COSPAR International Reference Atmosphere - 2012

CIRA-2012

Models of the Earth's Upper Atmosphere

Foreword

The Committee on Space research (COSPAR) International Reference Atmosphere 2012 (CIRA-2012) is the fifth in the series.

CIRA is prepared by an International Working Group jointly sponsored by COSPAR and URSI (Union of Radio Science). The Working Group has met regularly at the biennial COSPAR Scientific Assemblies between 2002 (Houston, USA) and 2012 (Mysore, India). The CIRA Working Group reviews progress with the development of an appropriate range of semi-empirical and other models of the Earth's Upper Atmosphere. The CIRA WG provides considered advice and recommendations to COSPAR Commission C (Earth and Planetary Upper Atmospheres and Ionospheres) on the appropriate contents of the current version of CIRA. Commission C is responsible for deliberating these recommendations and adopting the CIRA.

The current version is CIRA-2012, and it is initially published via the Web.

CIRA-2012 is now accessible through the Web Address:

➔ **http://sol.spacenvironment.net/CIRA-2012**

The Historical Development of CIRA Atmospheric Models.

The first edition of CIRA appeared in 1961. It contained the first models of the thermosphere which were based on direct observational data, namely air density data. These data were derived from measurements of the atmospheric drag effects on satellites following the launch into orbit of Sputnik 1 in October 1957 and the subsequent launches of USSR and USA satellites. Due to the rapid increase in data from rockets and satellites, a revised CIRA was published in 1965. This volume contained a mean atmospheric profile from 30 to 300 km, tables of atmospheric structure and its variations in the region from 30 to 100 km, and tables of mid-latitude atmospheric properties, including diurnal variations, for the region from 120 to 800 km, using a theoretical model to extend the limited observational data base available at that time.

A third edition appeared in 1972. By this time, there had been a considerable increase in the data on which the middle atmosphere models were based. However, the biggest advance was in the understanding and specification of the major causes of variations of thermospheric properties. Based on the development of thermospheric models (M. Nicolet) using temperature profiles and the assumption of diffusive equilibrium, families of empirical models were developed, defined by temperature profiles, with the exospheric temperature as the principal parameter. These properties were primarily dependent on local time, season, solar activity and a semi-annual variation. L.G. Jacchia provided tables for the altitude region from 110 to 2000 km. G.V. Groves prepared detailed tabulations of atmospheric properties for the region 25 to 110 km, as functions of latitude and time of year. Because the values of the Jacchia and Groves models were not continuous at 110 km, K.S.W. Champion prepared a single, continuous, mean atmospheric profile extending from 25 to 500 km altitude.

By 1986, the new data input on the Middle Atmosphere from satellite remote sensing provided global coverage of that region. In-situ satellite, combined with ground-based radar measurements of the thermosphere and ionosphere similarly provided a major increment in data availability for the thermosphere compared with 1972. Despite these advances, data availability on the upper mesosphere and lower thermosphere was still limited. New semi-empirical models and the first global three-dimensional time-dependent models of the thermosphere had become available, and the fourth edition of CIRA – CIRA 1986 was influenced strongly by the newly available data and models.

CIRA 1986 was published in two parts:

CIRA 1986: Part I [1] contains the thermospheric models

CIRA 1986: Part II [2] contains the middle atmosphere models, including a structural merging model to the lower thermosphere.

COSPAR International Reference Atmosphere (CIRA), Part III: Trace Constituent Reference Models [3] was published in 1990.

A series of merging models between models for the Thermosphere [1] and those for the Middle Atmosphere [2] (not based on direct measurements) were published in 1990 [4].

CIRA-2012 is the fifth edition. It contains updated versions of empirical models that have been developed further by means of the very considerable advances in direct measurements by appropriate space-based instrumentation of the 1980's, 1990's and early-mid 2000's.

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

[2] Rees, D., J. J. Barnett, 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.

[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] 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.

CHAPTER 1 – INTRODUCTION.

COSPAR and URSI have co-sponsored a series of International Reference Atmospheres, starting with CIRA-1961 [1]. These COSPAR International Reference Atmospheres have been generally published and referenced as the CIRA series.

As time has progressed since the early 1960's, information available on the atmosphere and its structure and variability has increased enormously. As the result, the models have become more ambitious.

The most recently published version, the CIRA 1986 sequence, was split into three separate publications:

Part 1 – Thermospheric Models [2];

Part II – Middle Atmosphere Models [3], and

Part III – Models of Trace and Minor Constituents [4].

