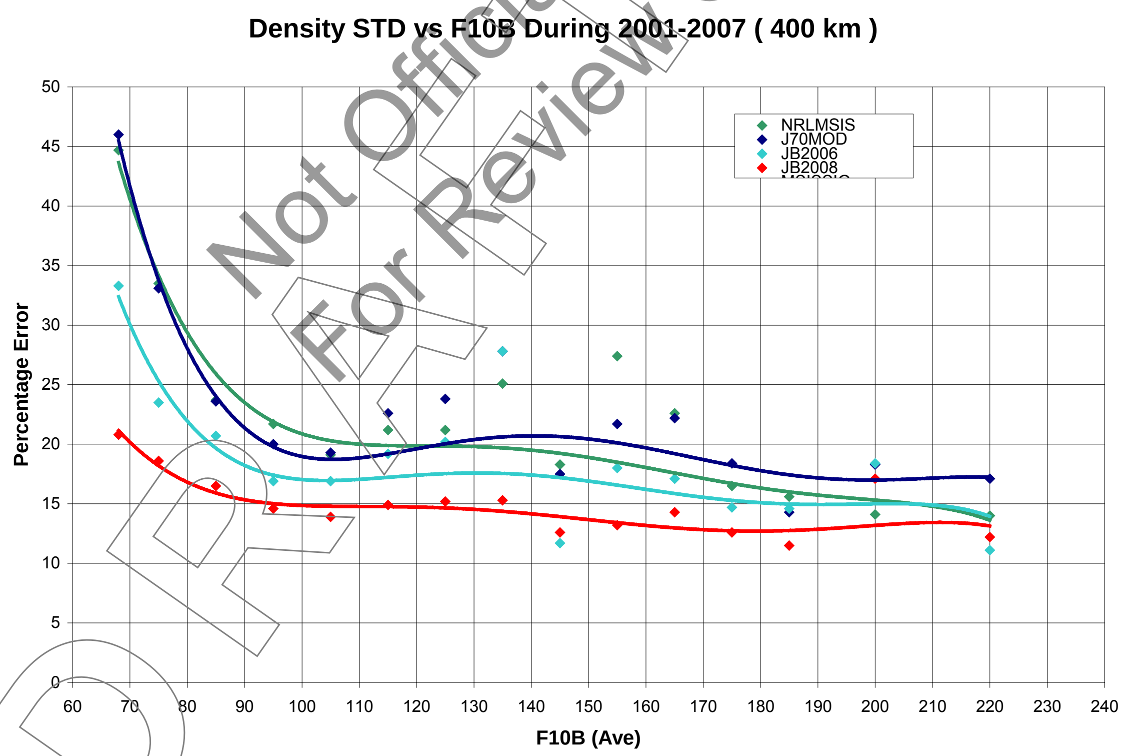

Figure 2 — Density percentage errors (1 standard deviation) from model density values at 400 km altitude compared to HASDM density values

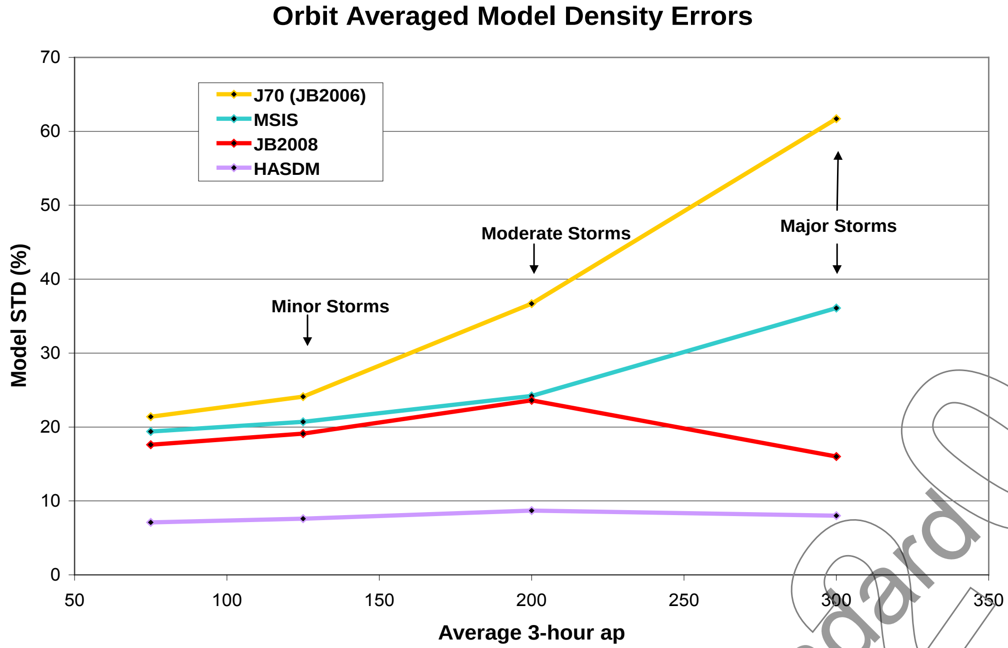

Figure 3 — Model density 1-standard deviation errors as a function of a_p ranges representing storm magnitudes. Values are based on orbit averaged percent density differences between the calibrated accelerometer density data, from both CHAMP and GRACE, and the different model values. JB2006 uses the same geomagnetic storm modeling as J70.

37.3 Basis of the model

The new Jacchia-Bowman Empirical Thermospheric Density Model (JB2008) was developed starting from the Jacchia-Bowman 2006 model which was based on the CIRA72 (Ref. 37.5.4) model atmosphere. The CIRA72 model integrates the diffusion equations using the Jacchia 71 (Ref. 37.5.5) temperature formulation to compute density values for an input geographical location and solar conditions. New semiannual density equations (Ref. 37.5.10) were developed to replace the older $\overline{F}_{10}$ formulation. New global nighttime minimum exospheric temperature equations, using additional solar indices, replaced the JB2006 Tc equation. In addition a new geomagnetic index Dst was used to replace the old ap index, and new temperature variation equations were developed using this new index. These model corrections are discussed in the sections that follow.

37.3.1 Global nighttime minimum exospheric temperature equation

The variations in the ultraviolet solar radiation that heats the earth's thermosphere consists of two components, one related to solar rotational modulation of active region emission, and the other long-term evolution of the main solar magnetic field. The passage of active regions across the disk during a solar rotation period produces irradiance variations of approximately 27 days, while the main solar magnetic field evolution produces irradiance variations over approximately 11 years. The 10.7-cm solar flux, F_{10}, has in the past been used to represent these effects. However, new solar indices have been recently (Ref. 37.5.8) used to compute better density variation correlations with ultraviolet radiation covering the entire Far UV as well as the EUV wavelengths. From the previous solar indices analysis (Ref. 37.5.6) the daily indices selected for this model development include F_{10}, S_{10}, Mg_{10}, and Y_{10}.

S_{10}: The NASA/ESA Solar and Heliospheric Observatory (SOHO) research satellite operates in a halo orbit at the Lagrange Point 1 (L1) on the Earth-Sun line, approximately 1.5 million km from the Earth. One of the instruments on SOHO is the Solar Extreme-ultraviolet Monitor (SEM) that has been measuring the 26–34 nm solar EUV emission since launch in December 1995. This integrated 26–34 nm emission has been normalized and converted to sfu through linear regression with F_{10}, producing the new index S_{10}. The broadband (wavelength integrated) SEM 26-34 nm irradiances are EUV line emissions dominated by the chromospheric He II line at 30.4 nm with contributions from other chromospheric and coronal lines. This energy principally comes from solar active regions.

Mg_{10}: The NOAA series of operational satellites, e.g., NOAA 16 and NOAA 17, host the Solar Backscatter Ultraviolet (SBUV) spectrometer that has the objective of monitoring ozone in the Earth's lower atmosphere. The chromospheric Mg II *h* and *k* lines at 279.56 and 280.27 nm, respectively, and the weakly varying photospheric wings (or continuum longward and shortward of the core line emission), are operationally observed by the instrument. The Mg II core-to-wing ratio (cwr) is calculated between the variable lines and nearly non-varying wings. The result is a measure of chromospheric and some photospheric solar active region activity independent of instrument sensitivity change through time, and is referred to as the Mg II cwr, which is provided daily by NOAA Space Environment Center. The Mg II cwr have been used in a linear regression with F_{10} to derive the Mg_{10} index in sfu units.

Y_{10}: The operational GOES X-ray Spectrometer (XRS) instrument provides the 0.1–0.8 nm solar X-ray emission. X-rays in the 0.1–0.8 nm range come from the cool and hot corona and are typically a combination of both very bright solar active region background that varies slowly (days to months) plus flares that vary rapidly (minutes to hours), respectively. The photons arriving at Earth are primarily absorbed in the mesosphere and lower thermosphere (80–90 km) by molecular oxygen and nitrogen where they ionize those neutral constituents to create the ionospheric D-region. An index of the solar X-ray active region background, without the flare component, has been developed. This is called the Xb10 index. The 0.1-0.8 nm X-rays are a major energy source in these atmospheric regions during high solar activity but relinquish their dominance to the competing hydrogen (H) Lyman-α emission during moderate and low solar activity. Lyman-α is also deposited in the same atmospheric regions, is created in the solar upper chromosphere and transition region, and demarcates the EUV from the FUV spectral regions. It is formed primarily in solar active regions, plage, and network; the photons, arriving at Earth, are absorbed in the mesosphere and lower thermosphere where they dissociate nitric oxide (NO) and participate in water (H2O) chemistry. Lyman-α has been observed by the SOLSTICE instrument on the UARS and SORCE NASA research satellites as well as by the SEE instrument on NASA TIMED research satellite Since these two solar emissions are competing drivers to the mesosphere and lower thermosphere, we have developed a mixed solar index Y_{10} of the Xb10 and Lyman-α (Lyα). It is weighted to reflect mostly Xb10 during solar maximum and to reflect mostly Lyman-α during moderate and low solar activity. The independent, normalized $\overline{F}_{10}$ is used as the weighting function and multiplied with the Xb10 and Lyman-α as fractions to their solar maximum values.

The new JB2008 midnight exospheric Tc equation is:

$$Tc = 392.4 + 3.227\ \overline{F}_s + 0.298\ \Delta F_{10} + 2.259\ \Delta S_{10} + 0.312\ \Delta M_{10} + 0.178\ \Delta Y_{10} \qquad (1)$$

The delta values (ΔF_{10}, ΔS_{10}, ΔMg_{10}, ΔY_{10}) represent the difference of the daily and 81-day centered average value of each index. The 81-day (3 solar rotation period) centered value was determined (Ref. 37.5.6) to be the best long-term average to use.

It was determined that a lag time of 1 day was the best to use for the F_{10} and S_{10} indices. For using the M_{10} index the analysis determined that the best (least squares minimum) lag time was 2 days, and for Y_{10} a best lag time of 5 days was obtained. Initially for the JB2006 model that did not use Y_{10} the lag time for M_{10} was determined to be 5 days. The M_{10} index was accounting for the longer lag times in the lower thermosphere. However, with the addition of the low altitude Y_{10} index the M_{10} lag time became shorter and the longer low altitude absorption lag time was captured by the combination of absorption of X-Rays and Lyman-alpha at altitudes around 80-90 km.

37.3.2 Semiannual density variation

The semiannual amplitude (Ref. 37.5.2, 37.5.10) is measured from the yearly minimum, normally occurring in July, to the yearly maximum, normally in October. During solar maximum, the semiannual variation can be as small as 30% at 220 km, and as large as 250% near 800 km. During solar minimum, the maximum variation near 800 km is only 60%. Thus, there is a major difference in amplitudes of the yearly variation from solar minimum to solar maximum, unlike the Jacchia models, which maintain constant amplitude from year to year. Using daily derived density data from 1979 through 2006 for numerous satellites with perigee heights from 200 km to 1100 km the following results concerning the thermospheric semiannual density variation have been obtained:

1. The semiannual effect is worldwide, and within each year the maxima and minima occur at the same dates independent of latitude, local solar time, or altitude.

2. The yearly amplitude can change from year to year by 60% during solar minimum to over 250% during solar maximum.
3. The time span between the July minimum and the October maximum dates can vary by as much as 80 days, especially during solar maximum.
4. The yearly variation in amplitude and phase of the semiannual variation is highly correlated with solar activity.
5. A combination of solar EUV and FUV indices is required to accurately model the semiannual amplitude and phase variations observed from year to year.

The JB2008 model includes a new 81-day average solar index F_{SM} that is computed using a combination of the 81-day average values of F_{10}, S_{10}, and Mg_{10}. Using this new index in new semiannual density variation equations results in extremely good modeling of the year to year amplitude and phase changes that have been observed from the satellite data.

37.3.3 Geomagnetic storm density correction

The Disturbance Storm Time (Dst) index is primarily used to indicate the strength of the geomagnetic storm-time ring current in the inner magnetosphere. During the main phase of magnetic storms, the ring current becomes highly energized and produces a southward-directed magnetic field perturbation at low latitudes on the Earth's surface. This is opposite to the normal northward-directed main field. The Dst index is determined from hourly measurements of the magnetic field made at four points around the Earth's equator. Most magnetic storms begin with sharp rises in Dst in response to increased solar wind pressure. Following a southward turning of the interplanetary magnetic field, Dst decreases as ring current energy increases during the storm's main phase. During the recovery phase the ring current energy decreases and Dst increases until the storm's end.

Use of Dst as a parameter of the energy deposited in the thermosphere during magnetic storms is more accurate than the use of the a_p index. The 3-hour a_p is an indicator of general magnetic activity over the Earth and responds primarily to currents flowing in the ionosphere and only secondarily to magnetospheric variations. The a_p index represents magnetic variations at 50 degrees magnetic latitude. Therefore, it may not reflect the energy input at auroral latitudes too well.

The thermosphere acts during storm periods as a driven-but-dissipative system whose dynamics is represented by a differential equation, with the changes in exospheric temperature change given as a function of Dst. To determine the exospheric temperature, and thereby the thermospheric density distribution at any time in a storm, it is necessary to integrate the differential equation for dTc starting at the storm commencement and proceeding throughout the entire storm period. For the JB2008 model new equations for the exospheric temperature change during a geomagnetic storm were developed using the Dst index as the geomagnetic index. High precision accelerometer density data from the CHAMP and GRACE missions were used for the development and validation of the new temperature equation coefficients to correlate the temperature, and thus density, change with the integrated Dst values.

37.4 Databases

The density data used to develop the new model equations are very accurate daily values (Ref. 37.5.3) obtained from drag analysis of numerous satellites with perigee altitudes of 200 km to 1100 km. Daily temperature corrections to the US Air Force High Accuracy Satellite Drag Model's (HASDM) (Ref. 37.5.8) modified Jacchia 1970 atmospheric model were obtained on the satellites throughout the period 1979 through 2006. Approximately 225,000 daily temperature values were computed using a special energy dissipation rate (EDR) method (Ref. 37.5.3), where radar and optical observations are fit with special orbit perturbations. For each satellite tracked from 1979 through 2006 approximately 100,000 radar and optical observations were available for the special perturbation orbit fitting. A differential orbit correction program was used to fit the observations to obtain the standard 6 Keplerian elements plus the ballistic coefficient. "True" ballistic coefficients (Ref. 37.5.7) were then used with the observed daily temperature corrections to obtain daily density values. The daily density computation was validated (Ref. 37.5.3) by comparing historical daily density values computed for the last 30 years for over 30 satellites. The accuracy of the density values was determined from comparisons of geographically overlapping perigee location data, with over 8500 pairs of density values used in the comparisons. The density errors were found to be less than 4% overall, with errors on the order of 2% for values covering the latest solar maximum. Additional the CHAMP and GRACE accelerometer density databases (5 to 10 sec values) were used for 2001 through 2005 time periods for geomagnetic storm modeling validation.

37.5 Publication references

37.5.1 Marcos, F.A., "Accuracy of Atmospheric Drag Models at Low Satellite Altitudes," *Advances in Space Research*, 10, p 417, 1990.

37.5.2 Bowman, B.R., "The Semiannual Thermospheric Density Variation From 1970 to 2002 Between 200-1100km," AAS 2004-174, *AAS/AIAA Spaceflight Mechanics Meeting*, Maui, HI, February, 2004.

37.5.3 Bowman, B.R., etc., "A Method for Computing Accurate Daily Atmospheric Density Values from Satellite Drag Data," AAS 2004-179, *AAS/AIAA Spaceflight Mechanics Meeting*, Maui, HI, Feb, 2004.

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37.5.8 Storz, M.F., etc., "High Accuracy Satellite Drag Model (HASDM)," AIAA 2002-4886, *AIAA/AAS Astrodynamics Specialist Conference*, Monterey, Ca, August, 2002.

37.5.9 Bowman, B.R., etc., "A New Empirical Thermospheric Density Model JB2006 Using New Solar Indices," AIAA 2006-6166, *AIAA/AAS Astrodynamics Specialist Conference*, Keystone, CO, August, 2006.

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37.6 Dates of development, authors and sponsors

37.6.1 **Dates:** 2008

37.6.2 **Authors**: Bowman, Bruce R., W. Kent Tobiska, Frank A. Marcos, Cheryl Y. Huang, and Chin S. Lin

37.6.3 **Sponsors:** Department of Defense, U. S. Air Force Space Command

37.7 Model codes and sources

A detailed description (Ref. 37.5.11) of the model, Fortran source code, new solar indices, and published papers describing the model equations can be obtained at the web site below, or by contacting Bruce R. Bowman, AFSPC/A9A, (719) 556-3710, bruce.bowman@peterson.af.mil.

