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

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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

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard 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/TR 11225 was prepared by Technical Committee ISO/TC 20, *Aircraft and space vehicles*, Subcommittee SC 14, *Space systems and operations*.

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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 Technical Report.

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

1 Scope

This Technical Report provides guidelines for selected reference and standard atmospheric models for use in engineering design or scientific research. It 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.

This Technical Report 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 specific 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/Add 1:1983, *Reference atmospheres for aerospace use — Addendum 1: Wind supplement*

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

ISO 5878:1982/Amd 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 latitude 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 coupled polar ionosphere/global thermosphere model is also presented, which demonstrates the major interactions between the thermosphere and ionosphere.

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Part I also contains five specialized chapters which review the major empirical contributions to our current understanding of the thermosphere. These sections discuss in situ mass spectrometer measurements of composition, temperature and winds; incoherent scatter radar measurements, satellite and ground-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.

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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.

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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 (ISO 5878:1982)

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.

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ISO 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 ISO 5878:1982 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 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.

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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 5878:1982, *Reference Atmospheres for Aerospace Use,* Technical Committee ISO/TC 20, Aircraft and Space Vehicles.

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

6.5.3 ISO 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 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 an ISO International Standard "Global Reference Atmosphere for Altitude 0-120 km for Aerospace Use".

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This planned new ISO International 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 October. 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 informational 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 (ISO 2533:1975)

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 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.*

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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: GOST 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 US Committee on Extension to the Standard Atmosphere: US Standard Atmosphere, 1962, US Government Printing Office, Washington, DC, 1962.

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

7.5 Publication references

ISO 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).

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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, • is the angular speed of rotation of the Earth, g_0 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:

$$\langle U_{eq} \rangle = -\frac{g_0}{\beta} \frac{\partial^2 \langle Z \rangle}{\partial y^2} \tag{2}$$

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

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

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

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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 Technical Report.

8.5 Publication references

8.5.1 Barnett, J. J., and M. Corney (1985), Middle atmosphere reference model derived from satellite data, *Middle Atmosphere Program, Handbook for MAP, 16,* edited by K. Labitzke, J. J. Barnett, and B. Edwards, pp. 47-85.

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, US 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.

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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.

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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 US Navy and US 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.

9.4.3 Hickey, M. P. (1988) The NASA Marshall Engineering Thermosphere Model, NASA CR-179359, July 1988.

9.4.4 Ruth, D. B. et al. (1993): "Global Upper Air Climatic Atlas (GUACA)." CD ROM data set, version 1.0 (vol. 1 1980 to 1987, vol.2 1985 to 1991). US Navy - US Department of Commerce (NOAA/NCDC), April.

9.4.5 Dartt, D. et al, (1988), User’s Guide to Satellite Based Global Atmospheric Reference Model Statistics (20 to 85 km), Final Report N00014-86-C-0076, Control Data Corporation.

9.5 Publication references

9.5.1 Justus, C. G. , A. W. Woodrum, R. G. Roper, and O. E. Smith (1974), “Four-D Global Reference Atmosphere, Technical Description. Part 1,” NASA Technical Memorandum NASA TMX-64871.

9.5.2 Justus, C. G., A. Woodrum, R. G. Roper, and O. E. Smith (1974), “Four-D Global Reference Atmosphere, Users’ Manual and Programmers’ Manual, Part 2,” NASA TMX-64871.

9.5.3 Justus, C. G., and A. Woodrum (1975), “Revised Perturbation Statistics for the Global Scale Atmospheric Model,” Georgia Institute of Technology Final Report Contract NAS2-30657.

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9.5.4 Justus, C. G., and W. R. Hargraves (1976), “The Global Reference Atmospheric Model - Mod 2 (with two scale perturbation model),” Georgia Institute of Technology Interim Technical Report - Contract NAS8-30657.

9.5.5 Justus, C. G., G. R. Fletcher, F. E. Gramling, and W. B. Pace (1980), “The NASA/MSFC Global Reference Atmospheric Model -- mod 3 (with spherical harmonic wind model),” NASA CR-3256.

9.5.6 Justus, C. G., F. N. Alyea, D. M. Cunnold, and D. L. Johnson (1986), GRAM-86, “Improvements in the Global Atmospheric Model,” NASA MSFC report ED-5-15-86.

9.5.7 Justus, C. G., F. N. Alyea, D. M. Cunnold, R. S. Blocker, and D. L. Johnson (1988), GRAM-88 “Improvements to the Perturbation Simulation of the Global Reference Atmospheric Model,” NASA-Marshall Space Flight Center Memorandum ES-44-11-9-88.

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.

9.5.9 Justus, C. G., F. N. Alyea, D. M. Cunnold, W. R. Jeffries, III, and D. L. Johnson (1991b), “The NASA/MSFC Global Reference Atmospheric Model - 1990 Version (GRAM-90): Part 2, Program/Data Listings” NASA TM 4268.

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.

9.5.13 Justus, C. G., and D. L. Johnson (1999), “The NASA/MSFC Global Reference Atmospheric Model - 1999 Version (GRAM-99)," NASA TM-1999-209630. <http://trs.nasa.gov/archive/00000503/>

9.5.14 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.

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

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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.

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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).

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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 US Navy and the US 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

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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

10.4.1 Justus, C.G. and F.W. Leslie, “The NASA MSFC Earth Global Reference Atmospheric Model—2007 Version”, NASA/TM –2008—215581, November 2008.

10.4.2 Bowman, B. R., Tobiska, W. K., and Marcos, F.A., “A New Empirical Thermodynamic Density Model JB2006 Using New Solar Indices”, Paper AIAA 2006-6166, Presented at AIAA/AAS Astrodynamics Specialist Conference, Keystone, Colorado, August 21 – 24, 2006.