This current publication CIRA–2012 – results from a number of years of preparation by the CIRA Working Group of COSPAR Commission C (with frequent interactions with members of URSI Commission G). CIRA-2012 was presented and discussed during dedicated Meetings held during the COSPAR Assemblies at Montreal, Canada in July 2008, Bremen, Germany in July 2010 and in Mysore, India July 2012. During these Meetings, each of the major components of the CIRA-2008 was presented by the expert authors, and discussed by the Working Group members present during the Meetings. Following these meetings, COSPAR Commission C recommended allowing the CIRA Working Group to continue its preparations, leading to the publication of the combined components as CIRA-2008.

As a break with the tradition of CIRA publications, in addition to a published version in Advances of Space Research, the new CIRA will also be made available via a dedicated Web Site. This is specifically intended to allow the timely updating of specific sections of the new CIRA. In this way, versions vetted and recommended by the International Community (as represented by the appropriate COSPAR and URSI Commissions) can be made available to the wider Community without the lengthy intervals between the formal publication of recent CIRA Volumes

1.1 CIRA-2012 – Model Content

CIRA-2012 will contain some ten Chapters.

This Chapter is the general introduction to CIRA-2012. It provides a brief background to the history and development of the CIRA Models.

Chapter 2 provides a more general and detailed background to the development of "Standard Atmospheres", including details of the publication of the three parts of the previous CIRA 1986 Models.

Chapter 3 introduces the four key semi-empirical models of the Atmosphere – the NRLMSISE-00 Model, the JB2008 Model, the GRAM-07 Model and the DTM Model. These four Models have been widely used by the international scientific and the engineering communities

Chapter 4 presents a background to the issue of the Solar and Geomagnetic indices that are the fundamental drivers of the semi-empirical models, and also the Physical (Theoretical or first-principles) Models of the atmosphere.

Chapter 5 reflects on certain critical issues that affect the uncertainties of derivation of Absolute Density in the upper atmosphere. Despite 50 years of measurements by many techniques and with increasing sophistication, relative precision and time and spatial resolution, there remain some outstanding uncertainties that still limit the accuracy of the information used to generate the semi-empirical models.

Chapter 6 describes the current state of knowledge and modelling of the metallic species. These metallic species – alkali metals, have remarkably strong influences on the neutral and ionised species of the upper mesosphere and lower thermosphere.

Chapter 7 describes two available semi-empirical models of winds within the Upper Atmosphere: The HWM-07 Model, and the GWEM (Global Winds Empirical model)

Chapter **8** provides a series of statistical comparisons between the semi-empirical models and actual data, including high resolution density and wind data obtained during geomagnetic storms. These studies provide examples of the errors and uncertainties that still occur within the semi-empirical and theoretical models, in comparison with real data.

Chapter **9** describes the current best understanding of the limitations of the current models: the errors and uncertainties. Some result from real unknowns concerned with the derivation, for example, of absolute density. Other uncertainties reflect the real difficulty of creating any completely realistic proxies for the highly structured spatial and temporal inputs of energy and momentum into the atmosphere, particularly during strong geomagnetic disturbances. At all levels within the atmosphere, there are strong interactions between processes occurring at different levels or altitudes. It is very difficult to process available empirical data to provide an exact replica of the physical, chemical, energetic and dynamical state of the atmosphere from the surface to the exosphere as the input to even the best of the current empirical models. As a result, the output of the Physical Models is limited by the detailed knowledge of such input conditions.

1.2 CIRA-2012 – Plans for Future Updates of CIRA.

As with previous versions of CIRA, CIRA-2012 represents a "snap-shot in time". There are a number of important research initiatives under way that offer substantial insights into the current uncertainties of both semi-empirical and Physical Models. In consultation with the researchers involved in these initiatives, it is possible to plot the potential for future improvements in the semi-empirical and Physical models.

In Chapter **10**, the process for future upgrades of CIRA-2012 is outlined. For the first time, CIRA-2012 is intended to be available, in its entirety, "on-line", reflecting the exact versions of the Models as approved and adopted by the CIRA Working Group.

The CIRA Working Group will continue to review available updates of Models etc. Previous versions of CIRA have necessarily involved a completely new Publication (recently at intervals of order 20 years). In the future, however, it is planned that CIRA upgrades will be available in a far more timely manner through the recommendations of the CIRA Working Group, suitably endorsed by the respective COSPAR and URSI Commissions. These updates will be provided to the global scientific and engineering

Communities through the Web Site, after full deliberation and approval by the Working Group and by COSPAR Commission C.