JB2008 model web site: http://sol.spacenvironment.net/~JB2008/

38 NASA Marshall engineering thermosphere model, version 2.0 (MET-V2.0), 2002

38.1 Model content

The *NASA Marshall Engineering Thermosphere (MET) Model-Version 2.0* is a product of the Science Directorate, NASA Marshall Space Flight Center, and consists of a technical report describing the computer program and subroutines which provide information on atmospheric properties for the altitude range 90 km to 2500 km as a function of latitude, longitude, time, and solar flux and geomagnetic indices. For a given latitude, longitude, and time, the NASA MET-V2.0 model yields values for the following parameters: Exospheric temperature (K); Local temperature (K); N_2 number density (m^{-3}); O_2 number density (m^{-3}); O number density (m^{-3}); Ar number density (m^{-3}); He number density (m^{-3}); H number density (m^{-3}); Average molecular weight (kg $kmol^{-1}$); Total mass density (kg m^{-3}); Log_{10} (mass density); Total Pressure (Pa); Local gravitational acceleration (m s^{-2}); Ratio of specific heats; Pressure scale height (m); Specific heat at constant pressure (m^2 s^{-2} K^{-1}); and Specific heat at constant volume (m^2 s^{-2} K^{-1}).

38.2 Model uncertainties and limitation

The NASA MET-V2.0 model is based upon the models developed by L. G. Jacchia of the Smithsonian Astrophysical Observatory. The historical development of the Jacchia models and subsequent NASA versions may be found in Reference 38.5.3. Data from satellite drag calculations were used to formulate the empirical functions used to derive the atmospheric parameters. Drag-based models are deficient in the way in which they represent the large variations in total density that are associated with short term (hourly-daily time periods) geomagnetic disturbances. The MET-V2.0 model reflects the J70/71 models' accuracy results at the approximate 15-percent level for estimating the neutral density (Ref. 38.5.4). The technical report (Ref. 38.5.3) also addresses the issues associated with the MET-V2.0 model's application for After-the-Fact, Real-Time, and Future calculations of the total neutral density. The major source of uncertainty for future thermospheric neutral density calculations is the uncertainty in the estimation of future solar EUV heat input as represented by the solar flux index used as input to the model. (Ref. 38.5.5) Some thermosphere models are based on data from satellite-borne mass spectrometers, accelerometers, and other sensors represent composition and changes in composition more accurately than do models based upon drag data. However, they are for the most part, not significantly better in their representation of the total neutral density. These latter models have used data from satellite-borne mass spectrometers, accelerometers and other instruments.

With regard to recent assessment of modeling errors associated with semiannual density variation magnitudes as function of solar cycle years, see Reference 38.5.4 in the Jacchia J70 Static Model write-up. Reference 38.5.7 provides a comparison of the MET-V2.0 with several other thermosphere models vs. altitude, latitude, local time, day of year, and solar and geomagnetic conditions.

38.3 Basis of the model

The MET-V2.0 model is a semi-empirical model using the static diffusion method with coefficients obtained from satellite drag analyses. It is based on the 1988 version of MET (Ref. 38.5.1 and 38.5.2) and work done on the 1999 version (Ref. 38.5.6), developed from the Jacchia series of models. With the proper input parameters an approximate exospheric temperature can be calculated. With the exospheric temperature specified, the temperature can be calculated for any altitude between 90 and 2,500 km from an empirically determined temperature profile. Density between 90 and 105 km is calculated by integration of the barometric equation. In the upper thermosphere, above 105 km, the density computation is accomplished by integrating the diffusion equation.

38.4 Databases

The databases for the MET model are identical to those used in the 1970 and 1971 "Static Models of the Thermosphere and Exosphere with Empirical Temperature Profiles" by L. G. Jacchia of the Smithsonian Astrophysical Observatory, Cambridge, Massachusetts, (SAO Special Reports 313 and 332). The databases used by Jacchia were derived from various satellite drag data. The 1971 model attempted to meet, as closely as possible, the composition and density data derived for a height of 150 km by U. von Zahn (*J. Geophys. Res., 75,* 5517-5527, 1970) and based upon all the available mass spectrometer and EUV absorption data.

38.5 Publication references

38.5.1 Hickey, M.P., "The NASA Marshall Engineering Thermospheric Model" NASA CR-179359, July 1988.

38.5.2 Hickey, M. P., "An Improvement in the Numerical Integration Procedure used for the NASA Marshall Engineering Thermosphere Model", NASA CR-179389, August 1988.

38.5.3 Owens, J. K., "NASA Marshall Engineering Thermosphere Model-Version 2.0", NASA TM-2002-211786, June 2002.

38.5.4 Marcos, F. A., J. N. Bass, C. R. Baker, and W. S. Borer: "Neutral Density Models for Aerospace Applications," AIAA Paper 94-0589, 32nd Aerospace Sciences Meeting and Exhibit, Reno, NV, January 10-13, 1994.

38.5.5 Vaughan, W. W., J. K. Owens, K. O. Niehuss, and M. A. Shea: "The NASA Marshall Solar Activity Model For Use In Predicting Satellite Lifetime," *Advances in Space Research,* Vol. 23, No. 4, 1999.

38.5.6 Owens, J. K., Niehuss, K. O., Vaughan, W. W., and Shea, M. A. (2000): "NASA Marshall Engineering Thermosphere Model-1999 Version (MET-99) and Implications for Satellite Lifetime Predictions," COSPAR, Advances in Space Research, 26(1), 157-162

38.5.7 Marcos, Frank A., Bruce R. Bowman, and Robert E. Sheedan, "Accuracy of Earth's Thermospheric Neutral Density Models", AIAA Paper Number AIAA 2006-6167, American Institute of Aeronautics and Astronautics, Reston, VA 20006.

38.6 Dates of development, authors and sponsors

38.6.1 Dates: 2002, based upon work done during previous years

38.6.2 Authors: Jerry K. Owens

38.6.3 Sponsors: National Aeronautics and Space Administration, Marshall Space Flight Center

38.7 Model codes and sources

The monthly Marshall Solar Activity Future Estimation (MSAFE) report provides expected 13-month Zurich smoothed solar and geomagnetic activity based on the most recent monthly mean data for use in the MET 2.0 model. It can be downloaded from http://sail.msfc.nasa.gov

Copies of the computer program for the MET V2.0 model are available upon request to the author, Jerry K. Owens, NASA Marshall Space Flight Center, Huntsville, AL 35812. (Jerry.K.Owens@nasa.gov) The model can also be addressed on the ESA Space Environment Information System (SPENVIS) at http://www.spenvis.oma.be/spenvis

39 NASA Marshall engineering thermosphere model version 2007 (MET-2007), 2007

39.1 Model content

The NASA Marshall Engineering Thermosphere Model version 2007 (MET-2007) is a product of the Natural Environments Branch, NASA Marshall Space Flight Center. Like previous versions of MET, the model consists of a computer program and subroutines which provide information on atmospheric properties for the altitude range 90 to 2500 km as a function of latitude, longitude, time, and solar flux and geomagnetic indices. For a given latitude, longitude, and time, the MET-2007 model yields values for the following parameters: exospheric temperature (K); local temperature (K); N_2 number density (m^{-3}); O_2 number density (m^{-3}); O number density (m^{-3}); Ar number density (m^{-3}); He number density (m^{-3}); H number density (m^{-3}); average molecular weight (kg/kmol); total mass density (kg/m^3); total pressure (pa); ratio of specific heats; pressure scale height (m); specific heat at constant pressure (J / kg K); and specific heat at constant volume (J / kg K). MET-2007 retains the capability of the previous version (MET-2.0) but also contains several improvements (Ref. 39.5.5) which include:

39.1.1 Corrections for inconsistency between constituent number density and mass density.

39.1.2 Representation of gravity above an oblate spheroid Earth shape, rather than using a spherical Earth approximation.

39.1.3 Treatment of day-of-year as a continuous variable in the semi-annual term, rather than as an integer day.

39.1.4 Treatment of year as either 365 or 366 days in length (as appropriate), rather than all years having length 365.2422 days.

39.1.5 Allows continuous variation of time input, rather than limiting time increments to integer minutes.

39.2 Model uncertainties and limitations

Since the MET-2007 is a formulation of the Jacchia 1970 (J70) model, the MET-2007 model reflects the J70 models' accuracy for estimating the neutral density, which is approximately 15-percent one standard deviation (Ref. 39.5.6). The major source of uncertainty for calculating future thermospheric neutral density values is the uncertainty in determining the future solar EUV radiation flux as represented by the solar 10.7 cm radio flux index used as input to the model (Ref. 39.5.11). Also, models based on satellite drag tend to be deficient in the way they represent variations in total density that are associated with short-term (hourly to daily time periods) thermospheric disturbances. Errors associated with modeling the semiannual density variation can also be present and tend to vary with the solar cycle. See the J70 Static Model section in Ref. 39.5.6 for an assessment of these errors. Also, Ref. 39.5.9 addresses the issues associated with the MET model's application for after-the-fact, real-time, and future calculations of the total neutral density. Some thermosphere models are based on data from satellite-borne mass spectrometers, accelerometers and other sensors. These models tend to represent composition and changes in composition more accurately than do models based upon drag data. However, they are for the most part not significantly better in their representation of the total neutral density. Ref. 39.5.7 provides a comparison of the MET model with several other thermosphere models vs. altitude, latitude, local time, day of year, and solar and geomagnetic conditions.

39.3 Basis of the model

The NASA MET-2007 model is based upon the J70 model (Ref. 39.5.3) with the inclusion of equations that characterize the effects of seasonal latitudinal density variations of density below 170 km altitude and that of helium above 500 km obtained from the Jacchia 1971 (J71) model (Ref. 39.5.4). Data from satellite drag calculations were used to formulate the empirical functions used to derive the atmospheric parameters. With the proper input parameters the model calculates an approximate exospheric temperature. With the exospheric temperature specified, the temperature can be calculated for any altitude between 90 and 2,500 km from an empirically determined temperature profile. Density between 90 and 105 km is calculated by integration of the barometric equation. In the thermosphere above 105 km the density is determined by the integration of the diffusion equation. The historical development of the Jacchia models and subsequent NASA versions may be found in Ref. 39.5.10 and 39.5.9. This current MET version is an extension of the original 1988 MET formulation (Ref. 39.5.1, 39.5.2) and includes modifications incorporated in the 1999 and 2.0 versions (Ref. 39.5.8, 39.5.9) and improvements described in Reference 39.5.5.

39.4 Databases

The databases for the MET model are identical to those in the J70 and J71 models. The databases used by Jacchia were derived from various satellite drag data. The J71 model attempted to meet, as closely as possible, the composition and density data derived for a height of 150 km by von Zahn (Ref. 39.5.12) based upon all the available mass spectrometer and EUV absorption data at the time.

39.5 Publication references

39.5.1 Hickey, M. P., "The NASA Marshall Engineering Thermosphere Model," NASA CR-179359, July 1988.

39.5.2 Hickey, M. P., "An improvement in the Numerical Integration Procedure Used for the NASA Marshall Engineering Thermosphere Model," NASA CR-179389, August 1988.

39.5.3 Jacchia, L. G., "New Static Models of the Thermosphere and Exosphere with Empirical Temperature Profiles," SAO Special Report 313 Smithsonian Astrophysical Observatory, Cambridge, Massachusetts, 1970.

39.5.4 Jacchia, L. G., "Revised Static Models of the Thermosphere and E xosphere with Empirical Temperature Profiles," SAO Special Report 332 Smithsonian Astrophysical Observatory, Cambridge, Massachusetts, 1971.

39.5.5 Justus, C. G., Duvall, A., and Keller, V. W. (2006): "Trace Constituent Updates in the Marshall Engineering Thermosphere and G lobal Reference Atmospheric Model," COSPAR, Advances in Space Research, Vol. 38, 2429-2432.

39.5.6 Marcos, F. A., J. N. Bass, C. R. Baker, and W. S. Borer: "Neutral Density Models for Aerospace Applications," AIAA paper 94-0589, 32nd Aerospace Sciences Meeting and Exhibit, Reno NV, January 10-13, 1994.

39.5.7 Marcos, Frank A., Bruce R. Bowman, and Robert E. Sheedan, "Accuracy of Earth's Thermospheric Neutral Density Models", AIAA Paper Number AIAA 2006-6167, American Institute of Aeronautics and Astronautics, Reston, VA 20006.

39.5.8 Owens, J. K., K. O. Niehuss, W. W. Vaughan, and M. A. Shea: "NASA Marshall Engineering Thermosphere Model-1999 Version (MET-99) and Implications for Satellite Lifetime Predictions," COSPAR, Advances in Space Research, Vol. 26, No. 1, 2000.

39.5.9 Owens, J. K., "NASA Marshall Engineering Thermosphere Model-Version 2.0," NASA TM-2002-211786, June 2002.

39.5.10 Smith, R. E., "The Marshall Engineering Thermosphere (MET) Model Volume I: Technical Description," NASA CR-207946, May 1998.

39.5.11 Vaughan, W.W., J. K. Owens, K. O. Niehuss, and M. A. Shea: "The NASA Marshall Solar Activity Model for Use in Predicting Satellite Lifetime," Advances in Space Research, Vol. 23, No. 4, 1999.

39.5.12 Von Zahn, U., "Neutral Air Density and Composition at 150 km," *J. Geophys. Res., 75,* 5517-5527, 1970.

39.5.13 Justus, C. G. and F. W. Leslie: "The NASA MSFC Earth Global Reference Atmosphere Model—2007 Version, " NASA/TM—2008—215581, November 2008.

39.6 Dates of development, authors and sponsors

39.6.1 **Dates:** 2007, based upon work done in previous years

39.6.2 **Authors:** Natural Environments Branch, NASA Marshall Space Fight Center

39.6.3 **Sponsors:** NASA Marshall Space Flight Center

39.7 Model codes and sources

The monthly Marshall Solar Activity Future Estimation (MSAFE) report provides expected 13-month Zurich smoothed solar and geomagnetic activity based on the most recent monthly mean data for use in the MET-2007 model. It can be downloaded from http://sail.msfc.nasa.gov

Copy of the computer program for the MET-2007 model is available upon request to David L. Edwards, Natural Environments Branch, NASA Marshall Space Flight Center, Huntsville, AL 35812 (David.L.Edwards@nasa.gov).

40 AFGL model of atmospheric structure, 70 to 130 km, 1987

40.1 Model content

The *Model of Atmospheric Structure, 70 to 130 km* consists of a report published and distributed by the Air Force Geophysics Laboratory. It gives monthly mean values of temperatures, pressure, density and constituent number density. The altitude range is 70 to 130 km and the latitude range is 80 deg S to 80 deg N. Monthly mean longitude values of temperature, pressure and density are tabulated at 20 deg latitude intervals for all months as well as for low and medium conditions of solar and geomagnetic activity: Appendices are given with geomagnetic Ap index values of 4 and 132 and the F10.7 solar radio fluxes of 70 and 150 x 10^{-2} W m^{-22} Hz^{-1}. Formulas by which temperature, pressure and density variations may be computed are included. An intercomparison of the temperature data from the sources used to develop the model is also made.

40.2 Model uncertainties and limitations

40.2.1 The only data used in the altitude range 75 to 125 km are temperature. Density data (which are relatively sparse) are not used. Both density and composition values can be computed from the model. No modeling of winds is included.

40.2.2 Local time dependence at 130 km is that given by MSIS-86 and at 70 km the variation is zero. At intermediate altitudes the dependence is determined by interpolation. Tidal components are not included.

40.2.3 Algorithms are not provided for longitudinal variations in the altitude region 70-130 km. At 70 and 130 km the variation are those given by the respective models and at intermediate altitudes are obtained by interpolation.

40.2.4 The models at 70 km have no dependence on geomagnetic or solar activity. At 130 km the dependences are those given in MSIS-86. The variations at intermediate altitudes are obtained by interpolation.

40.3 Basis of the model

The zonal mean values are derived from tabulations of temperature and other data obtained from an earlier northern hemisphere rocket-based reference atmosphere (CIRA 1972, Part 2) and on rocket and incoherent scatter data reviewed by Forbes (1984), Alcayde *et al* (1979), Wand (1983), and Forbes and Groves (1987) see section 4 for references). The model is constructed such that it can be linked to given lower and upper altitude models in temperature and other properties with respect to altitude. In this report the model has been derived to connect with the *Global Reference Atmosphere from 18 to 80 km* at 70 km and with MSIS-86 models at 130 km.

40.4 Databases

The model databases are contained in the following documents:

40.4.1 Alcayde, D., J. Fontanari, G. Kockarts, P. Bauer, and R. Bernard, "Temperature, Molecular Nitrogen Concentration, and Turbulence in the Lower Thermosphere Inferred from Incoherent Scatter Data," *Ann. Geophys., 35,* 41-51, 1979.

40.4.2 CIRA 1972: see pp. 1-4 of this document.

40.4.3 Forbes, J. M., "Temperature Structure of the 80 to 120 km Region," presented at the XXV COSPAR Meeting, Graz, Austria, 1984

40.4.4 Forbes, J. M., "Atmospheric Structure between 80 to 120 km," *Adv. Space Res., 7,* 135-141, 1987.

40.4.5 Wand, R. H., "Lower Thermospheric Structure from Millstone Hill Incoherent Scatter Radar Measurements, 2. Semidiurnal Temperature Component," *J. Geophys. Res., 88,* 7211-7224, 1983.

40.5 Publication references

Groves, G. V., "Modeling of Atmospheric Structure, 70 to 130 km," Air Force Geophysics Laboratory Report AFGL-87-0226, 15 July 1987.