10.4.3 Hedin, A.E., “A Revised Thermospheric Model Based on Mass Spectrometer and Incoherent Scatter Data: MSIS-83”, J. Geophys. Res., 88, 10170, 1983.

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

10.4.5 Ruth, D.B. *et al*, “Global Upper Air Climatic Atlas (GUACA)”. CD ROM data set, version 1.0 (vol. 1 1980 to 1987, vol. 2 1985 to 1991). US Navy – US Department of Commerce (NOAA/NCDC) April, 1993.

10.4.6 Suggs, R., "NASA Marshall Engineering Thermosphere Model - 2007 Version (MET-2007)", (see entry for the MET-2007 within text of this AIAA Guide.)

10.4.7 US Standard Atmosphere, 1976, US Government Printing Office, Washington, D.C., 1976.

10.5 Publication references

10.5.1 Adelfang, S. I. (1999), “User's Guide for Monthly Vector Wind Profile Model”, NASA/CR--1999-209759, May 1999

10.5.2 Braun, R.D., Powell, R.W., and Lyne, J.E. (1992) “Earth Aerobraking Strategies For Manned Return From Mars”, Journal of Spacecraft and Rockets, Vol.29 No.3 (297-304).

10.5.3 Decker, R. and Leach, R., “Assessment of Atmospheric Winds Aloft During NASA Space Shuttle Program Day of Launch Operations” (2005), AIAA-2005-266, 43rd AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, Jan. 10-13, 2005.

10.5.4 Desai, P.N., Braun, R.D.,Powell, R.W., Engelund, W.C., and Tartabini, P.V. (1997), “Six-Degree-of-Freedom Entry Dispersion Analysis for the METEOR Recovery Module”, Journal of Spacecraft and Rockets, vol.34 no.3 (334-340) 1997.

10.5.5 Desai, P.N., Mitcheltree, R.A., and F. Cheatwood, F.M. (1997), “Entry dispersion analysis for the Stardust comet sample return capsule”, AIAA-1997-3812, AIAA Atmospheric Flight Mechanics Conference, New Orleans, LA, Aug. 11-13, 1997.

10.5.6 Desai, P.N., Mitcheltree, R.A., and Cheatwood, F.M. (1999), "Entry Trajectory Issues for the Stardust Sample Return Capsule," International Symposium on Atmospheric Reentry Vehicles and Systems, March 1999, Arcachon, France.

10.5.7 Desai, P.N. and Cheatwood, F.M. (2001), “Entry Dispersion Analysis for the Genesis Sample Return Capsule”, Journal of Spacecraft and Rockets, vol.38 no.3 (345-350).

10.5.8 Hale, N., Lamotte, N., and Garner, T. (2002), “Operational Experience with Hypersonic Entry of the Space Shuttle”, AIAA-2002-5259, AIAA/AAAF 11th International Space Planes and Hypersonic Systems and Technologies Conference, Orleans, France, Sep. 29-Oct. 4, 2002.

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10.5.9 Harpold, J.C., and Graves, C.A. (1979), “Shuttle Entry Guidance,” NASA TM-79949.

10.5.10 Harpold, J.C., and Graves, C.A. (1979), “Shuttle Entry Guidance,” Journal of the Astronautical Sciences, vol. 27(3), pp. 239-268.

10.5.11 Justus, C.G., Woodrum, A., Roper, R.G., and Smith, O.E. (1974), "A Global Scale Engineering Atmospheric Model for Surface to Orbital Altitudes, 1: Technical Description", NASA TMX-64871.

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.

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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 US Standard Atmosphere, 1962

11.1 Model content

The *US 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 the US Standard Atmosphere, 1962 is provided for historical information. The reader is directed to the US 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 US 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. This model was subsequently extended by the 1966 Supplement and then superseded by the US 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

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

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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, US 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: US Extension to the ICAO Standard Atmosphere 1958

US Standard Atmosphere, 1962

11.6.2 Principal authors: M. Dubin, N. Sissenwine, and H. Wexler, Co-chairmen, US 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, US Air Force, US 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 US Standard Atmosphere, 1962 should be available from the US Government Printing Office, Washington, DC.

12 US 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 *US 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.

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12.2 Model uncertainties and limitations

The uncertainties and limitations are similar to those for the *US 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 *US 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 US Air Force, *US Standard Atmosphere Supplements, 1966,* U. S. Government Printing Office, 1966.

12.6 Dates of development, authors and sponsors

12.6.1 Dates: US Standard Atmosphere, 1962

US Standard Atmosphere Supplements1966

12.6.2 Principal authors: M. Dubin, N. Sissenwine, and S. Teweles, Co-chairmen, US 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 US 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 US Standard Atmosphere Supplements, 1966 should be available from the US Government Printing Office, Washington, DC.

13 US Standard Atmosphere, 1976

13.1. Model content

The *US Standard Atmosphere, 1976*, the successor to the *US 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 US 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

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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 Report 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 Report 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^* = 8.31432x10³ not 8.31432x10⁻³ Nm/(kmol K)
Page 2, Table 2. r_0 = 6.356766x10³ not 6.356766x10⁶ 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_{t0} = 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 US 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

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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

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

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

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

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, *US Standard Atmosphere 1976,* US 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: US Standard Atmosphere, 1962

US Standard Atmosphere Supplements, 1966

US 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.

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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, US 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 US Standard Atmosphere, 1976 has been provided as noted:

US Committee on Extension to the Standard Atmosphere, "US Standard Atmosphere, 1976", National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, US 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;

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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.

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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).

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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

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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 km [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.

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