Finally, there is a comprehensive bibliography to CIRA-2012 and to the related citations and models described within.

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CHAPTER 2 – INTRODUCTION.

Chapter 3: The Earth's Upper Atmosphere: Semi-Empirical Models.

3.1 Introduction

CIRA-2012 provides recommendations for a range of up-to-date semi-empirical models determining the structure, dynamics and other properties of the Earth's upper atmosphere (above 120 km).

A good knowledge of temperature, total density, concentrations of major and minor constituents and pressure is important for a wide range of scientific purposes and for the planning and execution of many space missions exploiting the low-earth orbit (LEO) regime below approximately 2500 km altitude. Aerodynamic forces on the spacecraft, due to the orbital motion of a satellite through a rarefied gas which itself can have variable high velocity winds, are important for planning satellite lifetime, maintenance of orbits, collision avoidance maneuvering and debris monitoring, sizing the necessary propulsion system, design of attitude control system, and estimating the peak accelerations and torques imposed on sensitive payloads. Surface corrosion effects due to the impact of large fluxes of atomic oxygen are assessed to predict the degradation of a wide range of sensitive coatings of spacecraft and instruments. The reactions of atomic oxygen around a spacecraft can also lead to intense "vehicle glow".

The structure of Earth's upper atmosphere, accepted empirical models that can specify the details of the atmosphere, and the details of those models (Section 3) are included in CIRA-2012. A detailed description of the Neutral Electromagnetic Radiation and Indices can be found in Chapter 4 of CIRA-2012.

3.2 Scope

CIRA-2012 specifies the structure of Earth's atmosphere above 120 km, provides accepted empirical models that can specify the details of the atmosphere, and uses Appendices to describe the details of those models. Its purpose is to create a standard method for specifying Earth atmosphere properties (densities, etc.) in the low Earth orbit regime for space systems and materials users.

3.3 Terms and definitions

For the purposes of CIRA-2012, the following terms and definitions apply.

Homosphere

The region of the atmosphere that is well mixed; i.e., the major species concentrations are independent of height and location.

This region extends from 0 to ~100 km, and includes the temperature-defined regions of the troposphere (surface up to ~ 8 - 15 km altitude), the stratosphere (~ 10 - 12 km up to 50 km altitude), the mesosphere (~50 km up to about 90 km altitude), and the lowest part of the thermosphere.

Heterosphere

The portion of the atmosphere, above ~125 km, where diffusive separation of species dominates and atmospheric composition depends on height.

Thermosphere

The region of the atmosphere between the temperature minimum at the mesopause (~90 km) and the altitude where the vertical scale height is approximately equal to the mean free path (400-600 km altitude, depending on solar and geomagnetic activity levels.

Exosphere

The region of the atmosphere that extends from the top of the thermosphere outward.

3.4 Recommended Semi-Empirical Models of the Thermosphere.

NRLMSISE-00 (Naval Research Labatory Mass Spectrometer, Incoherent Scatter Radar Extended Model [1])

Describes the neutral temperature and species densities in Earth's atmosphere

NOTE 1 It is based on a very large underlying set of supporting data from satellites, rockets, and radars, with extensive temporal and spatial distribution. It has been extensively tested against experimental data by the international scientific community. The model has a flexible mathematical formulation.

NOTE 2 It is valid for use from ground level to the exosphere. Two indices are used in this model: *F10.7* (both the daily solar flux value of the previous day and the 81-day average centred on the input day) and A_p (geomagnetic daily value).

JB2008 (Jacchia-Bowman 2008 Model [2])

Describes the neutral temperature and the total density in Earth's thermosphere and exosphere

NOTE 1 Its new features lead to a better and more accurate model representation of the mean total density compared with previous models, including the NRLMSISE-00.

NOTE 2 It is valid for use from an altitude of 120 km to 2500 km in the exosphere. Four solar indices and two geomagnetic activity indices are used in this model: *F10.7* (both tabular value one day earlier and the 81-day average centred on the input time); *S10.7* (both tabular value one day earlier and the 81-day average centred on the input time); *M10.7* (both tabular value five days earlier and the 81-day average centred on the input time); Y10.7 (both tabular value five days earlier and the 81-day average centred on the input time); a_p (3 hour tabular value); and *Dst* (converted and input as a dTc temperature change tabular value on the input time).