40.6 Dates of development, authors and sponsors

40.6.1 Dates: 1987

40.6.2 Authors: G. V. Groves

40.6.3 Sponsors: Air Force Geophysics Laboratory (now Air Force Research Laboratory)

40.7 Model codes and sources

The model is published in the form of tables and figures (Appendix F of the publication referenced in 40.5). The computer coding is described in Appendices D and E, and the formulation of the model and its parameters is given in Appendices A-C. Contact sponsors for additional information.

41 NRLMSISE-00 thermospheric model, 2000

41.1 Model content

The new NRLMSISE–00 (Mass Spectrometer and Incoherent Scatter Radar Extended) model and the associated NRLMSIS database now include the following data: 1) total mass density, from satellite accelerometers and from orbit determination (including the Jacchia data), (2) temperature from incoherent scatter radar, and (3) molecular oxygen number density, (O_2), from solar ultraviolet occultation aboard the Solar Maximum Mission (SMM). A new species, “anomalous oxygen,” allows for appreciable oxygen ion, (O^+) and hot atomic oxygen contributions to the total mass density at high altitudes and applies primarily to drag estimation. This is an empirical model of the neutral temperature and density (including N_2, O_2, O, N, He, Ar, and H) from the ground to exobase (< 1400 km). The model depends upon user-provided values of day, time (UT), altitude, latitude, longitude, local solar time, magnetic index (Ap), 10.7 cm solar radiation flux index.

The main differences from the MSISE-90 model involve (1) the extensive use of drag and accelerometer data on total mass density, (2) the addition of a component to the total mass density that accounts for possibly significant contributions of O^+ and hot oxygen at altitudes above 500 km, (3) the inclusion of the SMM UV occultation data on O_2 and self-consistent, seamless connectivity with the middle and lower atmospheric portions of the models.

41.2 Model uncertainties and limitations

The NRLMSISE-00, MSISE-90, and Jacchia-70 models were compared to the Jacchia data set, upon which the Jacchia-class operational models were based. The NRLMSISE-00 achieves an improvement over both MSISE-90 and Jacchia-70 by incorporating advantages of each. Statistical comparisons of the Jacchia data to the three models provides a bias and standard deviation for different altitude bands and levels of geomagnetic activity (Ref. 41.5.6). With regard to recent assessment of modeling errors associated with semi-annual density variation magnitudes as a function of solar cycle years, see Reference 41.5.4 in the Jacchia J70 Static Model write-up. For an overall evaluation of density errors at 400 km with comparisons of other currently used models refer to the JB2008 model description. Reference 41.5.5 also provides a comprehensive assessment of the MSIS model validity.

41.3 Basis of the model

41.3.1 The NRLMSISE-00 model extends the MSIS-86/MSISE-90 model formulation and database and is an empirical model based upon composition and temperature measurements by satellite, rocket, and incoherent scatter radar and by total mass density measured by accelerometers and inferred from low-Earth orbits.

41.3.2. Variations incorporated into the model: solar activity, magnetic activity, latitude, longitude, and UT; annual, semiannual, semidiurnal, terdiurnal, and diurnal.

41.4 Databases

A comprehensive description of the dataset utilized in the NRLMSISE-00 models can be found in the following publications and references therein;

41.4.1 Picone, J.M., A. E. Hedin, D. P. Drob, and A. C. Aikin (2002), NRLMSISE-00 empirical model of the atmosphere: Statistical comparisons and scientific issues, *J. Geophys. Res.*, *107*(A12), 1468, doi: 10.1029/2002JA009430.

41.4.2 Carignan, G. R., B. P. Block, J. C. Maurer, A. E. Hedin, C. A. Reber, and N. W. Spencer, "The Neutral Mass Spectrometer on Dynamics Explorer", *Space Sci. Instrum., 5*, 429-441, 1981.

41.4.3 Engebretson, M. J., K. Mauersberger, D.C. Kayser, W.E. Potter, and A.O. Nier, "Empirical Model of Atomic Nitrogen in the Thermosphere", *J. Geophys. Res., 82,* 461-471, 1977.

41.4.4 Engebretson, M. J., and K. Mauersberger, "The Response of Thermospheric Atomic Nitrogen to Magnetic Storms, *J. Geophys. Res., 88,* 6331-6338, 1983.

41.4.5 Engebretson, M. J., and J. T. Nelson, "Atomic Nitrogen Densities near the Polar Cusp., *J. Geophys. Res., 90,* 8407-8416, 1985.

41.4.6 Hedin, A. E., "A Revised Thermospheric Model Based on Mass Spectrometer and Incoherent Scatter Data": MSIS-83, *J. Geophys. Res., 88,* 10,170-10, 188, 1983.

41.4.7 Mauersberger, K., M. J. Engebretson, W. E. Potter, D. C. Kayser, and A. O. Nier, "Atomic Nitrogen Measurements in the Upper Atmosphere", *Geophys. Res. Lett., 2,* 337-340, 1975.

41.4.8 Oliver, W. L., "Improved Exospheric Temperature Measurements: Evidence for a Seasonal Variation of the Magnetic Activity Effect", *J. Geophys. Res., 85,* 4237-4247, 1980.

41.4.9 Spencer, N. W., L. E. Wharton, H. G. Niemann, A. E. Hedin, G. R. Carignan, and J. C. Maurer, The Dynamics Explorer Wind and Temperature Spectrometer," *Space Sci. Instrum., 5,* 417-428, 1981.

41.4.10 Wand, R.H., "Lower Thermospheric Structure from Millstone Hill Incoherent Scatter Radar Measurements, 1, Daily Mean Temperature", *J. Geophys. Res., 88,* 7201-7209, 1983.

41.4.11 Wand, R. H. "Lower Thermospheric Structure From Millstone Hill Incoherent Scatter Radar Measurements, 2, Semidiurnal Temperature Component," *J. Geophys. Res., 88,* 7211-7224, 1983.

41.5 Publication references

41.5.1 Hedin, A. E., "A Revised Thermospheric Model Based on Mass Spectrometer and Incoherent Scatter Data" MSIS-83, *J. Geophys. Res., 88,* 10,170-10,188, 1983.

41.5.2 Hedin, A. E., MSIS-86 thermospheric model, *J. Geophys. Res., 92*, 4649-4662, 1987.

41.5.3 Hedin, A. E., J. E. Salah, J. V. Evans, C. A. Reber, G. P. Newton, N. W. Spencer, D C. Kayser, D. Alcayde, P. Bauer, L. Cogger, and J. P. McClure, "A Global Thermospheric Model Based on Mass Spectrometer and Incoherent Scatter Data." MSIS 1, N2 density and temperature, *J. Geophys. Res., 82,* 2139-2147, 1977.

41.5.4 Hedin, A. E., C. A. Reber, G. P. Newton, N. W. Spencer, H. C. Brinton, H. G. Mayr, and W. E. Potter, "A Global Thermospheric Model Based on Mass Spectrometer and Incoherent Scatter Data" MSIS 2., Composition, *J.Geophys. Res., 82*, 2148-2156, 1977.

41.5.5 Lean, J. L., J. M. Picone, and J. T. Emmert, "Quantitative Forecasting of Near-term Solar Activity and Upper Atmosphere Density", J. Geophys. Res., 114, A07301, doi: 1029/2009JA014285.

41.5.6 Picone, J. M., A. E. Hedin, K. P. Drob, and J. Lean, "NRLMSISE-00 Empirical Atmospheric Model: Comparisons to Data and Standard Models. *Advances in the Astronautical Sciences,* Vol. 109 II//Pages 1385-1387, AAS/AIAA Astrodynamics Conference, July 30-Aug. 2, 2001, Quebec City, Que., Canada, ISSN 0065-3438.

41.5.7 Picone, J.M., Hedin, A.E., Drob, D.P., Meier, R.R., Lean, J., Nicholas, A.C. and Thonnard, S.E. Enhanced empirical models of the thermosphere. *Physics and Chemistry of the Earth Part C-Solar-Terrestrial and Planetary Science*, 25(5-6), 537-542, 2002.

41.5.8 Picone, J.M., A. E. Hedin, D. P. Drob, and A. C. Aikin (2002), NRLMSISE-00 empirical model of the atmosphere: Statistical comparisons and scientific issues, *J. Geophys. Res.*, *107*(A12), 1468, doi: 10.1029/2002JA009430.

41.5.9 See also http://en.wikipedia.org/wiki/NRLMSISE-00

41.6 Dates of development, authors and sponsors

41.6.1 **Dates:** OGO 6 model 1974

MSIS-77	1977
MSIS-83	1983
MSIS-86	1986
MSISE-90	1990

41.6.2 Authors: A. E. Hedin, J. M. Picone, D. P. Drob, and J. Lean

41.6.3 Sponsors: National Aeronautics and Space Administration, Naval Research Laboratory

41.7 Model codes and sources

The present NRLMSISE-00 distribution package is an ASCII file containing the model source, a test driver, and the expected output of the test driver. They are freely available. Users may download the official source code distribution from any one of the following web sites:

Community Coordinated Modeling Center (CCMC) at the NASA Goddard Space Flight Center http://ccmc.gsfc.nasa.gov/modelweb/#atmo.

Coupling, Energetics, and D ynamics of Atmospheric Regions web site under tools/models http://cedarweb.hao.ucar.edu/cgi-bin/ion-p?page=cedarweb.ion.

The ESA Space Environment Information System (SPENVIS) at http://www.spenvis.oma.be/spenvis.

42 U.S. Air Force high accuracy satellite drag model (HASDM), 2004

42.1 Model content

The High Accuracy Satellite Drag Model (HASDM) is the name of the operational model installed in the Astrodynamic Support Workstation at the Air Force 1st Space Control System. HASDM converts satellite drag data into global distributions of total neutral density and temperature.

The development of HASDM entailed the development and demonstration of the Dynamic Calibration Atmosphere (DCA) (Ref. 42.5.1) technique for density correction. Its primary goal was to improve the orbit determination process in terms of ballistic coefficient consistency, epoch accuracy, and epoch covariance realism.

42.2 Model uncertainties and limitations

The Air Force has expanded on an Air Force Research Laboratory (AFRL) technique (Ref. 42.5.3) for a simple data assimilation scheme that dramatically reduces satellite drag model errors (Ref. 42.5.4). Drag information from over 75 "calibration" satellites were used to solve for near real time thermospheric density corrections and were applied to a revised version of the Jacchia 1970 empirical density model. HASDM demonstrated the real-time capability to reduce satellite drag specification errors by at least a factor of two and the accuracy of real-time total mass density to about 5% versus approximately 15% by other empirical models. However, for long-term predictions of total mass density by HASDM, the density accuracy is dependent upon the accuracy of solar/EUV and geomagnetic activity predictions used as inputs to the model whose uncertainty can be significant based on current solar activity prediction capabilities.

An important limitation on the use of HASDM is that it requires the input of orbital tracking information from the real time tracking and drag effect analysis of the DCA satellites in order for it to achieve the approximate 5% accuracy in real-time total mass density.

Another objective was to improve the state accuracy at epoch. A related measure of success was enhanced realism of the state covariance error at epoch. A third essential criterion was a demonstrable reduction in density error over time as measured by better consistency in the ballistic coefficients. The results were favorable for all three measures. Epoch accuracy, covariance realism, and ballistic coefficient consistency all generally improved, dramatically so for some satellites.

There was a reduction of 74% in ballistic coefficient variation (from about 17% to 4.4%) across the core calibration satellites. The reduction across the highly tasked evaluation satellites was less optimal with a 53% improvement.

With regard to recent assessment of modeling errors associated with semiannual density variation magnitudes as function of solar cycle years, see Reference 42.5.4 in the Jacchia J70 Static Model write-up.

42.3 Basis of the model

42.3.1 Dynamic calibration atmosphere

The Dynamic Calibration Atmosphere (DCA) is the main component of the HASDM model. DCA adjusts the parameters of the Jacchia 70 (hereafter referred to as J70) density model in near real time by observing drag effects on a set of LEO calibration satellites for which ample Space Surveillance Network (SSN) tracking data were collected. Many calibration satellites are exploited to recover a temporally responsive density field with improved spatial resolution. The satellites are chosen so as to encompass a wide range of orbital altitudes (from 180 km to 800 km), inclinations, and ascending nodes. Only those satellites with reasonably constant frontal area are considered.

DCA determines its density corrections in a single weighted differential correction (DC) across all calibration satellites at once using their observations and statistical uncertainties directly, while simultaneously solving for their states. This is a departure from other methods that perform satellite-by-satellite reductions using indirect observations synthesized from particular behaviors (e.g., ballistic coefficient histories).

42.3.2 J70MOD

Within DCA is a subroutine called J70MOD which is a modified version of the J70 model. It converts the DCs from the drag measurements into a continuous model density distribution. Since the J70 model is based on diffusive equilibrium of densities with temperature, the partial derivatives of the drag perturbations must be converted to partial derivatives in temperature. This is done through a spherical harmonic expansion of the nighttime minimum exospheric temperature T_e (> 600 km altitude) and the inflection point temperature T_x (at 125 km altitude) with the DCs solving for coefficients of the spherical harmonic functions.

The local values for T_x and T_e are corrected indirectly through a global parameter known as the nighttime minimum exospheric temperature T_c . This is the principal parameter used in the J70 models to describe the state of the entire thermosphere in response to solar extreme ultraviolet heating. For the standard J70 model, this is given by the expression:

$$T_c = 383.0 + 3.32\, F_{10.7} + 1.8(F_{10.7} - \overline{F}_{10}) \qquad (1)$$

In J70MOD, a correction ΔT_c is added to the standard T_c value to produce a corrected value $T_c' = T_c + \Delta T_c$. The local exospheric temperature T_e' is obtained from T_c' in the same way the standard J70 obtains T_e from T_c; through multiplying by the diurnal and latitudinal variation factor ($D(\delta,\psi,\lambda)$, where δ, ψ, and λ refer to the solar declination, latitude, and local solar time, respectively). Adding the contribution to T_e due to geomagnetic activity $\Delta T(a_p)$, we get

$$T_e' = T_c' D(\delta,\psi,\lambda) + \Delta T(a_p) \qquad (2)$$

The local values of T_x (at 125 km altitude) are computed from the local exospheric temperature T_e' using the standard J70 expression:

$$T_x' = 444.38 + 0.02385\, T_e' - 392.83 \exp(-0.0021\, T_e') \qquad (3)$$

However in J70MOD the local inflection point T_x' is further corrected by adding a direct ΔT_x correction to T_x':

$$T_x'' = T_x' + \Delta T_x \qquad (4)$$

The double prime indicates that this inflection point temperature is corrected twice; once through ΔT_c and again through ΔT_x. Both ΔT_c and ΔT_x are expressed in terms of independent spherical harmonic expansions in latitude and local solar time.

When $\Delta T_x = 0$, the temperature profile is identical to a standard J70 profile for a given local exospheric temperature. Depending on the correction coefficients derived from the calibration satellites the shape of the temperature profile will vary depending on T_e' and ΔT_x. The actual profile may not be the *true* temperature profile, but is that profile which produces self-consistent model results in terms of the assimilation.

42.4 Databases

The only database is the drag measurements from the 75 calibration satellites. Some long-term orbiting satellites (30 years or more) were used to obtain mean ballistic coefficients. It is important to remember that the J70 model has not been changed just corrected with the calibration data.

42.5 Publication references

42.5.1 S. Casali and B. Barker, "Dynamic Calibration Algorithm (DCA) for High Accuracy Satellite Drag Model (HASDM)", AIAA/AAS Astrodynamics Specialist Conference and Exhibit, Monterey, California, August 5-8, 2002.

42.5.2 Tobiska, W. Kent; Woods, Tom; Eparvier, Frank; Viereck, Rodney; Floyd, Linton; Bouwer, Dave; Rottman, Gary and White, O. R.; "The SOLAR2000 Empirical Solar Irradiance Model and Forecast Tool", *Journ. of Atmos. and Solar-Terrestrial Physics*, April 2000.

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42.5.4 "Precision Low Earth Orbit determination Using Atmospheric Density Calibration" F. Marcos, M. Kendra, J. Griffin, J. Bass, J. Liu & D. Larson, *Advances in the Astronautical Sciences*, 97 (1), 515-527, AAS, 1998.

42.5.5. Storz, M., B. Bowman, and J. Branson, "High Accuracy Satellite Drag Model (HASDM)", AIAA/AAS Astrodynamic Specialist Conference and Exhibit, Monterey, California, August 5-8, 2002.

42.5.6. Bowman, Bruce R.; "Atmospheric Density Variations at 1500-4000 km Height Determined from Long Term Orbit Perturbation Analysis," AAS-2001-132, *AAS/AIAA Astrodynamics Specialist Conference* (Santa Barbara, California), Feb 2001.

42.6 Dates of development, authors and sponsors

42.6.1 Dates 2004

42.6.2 Authors: Casali, S., Barker, B., Storz, M. and B. Bowman

42.6.3 Sponsors: Department of Defense, U. S. Air Force Space Command

42.7 Model codes and sources

United States government agencies may apply for approval to obtain the J70MOD subroutine, which converts the HASDM temperature correction coefficients to densities, and also obtain historical HASDM temperature coefficients. Bruce Bowman, AFSPC/A9A, (719) 556-3710, bruce.bowman@peterson.af.mil, is the point of contact to initiate the approval process.