HWM07 (Horizontal Wind Model [3])

HWM07 contains comprehensive empirical global model of horizontal winds in the mesosphere and thermosphere (middle and upper atmosphere).

NOTE 1 Reference values for the ap index needed as input for the wind model are given in Section 3.

NOTE 2 HWM07 does not include a dependence on solar EUV irradiance. Solar cycle effects on thermospheric winds are generally small during the daytime, but can exceed 20 m/s at night.

NOTE 3 HWM07 thermospheric winds at high geomagnetic latitudes during geomagnetically quiet periods should be treated cautiously.

Earth GRAM 2007 Model [4]

The Earth GLOBAL Reference Atmosphere Models (latest version is Earth GRAM 2007) have been produced on behalf of NASA to describe the terrestrial atmosphere from ground level upward for operational purposes. These models are available via license from NASA to qualified users and provide usability and information quality similar to that of the NRLMSISE-00 Model. Earth GRAM 2007 includes options for NRLMSIS-00, HMW-93, and JB2006 models.

DTM-2009 (Drag Temperature Model 2009 [5])

Describes the neutral temperature and (major and some minor) species densities in Earth's atmosphere between an altitude of 120 km to approximately 1500 km.

NOTE 1: DTM-2000 is based on a large database going back to the early '70s, essentially the same that was used for NRLMSISE-00 except for the radar data. In addition, high-resolution CHAMP and GRACE accelerometer-inferred densities are assimilated in DTM-2009.

NOTE 2: it is valid from an altitude of 120 km to approximately 1500 km in the exosphere. Two indices are used in this model: F10.7 solar flux (both daily solar flux of the previous day and the 81-day average centered on the input day) and Kp (3-hour value delayed by three hours, and the average of the last 24 hours).

NOTE 3: the DTM model codes (DTM-94, DTM-2000, DTM-2009) are available for download on the ATMOP project website (http://www.atmop.eu/downloads.php)

Symbols and Abbreviated Terms

a_p	designates the 3-hour planetary geomagnetic index and is given in units nT
A_p	designates the daily planetary geomagnetic index and is given in units nT
CIRA	COSPAR International Reference Atmosphere
COSPAR	Committee on Space Research
Dst	designates the hourly disturbance storm time ring current index and is given in units nT
F10	designates the F10.7 solar proxy and is given in units of solar flux, $\times 10^{-22}$ W m^{-2}
M10	designates the M10.7 solar proxy and is given in units of solar flux, $\times 10^{-22}$ W m^{-2}
S10	designates the S10.7 solar index and is given in units of solar flux, $\times 10^{-22}$ W m^{-2}
URSI	International Union of Radio Science
Y10	designates the Y10.7 solar index and is given in units of solar flux, $\times 10^{-22}$ W m^{-2}

1 General Concept and Assumptions

1.1 *Earth Atmosphere Model Use*

The NRLMSISE-00 model [1] should be used for calculating both the neutral temperature and the detailed composition of the atmosphere.

The JB2008 model [2] should be used for calculating the total atmospheric density above an altitude of 120 km, for example as used in determining satellite drag in LEO.

The Earth-GRAM model 2007 [4] may be used for calculating the total atmospheric density above an attitude of 120 km, for example as used in determining satellite drag in LEO.

The DTM-2009 [5] may be used for calculating the total atmospheric density above an attitude of 120 km, for example as used in determining satellite drag in LEO.

For altitudes below 120 km, NRLMSISE-00 or Earth GRAM 2007 should be used for calculating the total air density.

NOTE 1 This usage follows the advice of the CIRA Working Group, sponsored by COSPAR and URSI, and following the resolution of the Assembly of COSPAR in Montreal in July 2008.

1.1.1 Application Guidelines

a) The NRLMSISE-00 model for species densities should not be mixed with the JB2008, Earth GRAM 2007 or DTM-2009 model for total density.

b) For worst-case high solar activity results and analysis periods not exceeding 1 week, high daily short-term values given in Section 3 should be used as input for daily activity together with the high long-term values for the 81-day average activity.

c) For analysis periods longer than 1 week the long term solar activity activities given in Section 3 should be used as input for both, the daily and the 81-day averaged values.

d) For analysis periods longer than 1 week and conditions specified in Section 3, the daily and 81-day averaged solar activities given in Section 3 should be used.

e) Short-term daily high solar activity values should not be used together with low or moderate long-term solar activity values.

NOTE 1 The JB2008, NRLMSISE-00, and Earth Gram 2007 models can only predict large scale and slow variations, on the order of 1000 km (given by the highest harmonic component) and 3 hours. Spacecraft can encounter density variations with smaller temporal and spatial scales partly since they are in motion (for example, +100% or -50% in 30 s), and partly because smaller-scale disturbances certainly occur during periods of disturbed geomagnetic activity.

NOTE 2 Reference values for the key indices needed as inputs for the atmosphere models are given in Section 3.

NOTE 3 The F10.7 81-day average solar activity can also be estimated by averaging three successive monthly predicted values.

NOTE 4 Information on density model uncertainties can be found in Section 3 and in [1] and [2].

NOTE 5 For high solar activities, the atmosphere models only give realistic results if high short-term values are combined with high 81-day averaged values.

NOTE 6 High Dst values can be used corresponding to low, moderate or high solar activities.

1.2 *Earth Wind Model Use*

The HWM07 wind model [3] should be used.

High daily short-term solar activity values should be used as worst-case for the daily activity but the 81-day average activity should not exceed the high long-term value.

NOTE 1 Reference values for the key Indices needed as inputs for the wind model are given in Section 3.

NOTE 2 The F10.7 81-day average solar activity can also be estimated by averaging three successive monthly predicted values as given in Section 3.

NOTE 3 The use of the HWM07 model at high geomagnetic latitudes and for disturbed geomagnetic periods necessitates caution in the interpretation of model results.

1.3 *Robustness of Models*

The Earth's upper atmosphere models described in CIRA-2012 are intended to be adapted and improved over time as the international scientific community obtains and assesses high quality data on the upper atmosphere. Therefore, the users of the models described should ensure they are utilizing the latest version of the respective models.

3. The Structure of the Earth's atmosphere

The Earth's atmosphere can be classified into different regions based on temperature, composition, or collision rates among atoms and molecules. For the purposes of the document, the atmosphere broadly divided into three regimes based on all three properties, as shown in Figure 3.1:

i) The homosphere is the portion of the atmosphere that is well mixed; i.e., the major species concentrations are independent of height and location. This region extends from 0 to ~100 km, and includes the temperature-defined regions of the troposphere (surface up to ~ 8 - 15 km altitude), the stratosphere (~ 10 - 12 km up to 50 km altitude), the mesosphere (~50 km up to about 90 km altitude), and part of the thermosphere.

ii) The thermosphere is the region between the temperature minimum at the mesopause (~90 km) and the altitude where the vertical scale height is approximately equal to the mean free path (400-600 km altitude, depending on solar and geomagnetic activity levels)

iii) the exosphere extends from the top of the thermosphere into space.

In practice, the boundaries between these regions, whether determined in altitude or in a pressure co-ordinate system, vary with solar, seasonal, latitudinal, and other conditions.

Due to winds and turbulent mixing the homosphere has a nearly uniform composition of about 78.1% N2, 20.9% O2, and 0.9% Ar. The temperature profile of the thermosphere increases rapidly above a minimum of ~180 K at the mesopause, then gradually relaxes above ~200 km to an asymptotic value known as the exospheric temperature.