43 Russian direct density correction method (DDCM) for computing near-real time corrections to an arbitrary Earth upper atmosphere density model, and for estimating the errors in an arbitrary Earth upper atmosphere density model, 2007

43.1 Model content

The Russian Direct Density Correction Method (DDCM) differs from the other thermosphere density models in that it offers a process for determining a near real-time correction to an arbitrary density model. The correction to the model is given as a multiplier as in Eq. (1):

$$\rho = \rho_{\text{mod}}(1 + \frac{\delta\rho}{\rho_{\text{mod}}}) \tag{1}$$

where ρ_{mod} is the arbitrary density model and $\delta\rho$ is the density fluctuation (Ref 5.1). The ratio of the density fluctuation to the modeled density is given by Eq. (2):

$$\delta\rho \Big/ \rho_{\text{mod}} = \sum_{i=1}^{n} b_i\, f_i(h, \delta, \alpha) \tag{2}$$

Here the b_i are numerical parameters and the $f_i(...)$ are the basis functions of the fluctuation model. The quantities h, δ, and α, are the altitude, latitude, and longitude, respectively.

The primary goal of the Russian DDCM is to improve the orbit determination process in terms of ballistic factor consistency, epoch element set accuracy, and covariance realism. Orbit prediction and forecasting of the density correction parameters are also considered. Prediction of satellite re-entry time is closely coupled to accuracy in the modeling of atmosphere drag. Finally, detection of space objects with changing aerodynamic characteristics due to attitude motion can be accomplished by comparison of ballistic factors variations, obtained with and without density corrections.

An individual set of the density parameters $b_i(i = 1,...,n)$ enables the computation of the corrected density over a finite interval of time. Investigations to date have primarily focused on updates to the density parameters on a once per day basis. This interval is dictated by the information used to compute the density parameters. Daily corrections to the atmosphere density with two parameters over a four year interval would result in a database with 2924 parameters.

The Russian DDCM has been used to compute corrections to the GOST-84 density model (Ref. 43.5.2) and to the NRL MSIS 2000 density model (Ref. 43.5.3) using Air Force Space Command Two-Line Element sets as the input data. Corrections to the Jacchia-Roberts density model (Ref. 43.5.4) have been computed using simulated observation data.

43.2 Model uncertainties and limitations

There are several limitations in the current implementation of the DDCM:

a. The choice of the basis functions

b. The method is currently used to compute corrections to the density in the 200 to 600 km altitude range

c. The method has been demonstrated for the computation of density corrections in the four-year interval from 1999 through 2003 which includes the last peak in the solar activity

d. The method has been used to compute density corrections to the GOST-84 density model and the NRLMSIS-00 density.

e. The real data used to the efforts to date has been the NORAD Two-Line Element (TLE) sets.

Originally (Ref. 43.5.1), it was planned to include in Eq. (2) the components characterizing the basic general trends in the spatial distribution of the density fluctuation. Assuming symmetric density fluctuations in the Northern and Southern hemispheres, the following basis functions were chosen:

$$
\begin{aligned}
f_1(\ldots) &= 1, \\
f_2(\ldots) &= \frac{h-h_0}{h_0} \\
f_3(\ldots) &= \cos\alpha\cos\delta \\
f_4(\ldots) &= \sin\alpha\cos\delta \\
f_5(\ldots) &= \sin^2\delta \\
f_6(\ldots) &= \cos\alpha\sin^2\delta\cos\delta \\
f_7(\ldots) &= \sin\alpha\sin^2\delta\cos\delta \\
f_8(\ldots) &= \sin^4\delta
\end{aligned}
\qquad (3)
$$

where α is the longitude and δ is the latitude. The parameter h_0 is a reference altitude. The coefficients of these basis functions in the density correction expansion were to be determined by least squares techniques. However, experimentation led to the conclusion that only the first two coefficients were observable from the then available orbit information. So the following reduced set of basis functions has been employed in the numerical studies done to date.

$$
\begin{aligned}
f_1(\ldots) &= 1, \\
f_2(\ldots) &= \frac{h-h_0}{h_0}
\end{aligned}
\qquad (4)
$$

In these studies (Ref. 43.5.5 and 43.5.6), the reference altitude has been chosen to be 400 km.

The current restriction of the DDCM to the 200 to 600 km altitude range is dictated by the availability of observed values of the ballistic factors with sufficient accuracy. There are few space objects with perigee heights near 200 km (see Figure 1). Above 600 km, the ballistic factor is less observable. In fact, for some space objects above 600 km, the ballistic factor is not a solve-for variable in the orbit determination process for the TLE near the minimum in the 11-year solar activity cycle. Work is currently ongoing to demonstrate the integration of additional observations of the atmosphere density with the Two-Line Element sets.

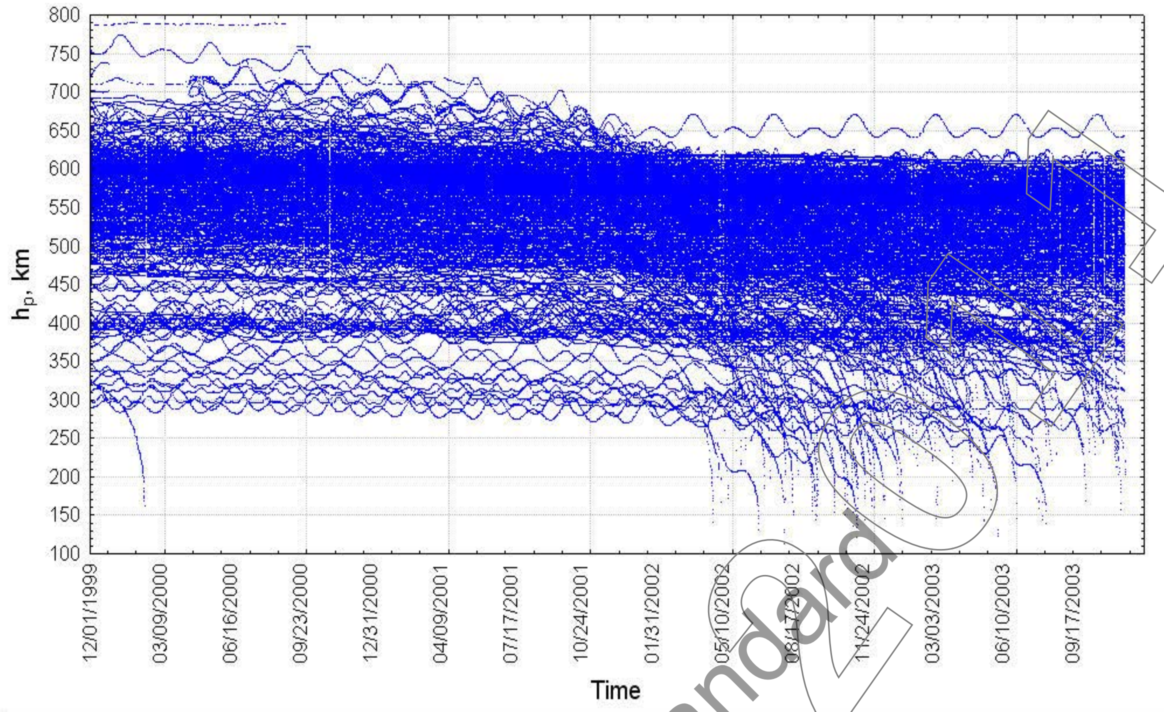

Figure 1 — Time-altitude distribution of ballistic coefficient estimates (for all SOs) 2000 – 2003

The real data numerical results to date (Ref. 43.5.5 and 43.5.6) consider the four year interval from late 1999 to late 2003. This interval is centered on the most recent peak in the solar activity. Work is ongoing to demonstrate the DDCM near minimums in the 11-year solar activity.

Based on the experience in using DDCM to determine corrections to the Jacchia, GOST, and MSIS atmosphere density models, we expect no difficulty in determining corrections to other atmosphere density models (such as DTM). We note that the DDCM aims at determining medium and long period corrections to the density. When these errors are understood, we will be better able to observe short period motion in the atmosphere density.

The primary issue in integrating multiple data sources will be in determining an appropriate procedure for weighting the different data sources.

43.3 Basis of the model

The GOST-84 atmosphere density corrections were determined using the Universal Semi analytical Theory (USM). The process is as follows (Ref. 43.5.7):

1. Select a set of 500 LEO space objects whose element sets are regularly updated in the US Space Catalog. All of the chosen space objects have a perigee height less than 600 km. For the chosen space objects, all of the US SSS TLE's available over the Internet have been collected daily.

2. Each of the TLE-format element sets is transformed into a USM mean element set. Since the transformation from TLE to the USM mean elements is accomplished without reference to the osculating space, the resulting elements are considered to be 'noisy' USM mean elements.

3. Establish solar flux and geomagnetic data base as follows:

   a. Daily averaged value of $F_{10.7}$

   b. F_{81} which is a weighted-average of the solar activity index $F_{10.7}$ for the preceding 81 days.

c. K_p which is the daily averaged quasi-logarithmic planetary index k_p measured every three hours

4. For each “measurement” epoch, determine smoothed USM mean elements and t he associated ballistic coefficient based on a least squares fit of the noisy USM elements created in Step 2. This least squares fit employs the actual values of the solar flux and geomagnetic data discussed in Step 3. This least squares fit process is called ‘secondary data processing.’

5. The fluctuations of atmospheric density (or corrections to density) are estimated based on the smoothed ballistic coefficients obtained as a result of the secondary data processing.

The data processing technology, implemented for the GOST-84 model, remained practically without change in performing calculations with the NRLMSIS-00 model. The distinctions consisted only in the following points:

1. The NRLMSIS-00 was used as a baseline model instead of the GOST one.
2. The Everhart numerical method (Refs. 5.8 and 5.9) was used for satellite motion propagation instead of the Universal Semi analytical Method (USM).
3. The osculating orbital elements, generated from TLE sets, were used as measurements at secondary data processing instead of the USM mean elements.
4. The 81-day averages of values, centered on the day of interest, were used instead of weighted-average values of solar activity index for preceding 81 days, which were applied in the GOST model.
5. The daily magnetic indices A_p were used in the NRLMSIS-00 model instead of mean diurnal indices K_p in the GOST model.
6. Different values of delays for indices of solar and geomagnetic activity are used in the NRLMSIS-00 and GOST models.

The density correction results given in Ref. 5.6 have been reproduced by Wilkins (Ref. 43.5.10)

ARIMA methodology (Ref. 5.11) has been applied to the problem of forecasting the density corrections.

43.4 Databases

Several databases have been generated as described in Reference 43.5.7. The file of Russia-generated b_1 and b_2 density correction factors for the time period from late 1999 to late 2003 has been transmitted to the US. These correction factors have been employed by Wilkins (Ref. 43.5.10) in the independent test of this method.

43.5 Publication references

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43.5.5 Yurasov, V.S., Nazarenko, A.I., Cefola, P.J., Alfriend, K. T. Results and Issues of Atmospheric Density Correction. *14th AAS/AIAA Space Flight Mechanics Conference*, Maui, Hawaii, Feb. 2004, AAS 04-305.

43.5.6 Yurasov, V.S., Nazarenko, A.I., Cefola, P.J., and Alfriend, K. T., “Density Corrections for the NRLMSIS-00 Atmosphere Model”, *15th AAS/AIAA Space Flight Mechanics Conference*, Copper Mountain, Colorado, Jan. 2005, AAS 05-168.

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43.5.12 Granholm, George R., Near-Real Time Atmospheric Density Model Correction Using Space Catalog Data, SM Thesis, Department Of Aeronautics And Astronautics, MIT, June 2000.

43.5.13 Bergstrom, Sarah E., An Algorithm for Reducing Atmospheric Density Model Errors Using Satellite Observation Data in Real-Time, SM Thesis, Department of Aeronautics and Astronautics, MIT, June 2002

43.6 Dates of development, authors and sponsors

43.6.1 Dates: 2007, based upon work done during previous years (1982-2007)

43.6.2 Authors: The primary authors are the Russian scientists Prof. A. I. Nazarenko and Dr. V. S. Yurasov. Additional testing and algorithm refinement activities have occurred at MIT in Cambridge, MA and at the Naval Postgraduate School, Monterey CA.

43.6.3 Sponsors: Russia

43.7 Model codes and sources

References 43.5.12 and 43.5.13 give source code associated with the estimation of the density correction parameters. The Granholm and Bergstrom efforts were part of the independent test of the algorithm. The algorithm also requires an orbit determination system. The USM and Everhart numerical methods have been employed in the Russian work. The GTDS has been the orbit determination system in the U.S. work.

44 Horizontal wind model (HWM), 1993

44.1 Model content

The Horizontal Wind Model (HWM93) provides a statistical representation of the horizontal wind fields of the Earth's atmosphere from the ground to the exosphere (0 to 500 km). It represents over forty years of satellite, rocket, and ground-based wind measurements via a compact Fortran subroutine. The computer model is a function of geographic location, altitude, day of the year, solar local time, as well as solar and geomagnetic activity. It includes representations of the zonal mean circulation, stationary planetary waves, migrating tides, and the seasonal modulation thereof.

44.2 Model uncertainties and limitations

The first edition of the model was released in 1987 (HWM87) was intended for winds above 220 km. Solar cycle variations are included (since HWM90), but they were found to be small and not always very clearly delineated by the current data. The HWM93 model extends down to the surface. In the thermosphere variations with magnetic activity (A_p) and Solar Flux (F10.7) are included in the model. In the thermosphere, the model describes the transition from predominately diurnal variations in the upper thermosphere to semidiurnal variations in the lower thermosphere and a transition from summer to winter flow above 140 km to winter to summer flow below. Significant altitude gradients in the wind extend up to 300 km at some local times.

Comparison of the various data sets with the aid of the model shows in general remarkable agreement, particularly at mid and low latitudes. The ground-based data allow modeling of seasonal/diurnal variations, which are most distinct at mid latitudes. While solar activity variations are now included, they are found to be small and not always very clearly delineated by the current data. They are most obvious at the higher latitudes.

The model represents a smoothed compromise between the original data sources. Although agreement between various data sources is generally good, some systematic differences are noted, particularly near the mesopause. Overall root mean square differences between data and model values are on the order of 15 m/s in the mesosphere and 10 m/s in the stratosphere for zonal winds, and 10 m/s and 5 m/s respectively for meridional winds. Systematic biases in the Medium Frequency Radar data sets use above 92 km altitude where identified since the creation of the model.

To correct many known issues with HWM93, an overhaul of the model (HWM07) is being developed at NRL using many recent research satellite- and ground-based data sets.

44.3 Basis of the model

The HWM93 is based on wind data obtained from the AE-E and DE 2 satellites. A limited set of vector spherical harmonics is used to describe the zonal and meridional wind components. With the inclusion of wind data from ground-based incoherent scatter radar and Fabry-Perot optical interferometers, HWM90 was extended down to 100 km and using MF/Meteor data. HWM93 was extended down to the ground. The HWM is constructed from the fitting of monthly mean winds from meteor radar and MF radar measurements at more than 40 stations, well distributed over the globe. The height-latitude contour plots of monthly mean zonal and meridional winds for all months of the year, and of annual mean wind, amplitudes and phases of annual and semiannual harmonics of wind variations were analyzed to reveal the main features of the seasonal variation of the global wind structures. Gradient winds from CIRA-86 plus rocket soundings, incoherent scatter radar, MF radar, and meteor radar provide the data base and are supplemented by previous data driven model summaries. Low-order spherical harmonics and Fourier series are used to describe the major variations throughout the atmosphere including latitude, annual, semiannual, local time (tides), and longitude (stationary wave 1), with a cubic spline interpolation in altitude.

44.4 Databases

44.4.1 See HWM88, HWM90, and HWM93 publications and references therein.

44.5 Publication references

44.5.1 A. E. Hedin, N. W. Spencer, and T. L. Killeen, Empirical Global Model of Upper Thermosphere Winds Based on Atmosphere and Dynamics Explorer Satellite Data, J. Geophysics. Res., 93, 9959- 9978, 1988.

44.5.2 Hedin, A.E., Biondi, M.A., Burnside, R.G., Hernandez, G., Johnson, R.M., Killeen, T.L., Mazaudier, C., Meriwether, J.W., Salah, J.E., Sica, R.J., Smith, R.W., Spencer, N.W., Wickwar, V.B. and Virdi, T.S. Revised Global-Model of Thermosphere Winds Using Satellite and G round-Based Observations. *J.Geophys.Res.-Space Physics*, 96(A5), 7657-7688, 1991.

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44.6 Dates of development, authors and sponsors

44.6.1 **Dates** : HWM87 1987

HWM90 1990

44.6.2 **Authors:** A.E. Hedin

44.6.3 **Sponsors:** National Aeronautics and Space Administration

44.7 Model codes and sources

The HWM93 distribution package is an ASCII file containing the model source, a test driver, and the expected output of the test driver. They are freely available. Users may download the official source code distribution from any one of the following web sites:

Community Coordinated Modeling Center (CCMC) at the NASA Goddard Space Flight Center http://ccmc.gsfc.nasa.gov/modelweb/#atmo.

Coupling, Energetics, and D ynamics of Atmospheric Regions website under tools/models http://cedarweb.hao.ucar.edu/cgi-bin/ion-p?page=cedarweb.ion.

NOTE Regarding the new HWM07 model: At the time this revision for the Guide to Reference and Standard Atmosphere Models was being prepared, the new Horizontal Wind Model (HWM07) was being documented for publication. This new HWM 07 model provides a statistical representation of the horizontal wind fields of the Earth's atmosphere from the ground to the exosphere (0 to 500 km). The HWM07 is comprised of two components, a quiet-time component for the background (Drob, D.P., et al., An Empirical Model of the Earth's Horizontal Wind Field: HWM07. Submitted to the Journal of Geophysical Research 2008) and a geomagnetic-storm component (Emmert, J.T., et al., DWM07 Global Empirical Model of Upper Thermosphere Storm-Induced Disturbance Winds. Submitted to the Journal of Geophysical Research, 2008). Interested users of the HWM should consult the Journal of Geophysical Research relative to the availability of the two papers noted for detail information on the HWM07 and availability of model software.