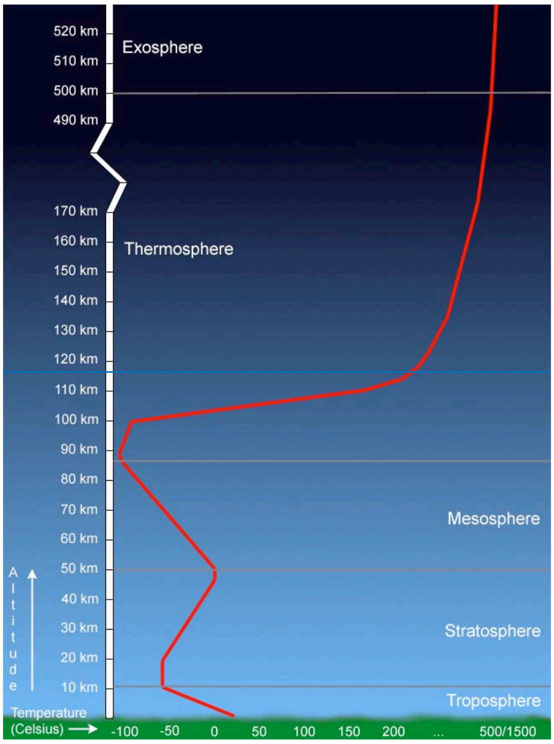

Figure 3.1— Temperature profile of the Earth's atmosphere

3.1 Development of Models of the Earth's Atmosphere

A "Standard Atmosphere" is defined as a vertical distribution of atmospheric temperature, pressure, and density, which by international agreement is taken to be representative of the Earth's atmosphere. The first "Standard Atmospheres" established by international agreement were developed in the 1920's primarily for purposes of pressure altimeter calibrations, aircraft performance calculations, aircraft and rocket design, ballistic tables, etc. Later some countries, notably the United States, also developed and published "Standard Atmospheres". The term "Reference Atmosphere" is used to identify vertical descriptions of the atmosphere for specific geographical locations or globally. These were developed by organizations for specific applications, especially as the aerospace industry began to mature after World War II. The term "Standard Atmosphere" has in recent years also been used by national and international organizations to describe vertical descriptions of atmospheric trace constituents, the ionosphere, atomic oxygen, aerosols, ozone, winds, water vapour, planetary atmospheres, etc.

Currently some of the most commonly used Standard and Reference Atmospheres [6] include:

The ISO Standard Atmosphere 1975, 1982;

The U. S. Standard Atmosphere Supplements, 1962, 1966, 1976;

The COSPAR International Reference Atmosphere (CIRA), 1986 (previously issued as CIRA 1961, CIRA 1965 and CIRA 1972);

The NASA/MSFC Global Reference Atmosphere Model, Earth GRAM 2007 (previously issued as GRAM-86, GRAM-88, GRAM-90, GRAM-95, and GRAM-99);

The NRLMSISE-00 Thermospheric Model, 2000 (previously issued as MSIS-77, -83, -86 and MSISE-90);

The JB2006 and JB2008 density models;

The DTM series of models, most recently the DTM-2009 [5].

3.11. NRLMSISE-00 - Additional Information

The Mass Spectrometer and Incoherent Scatter (MSIS) series of models developed between 1977 and 1990 are used extensively by the scientific community for their superior description of neutral composition. The models utilized atmospheric composition and temperature data from instrumented satellites and ground-based radars. The initial MSIS 1977 model utilized a Bates-Walker temperature profile (which is analytically integrable to obtain density), and allowed the density at 120 km to vary with local time and other geophysical parameters to fit the measurements. The temperature and density parameters describing the vertical profile were expanded in terms of spherical harmonics to represent geographic variations. Subsequent versions of the model include the longitude variations, a refined geomagnetic storm effect, improved high latitude, high solar flux data, and an extension of the lower boundary down to sea level.

3.1.2 JB2008 - Additional Information

The NRLMSISE-00 model represents atmospheric composition, temperature, and total mass density from the ground to the exosphere. Its formulation imposes a physical constraint of hydrostatic equilibrium to produce self-consistent estimates of temperature and density. NRLMSISE-00 includes the following enhancements compared to MSISE-90:

i) drag data based on orbit determination,

ii) more recent accelerometer data sets,

iii) new temperature data derived from Millstone Hill and Arecibo incoherent scatter radar observations,

iv) observations of O_2 by the Solar Maximum Mission (SMM), based on solar ultraviolet occultation.

v) a new species, “anomalous oxygen,” primarily for drag estimation, allows for appreciable O+ and hot atomic oxygen contributions to the total mass density at high altitudes.

The Jacchia-Bowman density (JB2008) model is based on the Jacchia model heritage. It includes two key novel features. Firstly, there is a new formulation concerning the semi-annual density variation observed in the thermosphere, but not previously included in any of the semi-empirical atmospheric models. Secondly, there is a new formulation of solar indices, relating more realistically the dependence of heat and energy inputs from the solar radiation to specific altitude regions and heating processes within the upper atmosphere.

The Dst index (equatorial magnetic perturbation) is used in JB2008 as the index representing the geomagnetic activity response. JB2008 inserts the improved J70 temperature formulations into the CIRA 1972 model to permit integrating the diffusion equation at every point rather than relying on look-up tables (the integration must be done numerically, in contrast to the analytically integrable Bates-Walker temperature formulation used in MSIS).

In order to optimally represent the orbit-derived mass density data on which JB2008 is based, the model formulation sacrifices the physical constraint of hydrostatic equilibrium since it does not include all physical processes that may actually be present in thermosphere affecting temperatures and densities.