45 Twenty-two range reference atmospheres, 2006

45.1 Model content

A Range Reference Atmosphere (RRA) is a statistical summary of atmospheric sounding observations at a specific geographical location. The 2006 RRA database contains separate models for 22 distinct geographic locations, as shown in Table 1. The RRA tabulates monthly and annual values for the mean values and measures of variability for an extensive set of measured and derived meteorological parameters. A list of the tabulated parameters, including their physical units, is given in Table 2. The vertical domain for the models is nominally from the surface to 30 km altitude. For sites with archived rocketsonde measurements, the vertical domain extends to 70 km altitude. Vertical resolution of the RRAs is 250 m from the surface to 30 km altitude, and 1 km from 30 to 70 km altitude. The period of record for the RRA data is 1990-2001, with the exceptions of China Lake and White Sands. These two sites had insufficient sample sizes to generate stable statistics due to incomplete observation and recording between 1990 and 2001. The period of record for these two sites was thus extended to the years 1984-2001. The model product itself is a comma-separated-variable (CSV) format file containing tabulated profiles of each parameter for both monthly and annual values.

Table 1 — Range reference atmosphere site locations and World Meteorological Organization (WMO) observation site identification number.

Range Reference Atmosphere Site	WMO ID #
Argentia, New Foundland	71801
Ascension Island, South Atlantic	61902
Barking Sands, Hawaii	91165
Cape Canaveral, Florida	74794
China Lake Naval Air Weapons Station, California	74612
Dugway Proving Ground, Utah	72572
Edwards Air Force Base, California	72381
Eglin Air Force Base, Florida	72221
El Paso, Texas	72270
Fort Huachuca Electronic Proving Ground, Arizona	72274
Fairbanks, Alaska	70261
Great Falls, Montana	72775
Kwajalein, Marshall Islands	91366
Nellis Air Force Base, Nevada	72387
Nimes-Courbessac, France	7645
Point Magu Naval Air Warfare Center, California	72391
Roosevelt Roads, Puerto Rico	78526
Taguac, Guam	91217
Vandenberg Air Force Base, California	72393
Wallops Island, Virginia	72402
White Sands Missile Range, New Mexico	72269
Yuma Proving Ground, Arizona	72293

Table 2 — Range reference atmosphere tabulated parameters and their physical units.

Parameter	Unit	Description
Z	km	Geometric altitude
Geo Ht	km	Geopotential height
Hydro P	mb	Hydrostatically derived pressure
Hydro D	g/m^3	Hydrostatically derived density
Hydro Tv	K	Hydrostatically derived virtual temperature
Mean U	m/s	Mean U wind component
Std Dev U	m/s	Standard deviation of U wind component
R	unitless	Coefficient of correlation between U and V wind components
Mean V	m/s	Mean V wind component
Std Dev V	m/s	Standard Deviation of V wind component
Mean WS	m/s	Mean wind speed
Std Dev WS	m/s	Standard deviation of wind speed
Skewness WS	unitless	Skewness of wind speed
Wind Obcount	number	Number of wind observations
Mean P	mb	Mean pressure
Std Dev P	mb	Standard deviation of pressure
Skewness P	unitless	Skewness of pressure
Mean T	K	Mean temperature
Std Dev T	K	Standard deviation of temperature
Skewness T	unitless	Skewness of temperature
Mean D	g/m^3	Mean density
Std Dev D	g/m^3	Standard deviation of density
Skewness D	unitless	Skewness of density
P Obcount	number	Number of pressure observations
T Obcount	number	Number of temperature observations
D Obcount	number	Number of density observations
Mean Vapor P	mb	Mean vapor pressure
Std Dev VP	mb	Standard deviation of vapor pressure
Skewness VP	unitless	Skewness of vapor pressure
Mean Tv	K	Mean virtual temperature
Std Dev Tv	K	Standard deviation of virtual temperature
Skewness Tv	unitless	Skewness of virtual temperature
Mean Td	K	Mean dewpoint temperature
Std Dev Td	K	Standard deviation of dewpoint temperature
Skewness Td	unitless	Skewness of dewpoint temperature
VP Obcount	number	Number of vapor pressure observations
Tv Obcount	number	Number of virtual temperature observations
Td Obcount	number	Number of dewpoint temperature observations

45.2 Model uncertainties and limitations

The model statistics are generated from sampled subsets of the population of all possible atmospheric states. The potential always exists that a given measurement will fall outside the specified variability limits, or otherwise depart from the sample-derived statistical distributions. All input data profiles are quality controlled using the Air Force's New Upper Air Validator (NUAV) system, as described in Air Force Technical Note AFGWC/TN-90/001. This program employs a series of well tested industry-standard quality control algorithms to filter and discard erroneous and/or suspect data. A typical accuracy uncertainty for an arbitrary measurement is less than 5%.

45.3 Basis of the model

The model is a statistical summary of a climatological sample of upper-air atmospheric measurements at a specific geographical location. Data sources include both rawinsonde and rocketsonde measurements made at, or very near, the site of interest. Input profile observations are quality controlled to ensure a valid data sample. From these data, distribution statistics are computed in a uniform manner, tabulated, and published in CSV format.

45.3.1 Winds

The model treats the winds at each data level as the vector sum of the U component (East and West) and the V component (North and South). Adopting a bivariate normal probability distribution as the statistical model of the winds allows a complete description of the variability of the vector wind using only five parameters. In Cartesian coordinates, these parameters are the mean of U, the mean of V, the standard deviation of U, the standard deviation of V, and the coefficient of correlation between U and V. Assumptions implicit in the adoption of the bivariate normal probability distribution include the following.

(1) Each wind component is itself univariate normally distributed.

(2) The conditional distribution of one component given a value of the other component is univariate normally distributed.

(3) The wind speed is of the form of a generalized Rayleigh distribution.

(4) The frequency distribution of wind direction can be derived.

(5) The conditional distribution of wind speed given a value of wind direction can be derived.

(6) The five tabulated wind statistical parameters with respect to the meteorological U and V coordinate system can be derived for any arbitrary rotation of the orthogonal axes.

45.3.2 Thermodynamics

A set of six parameters were selected to represent climatologically the thermodynamic state of the atmosphere. These parameters are pressure, density, temperature, dew point temperature, virtual temperature, and water vapor pressure. From these six parameters, a large number of additional quantities may be derived which may be useful in various meteorological and related analyses.

45.4 Databases

Input data consists of a climatological archive of operationally measured upper air profiles collected at the various RRA sites from both rawinsonde and rocketsonde platforms.

45.5 Publication references

The 2006 RRA models have been approved for publication by the Range Commanders Council Meteorology Group (RCCMG). The individual files are posted on the internet and available at https://bsx.edwards.af.mil/weather/rcc.htm.

45.6 Dates of development, authors and sponsors

45.6.1 Dates

The first RRA was issued in 1963 by the Inter-Range Instrumentation Group. The initial RRA site was Cape Canaveral, Florida, and RRAs for additional sites were soon added. A series of 17 revised RRAs were published from 1983 to 1984 by the RCCMG. Five additional sites were added between 1990 and 1991. A further set of 18 revised RRAs were published in 2001. The current set of 22 RRAs was published in 2006.

45.6.2 Authors

The data and descriptive text of the 1983 revised versions was prepared jointly by the Air Force Environmental Technical Applications Center (AFETAC) and the Marshall Space Flight Center. The 1991 data additions were produced by AFETAC. Both the 2001 and the 2006 revised data sets were produced by the Air Force Combat Climatology Center (AFCCC). Currently, AFCCC has an ongoing tasking directive to maintain, revise, and add additional sites, when requested, to the RRA model database.

45.6.3 Sponsors

The RCCMG maintains organizational authority over the RRA model databases.

45.7 Model codes and sources

The models are published in the form of CSV format files containing tabulations of both monthly and annual averages for vertical profiles of the specified parameters. The files themselves are operationally archived by the Edwards Air Force Base Weather Station, and are available from their web server at https://bsx.edwards.af.mil/weather/rcc.htm.

46 Reference atmosphere for Edwards Air Force Base, California, annual, 1975

46.1 Model content

The Reference Atmosphere for Edwards AFB, annual (1975 version), ERA-75, is a geographical variant of the Reference Atmosphere for Patrick AFB, Florida (1963 version) (PRA-63). Because of the close similarity to that model, the reader is referred to section 1 of the PRA-63 summary for details of the model content.

46.2 Model uncertainties and limitations

The reader is referred to section 2 of the PRA-63 summary for details on model uncertainties and limitations.

46.3 Basis of the model

The model is an extension of the Inter-Range Instrumentation Group (IRIG) Document No. 104-63, Edwards Air Force Base Reference Atmosphere (Part 1), September 1972. The mathematical techniques used and the data employed are identical to those used in the Reference Atmosphere for Vandenberg AFB, California, Annual (1971 Version) above 3250 meters altitude. Below 3250 meters the Edwards rawinsonde climatology was used.

46.4 Databases

The data used to derive the various atmospheric parameters were taken from the following references:

46.4.1 Range Reference Atmosphere Committee, Meteorological Working Group of the Inter-Range Instrumentation Group, Edwards Air Force Base Reference Atmosphere (Part 1), IRIG Document 104-63, Secretariat, Range Commanders Council, White Sands Missile Range, New Mexico, September 1972.

46.4.2 Johnson, D. L., “Hot, Cold, and Annual Reference Atmospheres for Edwards Air Force Base, California” (1974 Version), NASA TM X-64941, July 1975.

46.4.3 National Climate Center (Asheville, NC), “Uniform Summary of Rawinsonde Observations for Edwards AFB” (P.O.R.) (1953-1967)

46.4.4 Carter, E. A., and S. C. Brown, “A Reference Atmosphere for Vandenberg AFB, California,” Annual (1975 Version), NASA TM X-64590, May 10, 1975.

46.5 Publication references

46.5.1 Johnson, D. L., “Hot, Cold, and Annual Reference Atmosphere for Edwards AFB, California (1975 Version)”, NASA TM X-64590, November 1975. <http://trs.nasa.gov/archive/>

46.5.2 Anon. “Edwards Air Force Base Reference Atmosphere (Part 1)”, IRIG Document No. 104-63, September 1972. <http://trs.nasa.gov/archive/>

46.6 Dates of development, authors and sponsors

46.6.1 Dates: 1975

46.6.2 Authors: D. L. Johnson

46.6.3 Sponsors: National Aeronautics and Space Administration, Marshall Space Flight Center

46.7 Model codes and sources

The model is published in the form of tables and figures. A computer code is available as ERA-75 from the sponsor barry.c.roberts@nasa.gov.

47 Hot and cold reference atmospheres for Edwards Air Force Base, California, annual, 1975

47.1 Model content

The *Hot and Cold Reference Atmosphere for Edwards AFB, California, (1975 Version)* report provides tables and figures of extreme summer and winter atmospheric profile properties for the Edwards AFB area. It is an empirical model defined by computed values of pressure, kinetic temperature, virtual temperature, and density as a percent difference form the respective ERA-75 annual values, over the geometric altitude range from 706 meters to 90 km. Virtual temperature is the temperature, which would exist if the density were adjusted to reflect the removal of moisture. Virtual temperature is identical to the kinetic temperature above the moisture layer 7600 meters altitude (Hot) and 5,000 meters altitude (Cold).

47.2 Model uncertainties and limitations

47.2.1 The model refers only to a specific location, Edwards AFB, California.

47.2.2 The model is based on atmospheric data obtained prior to 1968 in probing of the upper atmosphere. It is subject to the errors in the measurements and the database cannot now be assessed satisfactorily.

47.3 Basis of the model

The two extreme Edwards AFB models were developed from analyses of Edwards's radiosonde data in which extremes at all altitude (pressure) levels were searched out. Correlation techniques were used on these extreme temperature profiles between near-surface levels and tropopause heights. Vandenberg Hot and Cold 1973 temperature values were applied and used at upper stratospheric altitude levels for Edwards AFB. The mathematical techniques for computing the properties from the basic data are described in detail.

47.4 Databases

The data used to derive the various extreme atmospheric profiles were taken from the following references:

47.4.1 National Climate Center (Asheville, NC), "Edwards AFB Constant Pressure-level Radiosonde Data," January 1961-May 1968.

47.4.2 Johnson, D. L., "Hot, Cold and Annual Reference Atmospheres for Vandenberg Air Force Base, California" (1973 Version), NASA TM X-64756, June 1973.

47.5 Publication references

47.5.1 Johnson, D. L., "Hot and Cold Atmospheres for Edwards AFB, CA" (1975 Version) NASA TM X-64970, November 1975. <http://trs.nasa.gov/archive/>

47.5.2 Johnson, D. L., "Terrestrial Environment (Climatic) Criteria Handbook for Use in Aerospace Vehicle Development," NASA HDBK-1001, August 2000. <http://standards.nasa.gov>

47.6 Dates of development, authors and sponsors

47.6.1 Dates: 1974-1975

47.6.2 Authors: D. L. Johnson

47.6.3 Sponsors: National Aeronautics and Space Administration, Marshall Space Flight Center

47.7 Model codes and sources

The model is published in the form of tables and figures. Computer codes are available as EHA-75 and ECA-75 from the sponsor barry.c.roberts@nasa.gov.

48 Hot and cold reference atmospheres for Kennedy Space Center, Florida, annual, 1971

48.1 Model contents

The *Hot and Cold Reference Atmospheres for Kennedy Space Center Florida, (1971 Version)* consists of a report containing tables and figures of extreme summer and winter atmospheric properties. It is an empirical model defined by computed values of pressure, kinetic temperature, virtual temperature and density. Virtual temperature is the temperature, which would exist if the density were adjusted to reflect the removal of moisture. Virtual temperature is identical to the kinetic temperature above the moisture layer at 6000 meters altitude (Hot) and 5000 meters altitude (Cold). In general, these parameters are tabulated for each 250-meter interval from 0 to 90 km altitude.

48.2 Model uncertainties and limitations

48.2.1 The model refers only to a specific location, Kennedy Space Center, Florida

48.2.2 The model is based on atmospheric data obtained prior to 1965 in probing the upper atmosphere. It is subject to the errors in the measurements and the database that cannot now be assessed satisfactorily.

48.3 Basis of the model

The two extreme Kennedy Space Center models were developed from an analysis of Kennedy Space Center and Patrick AFB, Florida radiosonde, rocket sonde and surface measurements. Extremes of temperature, pressure, and density were searched out at all altitude levels and inter-level correlative techniques were applied subjectively, between near-surface levels and tropopause heights, to construct a Hot (summer) and a Cold (winter) type of atmospheric profile. The mathematical techniques for computing the properties from the basic data are described in detail.

48.4 Databases

The data used to derive the various extreme atmospheric profiles were taken from the following references:

48.4.1 National Climate Center (Asheville, NC), "Cape Kennedy Florida Thermodynamic (Radiosonde) Quantities", Job. No. 6284, prepared for NASA-Marshall Space Flight Center, August 19, 1966.

48.4.2 National Climate Center (Asheville, NC), "Cape Kennedy, Florida Rocketsonde Data from: Meteorological Rocket Network Firings", World Data Center A -- Meteorology Data Reports (May 1959 through September 1967).

48.5 Publication references

Johnson, D. L., "Terrestrial Environment (Climatic) Criteria Handbook for Use in Aerospace Vehicle Development, NASA HDBK-1001, August 2000.

48.6 Dates of development, authors and sponsors

48.6.1 Dates: 1971

48.6.2 Authors: D. L. Johnson

48.6.3 Sponsors: National Aeronautics and Space Administration, Marshall Space Flight Center

48.7 Model codes and sources

The model is published in the form of tables and figures. Computer codes are available as KHA-73 and KCA-73 from the sponsor barry.c.roberts@nasa.gov.

49 Reference atmosphere for Patrick Air Force Base, Florida, annual, 1963

49.1 Model content

The *Reference Atmosphere for Patrick AFB, Florida, Annual (1963 Revision),* consists of a NASA report containing tables and figures of atmospheric properties. It is an empirical model defined by computed values of pressure, kinetic temperature, virtual temperature, molecular temperature, density, coefficient of viscosity, sound speed, molecular weight, pressure ratio, density ratio, viscosity ratio and temperature difference. "Ratio" as used in the report refers to the ratio of the value of the particular property to the value at the base of the atmosphere, while "pressure difference" refers to the difference between pressure at the base of the atmosphere and the pressure altitude. Virtual temperature is the temperature, which the atmosphere would have if the density were adjusted to reflect the removal of moisture.

In general, these parameters are tabulated for each 250-meter interval from 0 to 90 km altitude, each 1,000-meter interval from 90 to 300 km altitude, and each 2,000-meter interval from 300 to 700 km altitude. However, kinematic viscosity and kinetic temperature are computed from 0 to 90 km altitude only, virtual temperature becomes the same as kinetic temperature above the moisture layer (taken as approximately 10.8 km altitude), and molecular temperature is computed from 90 to 700 km only.

49.2 Model uncertainties and limitations

49.2.1 The model refers only to a specific location, Patrick AFB, Florida.

49.2.2 The model is based on data obtained early in the probing of the upper atmosphere. It cannot now be assessed satisfactorily.

49.3 Basis of the model

The model is an extension of the Atlantic Missile Range Atmosphere for Cape Kennedy, Florida, in which techniques described in the *U. S. Standard Atmosphere, 1962* are used. Median values of geopotential height, density, and temperature were computed from frequency distributions of each parameter for the standard pressure levels. The mathematical techniques for computing the properties from the basic data are described in detail.