3.1.3 GRAM-2007 - Additional Information

The National Aeronautics and Space Administration's NASA/MSFC Global Reference Atmospheric Model version 2007 (Earth GRAM 2007) is a product of the Natural Environments Branch, NASA Marshal Space Flight Center. These models are available via license to qualified users and provide usability and information quality similar to that of the NRLMSISE-00 Model. Like the previous versions of 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. 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 GRAM especially useful for Monte-Carlo dispersion analyses of guidance and control systems, thermal protection systems, and similar applications. GRAM has found many uses, both inside and outside the NASA community. Most of these applications rely on 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 2007 retains the capability of the previous version but also contains several new features. The thermosphere has 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.

3.1.4 HWM07 Additional Information

The HWM series of models empirically represent the horizontal neutral wind in the atmosphere, using a truncated set of vector spherical harmonics. The first edition of the model released in 1987 (HWM87) was intended for winds above 220 km. With the inclusion of wind data from ground-based incoherent scatter radar, MF/Meteor radar data, and Fabry-Perot optical interferometers, HWM90 was extended down to 100 km. HWM93 extended the model down to the ground. HWM07 is the most recent version of the HWM, and includes substantial new space-based data obtained since the early 1990s. Solar cycle variations are included in the earlier models, but they are found to be small and not always very clearly delineated by the current data; HWM07 does not depend on solar activity. HWM07 significantly improves the model's reliability in the lower thermosphere (90-200 km), and under geomagnetically disturbed conditions. However, during quiet conditions, the model does represent polar thermospheric vortices in full detail. The model describes the transition from predominately diurnal variations in the upper thermosphere to semidiurnal variations in the lower thermosphere and a transition from summer to winter flow above 140 km to winter to summer flow below. The model software provides zonal and meridional winds for specified latitude, longitude, altitude, time, and 3-hour ap index.

3.1.5 Atmosphere Model Uncertainties and Limitations

For mean activity conditions, the estimated uncertainty of the NRLMSISE-00 species density is 15%. For short term and local-scale variations, the estimated uncertainty of the NRLMSISE-00 species density is 100%. Within the homosphere (below 90 km), the uncertainty is below 5%. The Earth GRAM 2007 has a similar uncertainty within the homosphere.

For mean activity conditions, the estimated standard uncertainty of the JB2008 total density within the thermosphere is of order 10% (depending on altitude). For extreme conditions (very high solar or geomagnetic activities), this uncertainty can increase considerably, due to the lack of corresponding measurement data. The total density can have +/- 100% variation at 400-500 km for some activities and locations.

It should be noted that the models' accuracy of prediction of atmospheric density and other parameters is limited by the complex behaviour of the atmosphere, and the causes of variability. While certain aspects of atmospheric variability are more or less deterministic, meteorological variations of the homosphere are difficult to predict more than 3 – 5 days in advance, and yet have effects on the thermosphere. In the thermosphere, the response to varying solar and geomagnetic activity is complex, particularly with respect to the latter. Upper atmosphere density models can be used for prediction of future orbital lifetime, either to determine the orbital altitude insertions to ensure a given lifetime, or to estimate energy requirements for maintaining a particular orbit, for a particular spacecraft/satellite. When the sun is active, the primary influence on the accuracy of a model's density output will be the accuracy of the future predictions of solar and geomagnetic activity used as inputs, rather than the accuracy of the specific model in representing the density as a function of solar and geomagnetic activity.

3.1.6 Reference Data

NRLMSISE-00 altitude profiles at equatorial latitude of temperature and number densities (concentrations) are listed in Figure 3.1, Table 3.1, and Table 3.2 for low solar and geomagnetic activities ($F10.7 = F10.7_{avg} = 65$, $A_p = 0$), moderate solar and geomagnetic activities ($F10.7 = F10.7_{avg} = 140$, $A_p = 15$), and high long term solar and geomagnetic activities ($F10.7 = F10.7_{avg} = 250$, $A_p = 45$), respectively. The tables cover both homospheric and heterospheric altitudes from ground level up to 900 km, averaged over diurnal and seasonal variations. Figure 3.1 above illustrates the altitude profile of the temperature. Figure 3.2 shows the atomic oxygen number densities at low, moderate and high long-term activity conditions. For moderate activity levels, Figure 3.3 shows the logarithmic number concentration profiles of the main atmospheric constituents.