49.4 Databases

The data used to derive the various atmospheric parameters were taken from the following references:

49.4.1 Range Reference Atmosphere Committee, Meteorological Working Group of the Inter-Range Instrumentation Group, *Atlantic Missile Range Reference Atmosphere for Cape Kennedy, Florida (Part I),* IRIG Document 104-63, Secretariat, Range Commander's Council, ATTN: STEWS-ROD-RCC, White Sands Missile Range, New Mexico, April 16, 1963.

49.4.2 Smith, O. E., *A Reference Atmosphere for Patrick Air Force Base, Florida, Annual*, NASA Technical Note D-595, March 1961.

49.4.3 *U.S. Standard Atmosphere, 1962* (described elsewhere in this document).

49.5 Publication references

Smith, O. E., and D. K. Weidner, *A Reference Atmosphere for Patrick AFB, Florida, Annual (1963 Revision)*, Technical Memorandum X-53139, September 23, 1964. http://trs.nasa.gov/archive/

49.6 Dates of development, authors and sponsors

49.6.1 Dates: 1963

49.6.2 Authors: O. E. Smith and D. K. Weidner

49.6.3 Sponsors: National Aeronautics and Space Administration, Marshall Space Flight Center

49.7 Model codes and sources

The model is published in the form of tables and figures only. However, the derived coefficients for empirical polynomials in five legs up to 83 km for the model are given in Table II of the publication. No computer codes are available. Copy is available from sponsor. (barry.c.roberst@nasa.gov)

50 Reference atmosphere for Vandenberg Air Force Base, California, annual, 1971

50.1 Model content

The *Reference Atmosphere for Vandenberg AFB, California, and Annual 1971 Version* is a geographical variant of the *Reference Atmosphere for Patrick AFB, Florida* (1963 Revision). Because of the close similarity to that model, the reader is referred to section 1 of the preceding abstract on the *Reference Atmosphere for Patrick AFB, Florida, Annual* (1963 Revision) for details.

50.2 Model uncertainties and limitations

The reader is referred to section 2 of the preceding summary for Patrick Reference Atmosphere.

50.3 Basis of the model

The model is an extension of the Inter-Range Instrumentation Group (IRIG) *Reference Atmosphere for Point Arguello, California*, (launch site -- Vandenberg AFB). The mathematical techniques used are identical to those used in the *Reference Atmosphere for Patrick AFB, Florida, Annual (*1963 Revision).

50.4 Databases

The data used to derive the various atmospheric parameters were taken from the references listed in section 4 of the Reference Atmosphere For Patrick AFB, Florida, Annual, 1963 abstract, plus Spivey, S. A., *A Preliminary Reference Atmosphere for Point Arguello, California* from 25 to 90 km Altitude, Technical Memorandum 54/50-90, LMSC-HREC A784890, Lockheed Missiles and Space Co., Huntsville, AL, November 1967.

50.5 Publication references

Carter, E. A., and S. C. Brown, A *Reference Atmosphere for Vandenberg AFB, California, Annual* (1971 Version), NASA Technical Memorandum X-64590, May 10, 1971. http://trs.nasa.gov/archive/.

50.6 Dates of development, authors and sponsors

50.6.1 Dates: 1971

50.6.2 Authors: E. A. Carter and S. C. Brown

50.6.3 Sponsors: National Aeronautics and Space Administration, Marshall Space Flight Center.

50.7 Model codes and sources

The model is published in the form of tables and figures only. However, the derived coefficients for empirical polynomials in five legs up to 81 km are given in Table I of the publications. Copy is available from sponsor. (barry.c.roberts@nasa.gov)

51 Hot and cold reference atmosphere for Vandenberg Air Force Base, California, annual, 1973

51.1 Model content

The *Hot and Cold Reference Atmospheres for Vandenberg AFB, California, (1973 Version)* consists of a report containing tables and figures of extreme summer and w inter atmospheric profile properties for the Vandenberg AFB area. It is an empirical model defined by computed values of pressure, kinetic temperature, virtual temperature, density, and relative (percent) deviations of temperature, pressure and density as a percent difference from the respective VRA-71 annual values, over the geometric altitude range from 0 to 90 km. V irtual temperature is the temperature, which would exist if the density were adjusted to reflect the removal of moisture. Virtual temperature is identical to kinetic temperature above the moisture layer at 9,000 meters altitude (Hot), and 5,000 meters altitude (Cold). In general, these parameters are tabulated or each 250-meter interval from 0 to 90 km altitude.

51.2 Model uncertainties and limitations

51.2.1 The model refers only to a specific location, Vandenberg AFB, California.

51.2.2 The model is based on atmospheric data obtained prior to 1966 in probing the upper atmosphere. It is subject to the errors in the measurements and the database cannot now be assessed satisfactorily.

51.3 Basis of the model

The two extreme Vandenberg AFB models were developed from analysis of the Vandenberg radiosonde and Point Mugu, California rocketsonde data. Extremes of temperature, pressure, and density were searched out at all altitude levels and i nter-level correlative techniques were applied subjectively between near-surface levels and tropopause heights to construct a Hot (summer) and a Cold (winter) type of atmospheric profile. The mathematical techniques for computing the properties from the basic data are described in detail.

51.4 Databases

51.4.1 National Climate Center (Ashville, NC), “Point Mugu, CA Radiosonde (1967 Soundings) from the Meteorological Rocket Network Firings”, World Data Center A-Meteorology, Data Reports (May 1959 through September 1967).

51.4.2 U. S. Air Force Environmental Technical Applications Center, “Monthly Density and Wind Correlations and Associated Statistics — Point Arguello, California,” (July 1959 through March 1965), Book II, Air Weather Service (MAC), Data Processing Division, Asheville, NC.

51.4.3 U.S. Air Force Environmental Technical Applications Center, “Revised Summary of Surface Weather Observations — Part E, Extreme Maximum and Minimum Temperatures for Vandenberg AFB, CA” (1951-52 and 1958-65), Washington, DC.

51.5 Publication references

51.5.1 Johnson, D. L., “Hot and Cold Atmospheres for Vandenberg AFB, CA (1973 Version)”, NASA TM X-64756, June 26, 1973. <http://trs.nasa.gov/archive/>

51.5.2 Johnson, D. L., “Terrestrial Environment (Climatic) Criteria Handbook for Use in Aerospace Vehicle Development,” NASA HDBK-1001, August 2000. <http://standards.nasa.gov>

51.6 Dates of development, authors and sponsors

51.6.1 Dates: 1973

51.6.2 Authors: D. L. Johnson

51.6.3 Sponsors: National Aeronautics and Space Administration, Marshall Space Flight Center

51.7 Model codes and sources

The model is published in the form of tables and figures. Computer codes are available as VHA-73 and VCA-73 from the sponsor barry.c.roberts@nasa.gov.

52 NASA/MSFC Mars global reference atmospheric model (MARS-GRAM), 2001

52.1 Model content

The Mars Global Reference Atmospheric Model (Mars-GRAM; Ref. 52.5.7) is an engineering-oriented, empirical model of the Mars atmosphere. The model provides both mean and wave-perturbed atmospheric density for any location (heights 0 to ~1000 km, any latitude and longitude) and time (seasonal and diurnal). Other atmospheric variables provided include atmospheric temperature, pressure and wind components. Dust storm effects are included for all atmospheric parameters, as controlled by user-selected options. Optionally, the model can simulate either local-scale or global-scale dust storms, or density perturbations from parameterized wave fields. Recently added features include: (1) basic atmospheric states from output of NASA Ames Mars General Circulation Model (MGCM; 0-80 km) and University of Michigan Mars Thermospheric General Circulation Model (MTGCM; 80-170 km), (2) option to use topography and reference height surface from Mars Orbiting Laser Altimeter (MOLA), and (3) new surface layer data, improved boundary layer representation (based on MGCM output) and a method to compute solar and thermal radiation fluxes at the surface and top-of-atmosphere.

52.2 Model uncertainties and limitations

Limited amounts of observational data in the height range 40-100 km produces uncertainties in this altitude region. The model has been validated against accelerometer density data from Mars Global Surveyor (MGS) and Mars Odyssey (100 – 120 km) and against MGS Thermal Emission Spectrometer and radio Science data (0 – 40 km) (Ref. 52.5.8 and 52.5.9).

52.3 Basis of the model

Mars-GRAM is based on surface and atmospheric temperature, density, and pressure from output of NASA Ames Mars General Circulation Model (MGCM; 0-80 km) and University of Michigan Mars Thermospheric General Circulation Model (MTGCM; 80-170 km). At the higher altitudes (above about 170 km), Mars-GRAM is based on the Stewart thermospheric model (Ref 52.5.6), modified as discussed in Reference 52.5.4

52.4 Databases

Parameterizations for altitude, geographical and seasonal variation of atmospheric temperature, density, pressure and winds are from amplitudes and phases of diurnal and semi-diurnal tides from NASA Ames Mars General Circulation Model (MGCM; 0-80 km) and University of Michigan Mars Thermospheric General Circulation Model (MTGCM; 80-170 km).

52.5 Publication references

52.5.1 Justus, C.G. (1990): "A Mars Global Reference Atmospheric Model (Mars-GRAM) for Mission Planning and Analysis", AIAA 90-004, 28th Aerospace Sciences meeting, Reno, NV, January.

52.5.2 Justus, C.G. (1991): "Mars Global Reference Atmospheric Model for Mission Planning and Analysis", *J. Spacecraft and Rockets*, *28*(2), 216-221.

52.5.3 Justus, C.G., Bonnie F. James and Dale L. Johnson (1996): "Mars Global Reference Atmospheric Model (Mars-GRAM version 3.34): Programmer's Guide", NASA TM 108509, May. http://trs.nasa.gov/archive/

52.5.4 Justus, C. G., D. L. Johnson, and B. F. James (1996): "A Revised Thermosphere for the Mars Global Reference Atmospheric Model (Mars-GRAM Version 3.4)", NASA TM 108513, July. http://trs.nasa.gov/archive/

52.5.5 Justus, C. G., D. L. Johnson (1996): "Global Reference Atmospheric Model (GRAM) Thermospheres for Mars and Earth: Comparison Studies", AIAA 96-4338, Space Programs and Technologies Conference, Huntsville, AL, September.

52.5.6 Stewart, A. I. F. (1987): "Revised Time Dependent Model Of The Martian Atmosphere For Use In Orbit Lifetime And Sustenance Studies", LASP-JPL Internal Report PO NQ-802429, NASA Jet Propulsion Laboratory, Pasadena, CA, March.

52.5.7 Justus, C. G. and D. L. Johnson (2001): "Mars Global Reference Atmospheric Model 2001 (Mars-GRAM 2001): Users Guide", NASA/TM-2001-210961, April. http://trs.nasa.gov/archive/

52.5.8 Justus, C. G. and D. L. Johnson, "Mars-GRAM Validation With Mars Global Surveyor Data", Paper C4.2-0005-02, 34th COSPAR Scientific Assembly — The Second World Space Congress, Houston, TX, October, 2002b.

52.5.9 Justus, C.G. and D.L. Johnson, "Global summary MGS TES data and Mars-GRAM validation", Paper C4.2-0005-02, 34th COSPAR Scientific Assembly — The Second World Space Congress, Houston, TX, October, 2002b

52.6 Date of development, authors and sponsors

52.6.1 Dates

Version 1.00	1988
Version 2.xx	1989
Version 3.0	1991
Version 3.1	1992
Version 3.2	1994
Version 3.3x	1995
Version 3.4	April 1996
Version 3.5	July 1996
Version 3.6	November 1996
Version 3.7	1997
Version 3.8	1998
Version 2000	2000
Version 2001	2001

52.6.2 Principal authors: C. G. Justus

52.6.3 Sponsors: National Aeronautics and Space Administration, Marshall Space Flight Center

52.7 Model codes and sources

A description and users manual for Mars-GRAM 2001 is provided in Reference 52.5.7. Mars-GRAM source code (suitable for PC or UNIX platforms) and data files are available. Contact NASA Marshall Space Flight Center, Natural Environments Branch, Marshall Space Flight Center, AL 35812, or jere.justus@msfc.nasa.gov or barry.c.roberts@nasa.gov for further information.

53 NASA/MSFC Neptune global reference atmosphere model (NEPTUNE-GRAM), 2003

53.1 Model content

The National Aeronautics and Space Administration's NASA/MSFC Neptune Global Reference Atmospheric Model (Neptune-GRAM 2003; Justus et al. 2003) program is under development. It is being used by several NASA centers for systems analysis and mission planning studies for future missions to the planet Neptune. Applications include analysis of guidance algorithms and thermal protection systems for missions involving aerocapture. Other Neptune-GRAM applications include scientific studies, orbital mechanics and lifetime studies, vehicle design and performance criteria, attitude control analysis problems, and dynamic response to turbulence or density shears.

In addition to evaluating the mean density, temperature, pressure, and wind components at any height (0-4000 km), Neptune-GRAM also allows for the simulation of "random perturbation" profiles about the mean conditions. This feature permits the simulation of a large number of realistic density, temperature and wind profile realizations along the same trajectory through the atmosphere, with realistic values of the scales of variation and peak perturbation values (e.g., the random perturbation profiles produce values which exceed the three standard deviation values approximately 0.1 percent of the time).

A simplified approach is adopted in Neptune-GRAM whereby effects of seasonal and latitudinal variations (as well as effects of relatively large measurement uncertainties for Neptune) are represented within a prescribed envelope of minimum-average-maximum density versus altitude. This envelope for Neptune is based on data from Cruikshank (1995). A single model input parameter ($F_{min-max}$) allows the user of Neptune-GRAM to select where within the min-max envelope a particular simulation will fall. $F_{min-max}$= -1, 0, or 1 selects minimum, average, or maximum conditions, respectively, with intermediate values determined by interpolation (i.e. min-max between 0 and 1 produces values between average and maximum). Effects such as variation with latitude along a given trajectory path can be computed by user-selected representations of variation of $F_{min-max}$with latitude. Atmospheric density perturbation magnitudes in Neptune-GRAM are estimated from a methodology similar to that of Strobel and Sicardy (1997) based on expected wave saturation effects.

In order to use the model, appropriate input parameters must be supplied, consisting of: (1) values of the program options, the initial position, the profile increments, and other information required before calculations are begun; and (2) a data base containing parameter values for the $F_{min-max}$. If it is desired to compute atmospheric properties along any trajectory other than a linear profile, then a third type of data – the trajectory positions – must be supplied.

Output consists of mean pressure, density, temperature, and wind velocity components, and random perturbation values of pressure, density, temperature and wind components. All the statistically different profiles of random perturbations desired can be evaluated by computing along the same trajectory with different input starting conditions for the random perturbation values.

53.2 Model uncertainties and limitations

53.2.1 The model does not predict any parameters in the sense of a forecast model. It only provides estimates of mean values and statistically realistic deviations from the mean.

53.2.2 The model does not take explicit account of seasonal, latitudinal, or time-of-day variations. It relies instead on the envelope of minimum-average-maximum values as described above.

53.2.3 Only limited observational data on Neptune are available, from Voyager flyby missions, Hubble and ground-based telescopic observations.

53.3 Basis of the model

A prescribed envelope of minimum-average-maximum density versus altitude is used to characterize the range of atmospheric variability. This envelope for Neptune is based on atmospheric data from Cruikshank (1995). A single model input parameter ($F_{min-max}$) allows the user of Neptune-GRAM to select where within the min-max envelope a particular simulation will fall. $F_{min-max}$= -1, 0, or 1 selects minimum, average, or maximum conditions, respectively, with intermediate values determined by interpolation (i.e. $F_{min-max}$between 0 and 1 produces values between average and maximum). Effects such as variation with latitude along a given trajectory path can be computed by user-selected representations of variation of $F_{min\text{-}max}$ with latitude. Atmospheric density perturbation magnitudes in Neptune-GRAM are estimated from a methodology similar to that of Strobel and Sicardy (1997) based on expected wave saturation effects.

53.4 Databases

Cruikshank, D.P., editor (1995): *Neptune and Triton*, University of Arizona Press, 1249 pages.

53.5 Publication references

53.5.1 Strobel, D.F., and B. Sicardy (1997): Gravity Waves and Wind Shear Models", in *Huygens Science, Payload and Mission*, ESA SP-1177, August.

53.5.2 Cruikshank, D.P., editor (1995): *Neptune and Triton*, University of Arizona Press, 1249 pages.

53.5.3 C.G. Justus, Aleta Duvall, and D .L. Johnson (2003): "Engineering-Level Model Atmospheres For Titan And Neptune", AIAA Joint Propulsion Conference, Huntsville, AL, 20-23 July.

53.6 Dates of development, authors and sponsors

53.6.1 Dates: Original beta-test model version 2002

General release version 2003

53.6.2 Principal authors: C. G. Justus

53.6.3 Sponsors: National Aeronautics and Space Administration, Marshall Space Flight Center

53.7 Model codes and sources

For information on the Neptune-GRAM computer code, "README" files, model description and user's manual, contact NASA Marshall Space Flight Center, Natural Environments Branch, Marshall Space Flight Center, AL 35812 or jere.justus@msfc.nasa.gov or barry.c.roberts@nasa.gov.

54 NASA/MSFC Titan global reference atmosphere model (TITAN-GRAM), 2003

54.1 Model content

The National Aeronautics and Space Administration's NASA/MSFC Titan Global Reference Atmospheric Model (Titan-GRAM 2003; Justus et al. 2003) program is under development. It is being used by several NASA centers for systems analysis and mission planning studies for future missions to Saturn's moon Titan. Applications include analysis of guidance algorithms and thermal protection systems for missions involving aerocapture. Other Titan-GRAM applications include scientific studies, orbital mechanics and lifetime studies, vehicle design and performance criteria, attitude control analysis problems, and dynamic response to turbulence or density shears.

In addition to evaluating the mean density, temperature, pressure, and wind components at any height (0-2200 km), Titan-GRAM also allows for the simulation of "random perturbation" profiles about the mean conditions. This feature permits the simulation of a large number of realistic density, temperature and wind profile realizations along the same trajectory through the atmosphere, with realistic values of the scales of variation and peak perturbation values (e.g., the random perturbation profiles produce values which exceed the three standard deviation values approximately 0.1 percent of the time).

A simplified approach is adopted in Titan-GRAM whereby effects of seasonal and latitudinal variations (as well as effects of relatively large measurement uncertainties for Titan) are represented within a prescribed envelope of minimum-average-maximum density versus altitude. This envelope for Titan, is based on engineering atmospheric profiles of Yelle et al. (1997). A single model input parameter ($F_{min-max}$) allows the user of Titan-GRAM to select where within the min-max envelope a particular simulation will fall. $F_{min-max}$= -1, 0, or 1 selects minimum, average, or maximum conditions, respectively, with intermediate values determined by interpolation (i.e. $F_{min-max}$between 0 and 1 produces values between average and maximum). Effects such as variation with latitude along a given trajectory path can be computed by user-selected representations of variation of $F_{min-max}$with latitude. Atmospheric density perturbation magnitudes in Titan-GRAM are estimated from a methodology similar to that of Strobel and Sicardy (1997) based on expected wave saturation effects.

In order to use the model, appropriate input parameters must be supplied, consisting of: (1) values of the program options, the initial position, the profile increments, and other information required before calculations are begun; and (2) a data base containing parameter values for the $F_{min-max}$. If it is desired to compute atmospheric properties along any trajectory other than a linear profile, then a third type of data – the trajectory positions – must be supplied.

Output consists of mean pressure, density, temperature, and wind velocity components, and random perturbation values of pressure, density, temperature and wind components. All the statistically different profiles of random perturbations desired can be evaluated by computing along the same trajectory with different input starting conditions for the random perturbation values.

54.2 Model uncertainties and limitations

54.2.1 The model does not predict any parameters in the sense of a forecast model. It only provides estimates of mean values and statistically realistic deviations from the mean.

54.2.2 The model does not take explicit account of seasonal, latitudinal, or time-of-day variations. It relies instead on the envelope of minimum-average-maximum values as described above.

54.2.3 Only limited observational data on Titan are available, from Voyager flyby missions, Hubble and ground-based telescopic observations.

54.3 Basis of the model

A prescribed envelope of minimum-average-maximum density versus altitude is used to characterize the range of atmospheric variability. This envelope for Titan is based on engineering atmospheric profiles of Yelle et al. (1997). A single model input parameter ($F_{min-max}$) allows the user of Titan-GRAM to select where within the min-max envelope a particular simulation will fall. $F_{min-max}$= -1, 0, or 1 selects minimum, average, or maximum conditions, respectively, with intermediate values determined by interpolation (i.e., $F_{min-max}$ between 0 and 1 produces values between average and maximum). Effects such as variation with latitude along a given trajectory path can be computed by user-selected representations of variation of $F_{min\text{-}max}$ with latitude. Atmospheric density perturbation magnitudes in Titan-GRAM are estimated from a methodology similar to that of Strobel and Sicardy (1997) based on expected wave saturation effects.

54.4 Databases

Yelle, R.V. et al. (1997): "Engineering Models for Titan's Atmosphere", in *Huygens Science, Payload and Mission*, ESA SP-1177, August.

54.5 Publication references

54.5.1 Strobel, D.F., and B. Sicardy (1997): Gravity Waves and Wind Shear Models", in *Huygens Science, Payload and Mission*, ESA SP-1177, August.

54.5.2 Yelle, R.V. et al. (1997): "Engineering Models for Titan's Atmosphere", in *Huygens Science, Payload and Mission*, ESA SP-1177, August.

54.5.3 C.G. Justus, Aleta Duvall, and D.L. Johnson (2003): "Engineering-Level Model Atmospheres For Titan And Neptune", AIAA Joint Propulsion Conference, Huntsville, AL, 20-23 July.

54.6 Dates of development, authors and sponsors

54.6.1 Dates: Original beta-test model version 2002

General release version 2003

54.6.2 Principal authors: C. G. Justus

54.6.3 Sponsors: National Aeronautics and Space Administration, Marshall Space Flight Center

54.7 Model codes and sources

For information on the Titan-GRAM computer code, "README" files, model description, and user's manual, contact NASA Marshall Space Flight Center, Natural Environments Branch, Marshall Space Flight Center, AL 35812 or jere.justus@msfc.nasa.gov or barry.c.roberts@nasa.gov.

55 NASA/MSFC Venus global reference atmosphere model (Venus-GRAM), 2003

55.1 Model content

The National Aeronautics and Space Administration's NASA/MSFC Venus Global Reference Atmospheric Model (Venus-GRAM 2005; Duvall et al. 2005) program has been used by several NASA centers for systems analysis and mission planning studies for future missions to Venus. Applications include analysis of guidance algorithms and thermal protection systems for missions involving aerocapture. Other potential Venus-GRAM applications include scientific studies, orbital mechanics and lifetime studies, vehicle design and performance criteria, attitude control analysis problems, and dynamic response to turbulence or density shears.

In addition to evaluating the mean density, temperature, pressure, and wind components at any height (0-1000 km), Venus-GRAM also allows the simulation of “random perturbation” profiles about the mean conditions. This feature permits the simulation of a large number of realistic density, temperature and wind profile realizations along the same trajectory through the atmosphere, with realistic values of the scales of variation and peak perturbation values (e.g., the random perturbation profiles produce values which exceed three standard deviation values approximately 0.1 percent of the time).

Up to 250-km altitude, dependence of Venus-GRAM mean atmospheric parameters on height, latitude, and time-of-day (or solar zenith angle) is based primarily on “The Venus International Reference Atmosphere” (Kliore et al., 1986), referred to here as VIRA. Above 250 km, rather that utilize the VIRA thermosphere extension of Keating et al. (1996), Venus-GRAM is based on an MSFC-developed Venus thermosphere model (Justh et al., 2006). Atmospheric perturbation magnitudes in Venus-GRAM are estimated from a methodology similar to that used in other MSFC GRAM models, based on expected wave saturation effects.

Output consists of mean pressure, density, temperature, and wind velocity components, and random perturbation values of pressure, density, temperature and wind components. All the statistically different profiles of random perturbations desired can be evaluated by computing along the same trajectory with different input starting conditions for the random perturbation values.

55.2 Model uncertainties and limitations

55.2.1 The model does not predict any parameters in the sense of a forecast model. It only provides estimates of mean values and statistically realistic deviations from the mean.

55.2.2 At low altitudes (0-100 km), the VIRA model depends on latitude only. At middle altitudes (100-150 km), VIRA depends on time-of-day only. At high altitudes (150-250 km), VIRA depends on solar zenith angle only

55.2.3 Above 250 km, the Venus-GRAM thermosphere assumes an isothermal temperature profile, initialized with VIRA conditions at 250 km. Constituent partial pressures are computed assuming diffusive separation, based on constituent molecular weights.

55.3 Basis of the model

Dependence of Venus-GRAM mean atmospheric parameters on height, latitude, and time-of-day (or solar zenith angle) is primarily based on the Venus International Reference Atmosphere model (Kliore et al., 1985), referred to here as VIRA. Other major data sources include "Venus" (Hunten et al., 1983), "Venus II", (Bougher et al., 1997), and "The Planet Venus" (Marov, and Grinspoon, 1998).

Mean zonal wind (u) versus height up to 80 km is from approximations to VIRA data, the "VIRA model", and from Fig. 5, page 469 of "Venus II", with latitude variation from Fig. 8, page 696 of "Venus". Mean meridional wind (v) versus height up to 80 km and versus latitude is from Fig. 3, page 466 of "Venus II". Up to 80 km, magnitudes of zonal and meridional wind perturbations are from approximations to VIRA data and the "VIRA Model”.

Magnitudes of density perturbations are estimated from temperature variations observed by Pioneer probes, taken from Figs. 1-8(d) and 1-12(a) of Seiff et al. VIRA data, pages 247, 259, and 278 of "Venus", pages 200 and 201 of "The Planet Venus", observed by Pioneer orbiter, taken from page 283 of "Venus II".

Additional data sources are described in Venus-GRAM documentation (README files), supplied with the program.

55.4 Databases

Tabular data from the Venus International Reference Atmosphere (VIRA; Kliore et al., 1985) were prepared as a database that is read in by Venus-GRAM. A database of appropriate "annual average" values was also calculated from the VIRA data tables.

55.5 Publication references

55.5.1 Duvall, Aleta L., C. G. Justus, and Vernon W. Keller (2005): "Global Reference Atmospheric Models For Aeroassist Applications", 3rd International Planetary Probe Workshop, 27 June – 1 July, Anavyssos, Attiki, Greece.

55.5.2 Keating, G.W., N.C. Hsu, and J . Lyu (1996): "Improved thermospheric Model for the Venus International Reference Atmosphere", Paper C3-1.0033, 31st Scientific Assembly of Committee on Space Research (COSPAR), University of Birmingham, England, July.

55.5.3 Justh, Hilary L., C. G. Justus, and Vernon W. Keller, (2006): "Global Reference Atmospheric Models, Including Thermospheres, for Mars, Venus and Earth," Paper AIAA-2006-6394, AIAA/AAS Astrodynamics Specialist Conference & Exhibit, 21-24 August, Keystone, CO.

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55.5.5 Hunten, D. M., L. Colin, T.M. Donahue, and V.I. Moroz, editors, (1983): "Venus", University of Arizona Press, Tucson.

55.5.6 Bougher, S.W., D.M. Hunten, and R.J. Phillips, editors, (1997): "Venus II", University of Arizona Press, Tucson.

55.5.7 Marov, M.Y., and D.H. Grinspoon, editors, (1998): "The Planet Venus", Yale University Press, New Haven.

55.6 Dates of development, authors and sponsors

55.6.1 Dates: General release version 2005

55.6.2 Principal authors: C. G. Justus

55.6.3 Sponsors: National Aeronautics and Space Administration, Marshall Space Flight Center

55.7 Model codes and sources

Venus-GRAM is available for use by NASA Centers and NASA-approved requestors. A description and users manual for Venus-GRAM is not yet available. Currently available documentation consists of "README" files. Contact barry.c.roberts@nasa.gov NASA Marshall Space Flight Center, Natural Environments Branch, Code EV44, Marshall Space Flight Center, AL 35812 for further information.

56 Venus international reference atmosphere (VIRA) structure and composition, surface to 3500 km, 1985

56.1 Model content

The VIRA structure and composition model details are described in chapters I, IV, and V of reference 5.1. The model formulation divides the atmosphere into four regions: surface to 100 km, 100 to 150 km, 150 to 250 km, and 250 to 3,500 km. The surface to 100 km region provides latitude dependent values of temperature, pressure, density and composition profiles, including gaseous constituents CO, N_2, Ar, Ne, Kr, O_2, H_2, H_2O, SO_2, D, and NH_3. The 100- to 150-km region provides latitude, night-side and day-side dependent values of temperature, pressure, density, CO_2, O, CO, N_2, He, and N plus speed of sound, mean free path and pressure and density scale heights. The 150 to 250 km region provides latitude, noon, and midnight, solar zenith angle, solar activity dependent values of density, temperature, pressure, mean molecular weight, speed of sound, mean free path, pressure and density scale heights plus gaseous constituents of CO_2, O, CO, N_2, N, He, C, and H. The 250 to 3,500 km region provides latitude, day-side, night-side, solar activity dependent values of temperature, pressure, density, and thermal and non-thermal components of a number of species, i.e., H, O_2, N, CO.

Reference 56.5.3 provides a recommended new improved Venus thermospheric model based on a limited number of thermospheric measurements obtained since publication in 1985 of the thermospheric model in VIRA. These measurements were obtained by means of both spacecraft orbital decay and mass spectrometry. These new measurements are incorporated into this recent VIRA model of the thermosphere, which should be consulted relative to use of the VIRA 1985 thermosphere model.

56.2 Model uncertainties and limitations

The nearly global infrared remote sensing measurements were limited in vertical resolution to about 10 km. In situ measurements were limited to a few soundings which sampled the instantaneous profiles with good resolution but could not of themselves define global or temporal mean conditions. The limited amount of measurements introduces variable uncertainties to the model. The models are not reliable for large atmospheric disturbances, including gravity waves and other waves propagating in middle atmosphere. To the degree practical, the scientific team used theoretical physical relationships with the measurements to produce a viable model of the Venus atmosphere.

Reference 56.5.2 provides a current review of the 1985 VIRA model relative to new data and important findings in the past decade from experiments on Soviet and U.S. spacecraft and Earth-based observations for an updated VIRA. It should be consulted for further information on this subject.

56.3 Basis of the model

The VIRA is based on analysis and synthesis of remote sensing and in situ measurements from the four Pioneer Venus Probes, the Pioneer Venus Orbiter, and the Venera 10, 12, and 13 landers. The model is consistent with the data sets within the measurement uncertainties and established variability of the atmosphere.

Given the surface conditions and temperature profile, the pressure and density profiles were constructed by requiring that the atmosphere be in hydrostatic equilibrium and obey the equation of state from surface up to 100 km. For the 150 to 250 km region, diffusive equilibrium is assumed and each species distributes itself independently according to its molecular weight. Average density, temperature, and composition were determined as a function of solar zenith angle. The 100-to-150-km model assumes the 150 km mixing ratios given in the 150-to-250 km model making a transition near the homopause (about 130 km). Above 250 km the philosophy of model formulation was basically to estimate thermal components by extrapolating in situ measurements and use airglow measurements to estimate the non-thermal components.

The VIRA model is a product of the task group formed under the impetus of the Committee on Space Research's (COSPAR) Interdisciplinary Scientific Commission C (Space Studies of the Upper Atmospheres of Earth and Planets, including Reference Atmospheres).

56.4 Databases

The database below 100 km used to construct the model included temperature retrievals of the infrared soundings, average temperature profiles from radio occulations, temperature variations from radio occulations, temperature profiles from net flux radiometer measurements, temperature profiles obtained during entry of Venera 13 and 14. Mass spectrometer measurements provided data on gaseous constituents of the atmosphere along with measurements from gas chromatographs, x-ray fluorescence spectrometers, and infrared radiometer. Above 100 k m, the databases also included spacecraft drag, accelerometer, mass spectrometer, microwave measurements of the thermodynamic properties, and composition.

56.5 Publication references

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56.5.2 Moroz, V. I. And L. V. Zaseva (1996): "A Review of Inputs for Updating of Venus International Reference Atmosphere," Paper Number C3-1.0005, 31st Scientific Assembly of Committee on S pace Research (COSPAR), university of Birmingham, England, July 1996.

56.5.3 Keating, G. M., N. C. Hsu, and J . Lyu (1996): "Improved Thermospheric Model for the Venus International Reference Atmosphere," Paper Number C3-1.0033, 31st Scientific Assembly of Committee on Space Research (COSPAR), University of Birmingham, England, July 1996.

56.6 Dates of development, authors and sponsors

56.6.1 Dates:	Plenary Meeting (COSPAR)	1982
	Workshop (VIRA)	1983
	Workshop (VIRA)	1984
	Plenary Meeting (COSPAR)	1996

56.6.2 Principal authors: Many scientists made contributions to the VIRA model development. They are detailed in Reference 56.5.1.

56.6.3 Sponsors: COSPAR

56.7 Model codes and sources

The VIRA model is published in the form of tables and figures. See Reference 56.5.1 for details.

57 Mars climate database (MCD), 2008

57.1 Model Content

This Mars Climate Database (MCD), provides not only the mean climatological values of main meteorological variables (i.e. atmospheric temperature, density, pressure and wind velocity) but also information about atmospheric composition (including dust and water vapor and ice content), as the General Circulation Model (GCM) from which the datasets are obtained includes both chemistry [Ref 57.5.6] and full water cycle [Ref 57.5.7] models. Successive improvements of GCMs have over the years lead to releases of improved versions of the Mars Climate Database. At the time of writing of the present document, the latest version of the MCD is MCD version 4.3 (released in May 2008).

The MCD extends up to ~350 km, i.e. up to and including the thermosphere [Ref 57.5.8 and 57.5. 9]. As the influence of Extreme Ultra Violet (EUV) input from the Sun is significant in the latter, three EUV scenarios (solar minimum, average and maximum) are considered to account for (and bracket) the impact of the various states of the solar cycle. The well known high variability of the Martian atmosphere due to atmospheric dust distribution is accounted for by considering four different dust scenarios which describe extreme cases (from very clear skies to global planet-wide dust storms) and a baseline scenario for which the dust loading of the atmosphere is that obtained from assimilation of Thermal Emission Spectrometer (TES) observations [Ref 57.5.10] in 1999-2001.

For all provided dust and EUV scenarios, the following mean values are provided (for any location and time of year and of day, via interpolation of the MCD datasets, see [Ref 57.5.4] for a detailed description):

- Atmospheric density, pressure, temperature and winds (horizontal and vertical),
- Surface pressure and temperature,
- CO_2 ice cover,
- Atmospheric turbulent kinetic energy,
- Thermal and solar radiative fluxes,
- Dust column opacity and mass mixing ratio,
- [H_2O] vapor and [H_2O] ice columns and mixing ratios,
- [CO], [O], [O_2], [N_2], [CO_2], [H_2] and [O_3] volume mixing ratios,
- Air specific heat capacity, viscosity and molecular gas constant R.

The MCD post-processing software moreover includes schemes which create a **"high resolution database"** which aims at predicting atmospheric fields like pressure, temperature or density with a resolution better than 2 km and improved accuracy. In practice, we combine high resolution (32 pixels/degree) MOLA topography and Viking Lander 1 pressure records with raw "low resolution" MCD surface pressure and reconstructs surface pressure at high resolution. The latter is also then used to reconstruct vertical fields and, within the restriction of the procedure, yield high resolution values of atmospheric variables.

Apart from the mean values of main variables, the MCD also provides information about the variability of the Martian climate. In addition to the seasonal and diurnal variations which are directly stored in the database, the day to day (RMS) variability of the main meteorological variables (e.g. atmospheric temperature, density, pressure, winds, …) is provided. The supplied RMS is moreover given either pressure-wise or altitude-wise, depending on the vertical coordinate system selected by the user.

The MCD software provides users with the possibility to reconstruct realistically the variability of the Martian weather by adding perturbations to the aforementioned mean values of main meteorological variables. These perturbations may be small scale or large scale. The small scale variability model adds (user-defined wavelength) gravity waves to the background mean field and the large scale perturbation model uses a set of Empirical Orthogonal Functions (EOFs) derived from the original GCM runs to recreate coherent (time-wise and location-wise) fluctuations about mean atmospheric states.

57.2 Model uncertainties and limitations

The MCD has been validated using available observational data. These comparisons, which are detailed in the MCD's **validation document** [Ref 57.5.5], include:

- Comparisons with the values of *surface temperature*, *atmospheric temperature* and *water vapour column* retrieved by the Thermal Emission Spectrometer (TES) onboard Mars Global Surveyor (MGS) collected over almost three full Mars years.
- Comparisons with the values of *atmospheric temperature* derived from radio occultation using the ultra stable oscillator onboard MGS.
- Comparisons with the values of *surface pressure* recorded by the Viking Landers and Pathfinder.

57.3 Basis of model

The Mars Climate Database (MCD) is a database of meteorological fields derived from General Circulation Model (GCM) numerical simulations of the Martian atmosphere and validated using available observational data. The GCM was developed at Laboratoire de Météorologie Dynamique du CNRS (Paris, France) [Ref 57.5.1 and 57.5.2] in collaboration with the Open University (UK), the Oxford University (UK) and the Instituto de Astrofisica de Andalucia (Spain) with support from the European Space Agency (ESTEC contract 11369/95/NL/JG “Mars Climate Database and Physical Models”) and the Centre National d'Etudes Spatiales (CNES contract “Base de Données Climatique Martienne”).

The 3D Mars GCM that has been used to build the MCD is the result of an ongoing collaboration between teams based in France (LMD, Paris and SA, Paris), the UK (The Open University, Milton Keynes and the University of Oxford) and Spain (IAA, Granada), with the support of ESA and CNES.

The MCD includes access software which, using the GCM output datasets, provides mean values and statistics of Martian meteorological quantities. The access software moreover includes complementary post-processing schemes which enable high spatial resolution reconstruction of environmental data and multiple means of realistically reconstructing the variability thereof.

The General Circulation Models now includes schemes to simulate the cycle of water vapor and clouds [Ref 57.5.7 and 57.5.13] as well as the photochemistry of many components of the atmosphere [Ref 57.5.6, 57.5.9, and 57.5.13] with high accuracy compared to available observations. It can also be used to model the lifting, transport and deposition of dust to simulate dust storms and the distribution of dust particles in the atmosphere [Ref 57.5.14, 57.5.15, 57.5.16, and 57.5.17]. Last, a mesoscale (high resolution) dynamical model of the Martian atmosphere has been derived from the GCM, in order to simulate the details of the atmospheric physics and circulation with a resolution ranging from a few tens of meters to a few tens of kilometers [Ref 57.5.18]

57.4 Databases

The Mars GCM was originally [Ref 57.5.11] derived from the models used on Earth for weather forecasting and climate change studies. It has since then constantly evolved and been improved [Ref 57.5.12] with the aim to be able to reproduce (based only of physical equations and without any tailor-made forcings) all the available observations of the Martian climate.

A thorough description of the basic version of the LMD GCM can be found in [Ref 57.5.1]. To summarize, the GCM is a grid-point model which consists of a dynamical core (which integrates in space and time the hydrostatic primitive equations of dynamical meteorology) coupled to a (Mars-specific) package of physical parameterizations (radiative transfer, surface processes, sub-grid-scale dynamics, CO_2 condensation and sublimation, …). The grid point formulation enables to run the model at various longitudexlatitudexaltitude resolutions. The GCM is typically (as was the case for the runs used to generate the datasets for the MCD) run with the resolution of 64x48 horizontal resolution, which corresponds to a 5.625°x3.75° longitudexlatitude grid. The vertical GCM coordinate is a hybrid coordinate which corresponds to a mix of terrain-following sigma (ratio of pressure to surface pressure) coordinates near the surface and pressure levels in altitude. This irregular grid (see Ref 57.5.4) for a detailed description) roughly corresponds to having the first layers typically located around 5m, 20m, 40m, 100m, up to 80km (in a 25 layer version), 120km (32 layer version which includes non-LTE radiative transfers in CO_2 [Ref 57.5.8]) or more than 300km (in the 50 layer version which includes the thermosphere [Ref 57.5.9] and was used to generate the MCD datasets [Ref 57.5.4]).

57.5 Publication references

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57.5.10 Montabone L. et al. (2006) "Results on dust storms and stationary waves in three Mars years of data assimilation", *2nd International Workshop on Mars Atmosphere Modeling and Observations*, available online at http://www-mars.lmd.jussieu.fr/granada2006/abstracts/Montabone_Granada2006.pdf

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57.5.14 Newman, C. E., S. R. Lewis, P. L. Read, and F. Forget Modelling the Martian dust cycle. 1: Representation of dust transport processes, J. Geophys. Res. 107, E10, 2002

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57.5.16 Forget, F. *Martian Dust density, particle size and spatial distribution: Part 1) Multisize dust transport design*. CNES report, 2008

57.5.17 Forget, F. *Martian Dust density, particle size and spatial distribution: Part 2) Dust size observations and 3D model results*. CNES report, 2008

57.5.18 Spiga, A. and Forget, Realistic modeling of the Martian mesoscale and m icroscale circulation: validation and first results. Journal of Geophysical Research, submitted (2008)

57.6 Dates of development, authors and sponsors

In 1995, at the initiative of the European Space Agency, the LMD (Laboratoire de Météorologie Dynamique du CNRS, Université Paris 6) and AOPP (Atmospheric, Oceanic and Planetary Physics, University of Oxford) teamed up to develop their respective GCMs and build a Mars Climate Database.

The MCD and associated GCM are currently developed at LMD (Paris, France) in collaboration with the Open University (UK), the Oxford University (UK) and the Instituto de Astrofisica de Andalucia (IAA, Granada, Spain) with support from the European Space Agency (ESTEC contract 11369/95/NL/JG "Mars Climate

Database and Physical Models") and the Centre National d'Etudes Spatiales (CNES contract "Base de Données Climatique Martienne").

The Mars Climate Database is currently maintained and developed by F. Forget[1], E. Millour[1] and S.R. Lewis[2], and the development of the associated GCM results from the combined efforts of many, namely (only recent contributors are cited here) F. Forget[1], E. Millour[1], F. González-Galindo[1], A. Spiga[1], J.-B. Madeleine[1], P.-Y. Meslin[1], S. Lebonnois[1], F. Hourdin[1], L. Montabone[1,2], S.R. Lewis[2], P.L. Read[3], M.A. López-Valverde[4], G. Gilli[4], F. Lefèvre[5], F. Montmessin[5].

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[2]Department of Physics and Astronomy, The Open University, Milton Keynes, UK

[3]Atmospheric, Oceanic & Planetary Physics, University of Oxford, Oxford, UK

[4]Instituto de Astrofísica de Andalucía, Granada, Spain

[5]Service d'Aéronomie, IPSL, UPMC, Paris, France

57.7 Model codes and sources

The MCD is freely distributed and available in two different forms, either (for moderate needs) in a simplified form as an online interactive interface or as a full version (necessary for intensive and precise work) freely available on DVD.

The MCD World Wide Web interface (which is based on a Live Access Server) is available at http://www-mars.lmd.jussieu.fr and gives access to:

- Mean monthly value of main variables, at twelve times of the day, for all dust and EUV scenarios.
- The possibility to choose between three different vertical coordinates (pressure levels, altitude above areoid or above local surface) along which to output data.
- A wide range of output formats: Images (gif or postscript files), NetCDF data files and various formats of text files.
- Computation of simple user-defined variables (averages, minimum or maximum values).
- An Earth date to Mars date (value of solar longitude Ls) converter.

The freely distributed MCD DVD-ROM (simply contact francois.forget@lmd.jussieu.fr and/or ehouarn.millour@lmd.jussieu.fr to obtain a copy) contains:

- The MCD documentation: a **user manual** [3], along with a **validation document** [5] which details comparisons of MCD outputs with available measurements and a **detailed design document** [4] which describes the technical aspects of how the data is stored and processed.
- The data files (in NetCDF format).
- Access software (a Fortran 77 subroutine "call_mcd") which does all the necessary post-processing to include and account for sub-grid scales, day to day variability, ...
  It is provided as source code to be compiled by the user and has been developed on Unix (but can be ported to Windows).
- Examples of IDL, Matlab, Scilab, C and C++ interfaces to the MCD access software.
- A lighter standalone high resolution surface pressure predictor, "pres0".

58 Extra-terrestrial space environment: a reference chart, 2007

58.1 Chart content

This 25 ½ inch by 33 inch Reference Chart of the Extra-Terrestrial Space Environment provides information on the atmospheres of the planets, dwarf planets, comets, and asteroids as follows:

Mercury: Cross section of the magnetosphere and tabulation of the neutral and ion densities of exosphere and exo-ionosphere.

Venus: Cross section of the magnetosphere, atmospheric density profiles, vertical density profiles for the major ion species in the dayside ionosphere, calculated electron and ion temperatures for zero magnetic field and 60 deg solar zenith angle.

Earth: Cross section of the magnetosphere, atmospheric density profiles versus altitude for the Earth's mean atmosphere, densities of Earth's ionospheric species versus altitude for daytime conditions and s olar minimum, and daytime temperatures at Equinox versus altitude for the Earth's neutral atmosphere, ions, and electrons at solar maximum and solar minimum.

Mars: Cross section of the magnetosphere, Martian atmosphere versus altitude, estimated ion density profiles for the dayside ionosphere, and calculated electron and ion temperatures.

Jupiter: Cross section of the magnetosphere, Jovian atmospheric densities versus altitude, modeled ion and electron (Ne) density profiles, and Jovian temperature versus altitude.

Saturn: Cross section of the magnetosphere, atmospheric density and composition versus altitude, modeled ionospheric density profiles, and atmospheric temperature profile versus altitude.

Uranus: Cross section of the magnetosphere, schematics of the Uranian magnetosphere, abundance profiles inferred from observations, theoretical electron and ion number densities for an isothermal atmosphere, and temperature versus altitude profile inferred from observations.

Neptune: Cross section of the magnetosphere, schematics of the Neptunian magnetosphere, atmospheric density versus altitude, theoretical electron and ion number densities, and temperature versus altitude.

Pluto: Cross section of the magnetosphere, calculated chemical structure of mean atmosphere assuming a distance of ~40 AU, ionospheric structure for an atmosphere assuming a distance of ~40 AU, atmospheric temperature profile versus altitude for a mean atmosphere assuming hydrostatic equilibrium and an isothermal atmosphere at 104 deg K above the occultation half-light point.

Comets: schematic of the interaction of the solar wind with a comet, representative atmospheric density profiles for a comet showing how composition might vary with distance for Comet P/Halley at 1 AU, and model of Comet P/Halley ion and electron populations at 1 A versus radial distance from the nucleus.

Asteroids: Locations of the principle asteroids in the solar system.

Comparisons: Tabulation of various planetary characteristics, comparisons between the scale sizes of various planetary magnetospheres in the solar system, comparison of the electron densities of the ionospheres of the various planets versus altitude, comparison of the pressure versus temperature profiles for various planets and Titan, temperature distributions for Venus, Earth, and Mars consistent with current understanding of these planetary atmospheres. Relative sizes of the known satellites of the solar system shown with the Earth and Mars for comparison.

58.2 Model uncertainties and limitation

The references within the Reference Chart (Ref. 5.1) provide the planetary model uncertainties and limitations used to produce the contents of this Reference Chart and should be consulted accordingly for this information.

58.3 Basis of the chart contents

The research relative to the preparation of this Reference Chart was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

58.4 Databases

The references within the Reference Chart (Ref. 58.5.1) provide the detail information of the contents of this Reference Chart. They should be consulted for descriptions of the databases used in the development of the inputs used in preparation of the contents of this Reference Chart.

58.5 Publication references

58.5.1 Garrett, Henry B. and Robin W. Evans, "The Extra-Terrestrial Space Environment: A Reference Chart", AIAA SP-078, American Institute of Aeronautics and Astronautics, and JPL 400-1281, Jet Propulsion Laboratory, California Institute of Technology.

58.6 Dates of development, authors and sponsors

58.6.1 Dates: April 2007

58.6.2 Authors: Henry B. Garrett and Robin W. Evans, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109

58.6.3 Sponsors: National Aeronautics and Space Administration

58.7 Model codes and sources

The Extra-Terrestrial Space Environment: A Reference Chart may be obtained from the American Institute of Aeronautics and Astronautics as AIAA SP-078. E-mail address: custserv@aiaa.org or http://www.aiaa.org. Mail address: 1801 Alexander Bell Drive, Suite 500, Reston, VA 20191-4344.

Annex
(normative)

Glossary of acronyms

AE	Atmosphere Explorer (spacecraft)
AFB	Air Force Base (USAF)
AFCRL*	Air Force Cambridge Research Laboratory (now AFGL)
AFETAC*	Air Force Environmental Technical Applications Center
AFGL*	Air Force Geophysics Laboratory
AFRL*	Air Force Research Laboratory
AFSC*	Air Force Space Command
AGU	American Geophysical Union
AIAA	American Institute of Aeronautics and Astronautics
CASI*	China Astronautics Standards Institute
CIRA	COSPAR International Reference Atmosphere
CNES	Centre National d'Etudes Spatiales
COESA	Committee on Extension of the Standard Atmosphere
COSPAR*	Committee on Space Research
DDCM	Direct Density Correction Method
DE	Dynamic Explorer (spacecraft)
DOE*	Department of Energy
ECA	Edwards (AFB) Cold Atmosphere (model)
ECSS	European Cooperation for Space Standardization
EHA	Edwards (AFB) Hot Atmosphere (model)
ERA	Edwards Reference Atmosphere
ESRO	European Space Research Organization
GCM	General Circulation Model
GOST*	Government Standard (of the USSR)
GRAM	Global Reference Atmosphere Model
GSFC*	Goddard Space Flight Center (NASA)
GUACA	Global Upper Air Climatic Atlas
HASDM	High Accuracy Satellite Drag Model
ICAO*	International Civil Aviation Organization
ICSU*	International Council of Scientific Unions
IIT	Indian Institute of Science
IRI*	International Reference Ionosphere
IRIG*	Inter-Range Instrumentation Group
ISO*	International Organization for Standardization

ISRO*	Indian Space Research Organization
KCA	Kennedy (SFC) Cold Atmosphere (model)
KHA	Kennedy (SFC) Hot Atmosphere (model)
LMD	Laboratoire de Meteorologie Dynamique
MAP	Middle Atmosphere Program
MET	Marshall Engineering Thermosphere (model)
MGCM	Mars General Circulation Model
MOLA	Mars Orbiting Laser Altimeter
MRN	Meteorological Rocket Network
MSFC*	Marshall Space Flight Center (NASA)
MSIS	Mass Spectrometer-Incoherent Scatter Radar (measuring techniques)
MSISE	Mass Spectrometer-Incoherent Scatter Radar Extended
MTGCM	Mars Thermospheric General Circulation Model
NASA*	National Aeronautics and Space Administration
NCDC	National Climatic Data Center
NMC	National Meteorological Center
NOAA*	National Oceanic and Atmospheric Administration
NRL*	Naval Research Laboratory
NSSDC	National Space Science Data Center
OGO	Orbiting Geophysical Observatory (spacecraft)
PMR	Pressure-Modulated Radiometer
PRA	Patrick Reference Atmosphere
QBO	Quasi-Biennial Oscillation
RCCMWG*	Range Commanders Council Meteorological Working Group
RRA	Range Reference Atmosphere
SAO*	Smithsonian Astrophysical Observatory
SCOSTEP*	Scientific Committee on Solar-Terrestrial Physics
SCR	Selective Chopper Radiometer
SMM	Solar Maximum Mission
TIME-GCM	Thermosphere-Ionosphere-Mesosphere-Electrodynamics General Circulation Model
URSI*	International Union of Radio Science
USAF*	United States Air Force
USM	Universal Semi-analytical Theory
VCA	Vandenberg (AFB) Cold Atmosphere
VHA	Vandenberg (AFB) Hot Atmosphere
VIRA	Venus International Reference Atmosphere
WMO	World Meteorological Organization

NOTE Entries with asterisks indicate that some of the sponsoring organizations for one or more models are presented in this guide.