JB2008 short-term, intermediate-term and long-term solar variability reference values are provided in Tables 3.4, 3.5, and 3.6. Figure 3.4 shows the variation of the JB2008 mean air density with altitude for low ($F10.7 = F10.7_{avg} = 65$, $S10.7 = S10.7_{avg} = 60$, $M10.7 = M10.7_{avg} = 60$, $Y10.7 = Y10.7_{avg} = 60$, $A_p = 0$, Dst = -15), moderate ($F10.7 = F10.7_{avg} = 140$, $S10.7 = S10.7_{avg} = 125$, $M10.7 = M10.7_{avg} = 125$, $Y10.7 = Y10.7_{avg} = 125$, $A_p = 15$, Dst = -15), high long-term ($F10.7 = F10.7_{avg} = 250$, $S10.7 = S10.7_{avg} = 220$, $M10.7 = M10.7_{avg} = 220$, $Y10.7 = Y10.7_{avg} = 220$, $A_p = 45$, Dst = -100), and high short-term ($F10.7 = 300$, $F10.7_{avg} = 250$, $S10.7 = 235$, $S10.7_{avg} = 220$, $M10.7 = 240$, $M10.7_{avg} = 220$, $Y10.7 = Y10.7_{avg} = 220$, $A_p = 240$, Dst = -300) solar and geomagnetic activity.

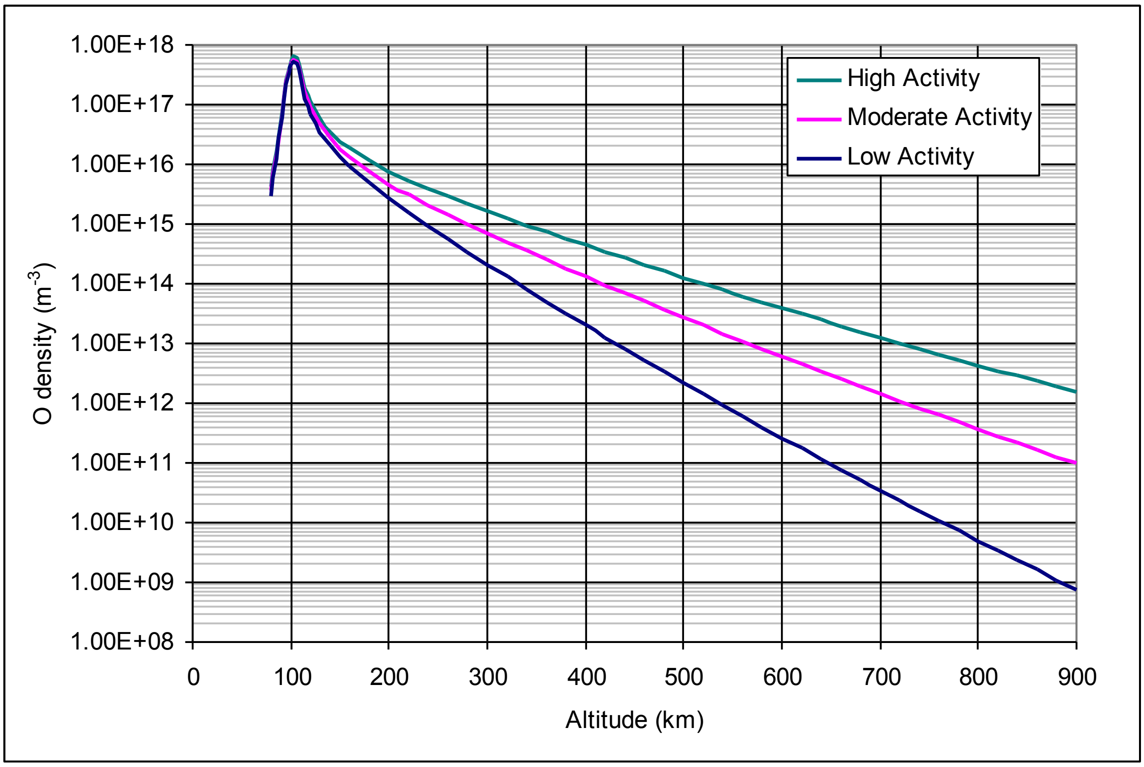

Figure 3.1 — NRLMSISE-00 mean atomic oxygen for low, moderate, and high long-term solar and geomagnetic activity

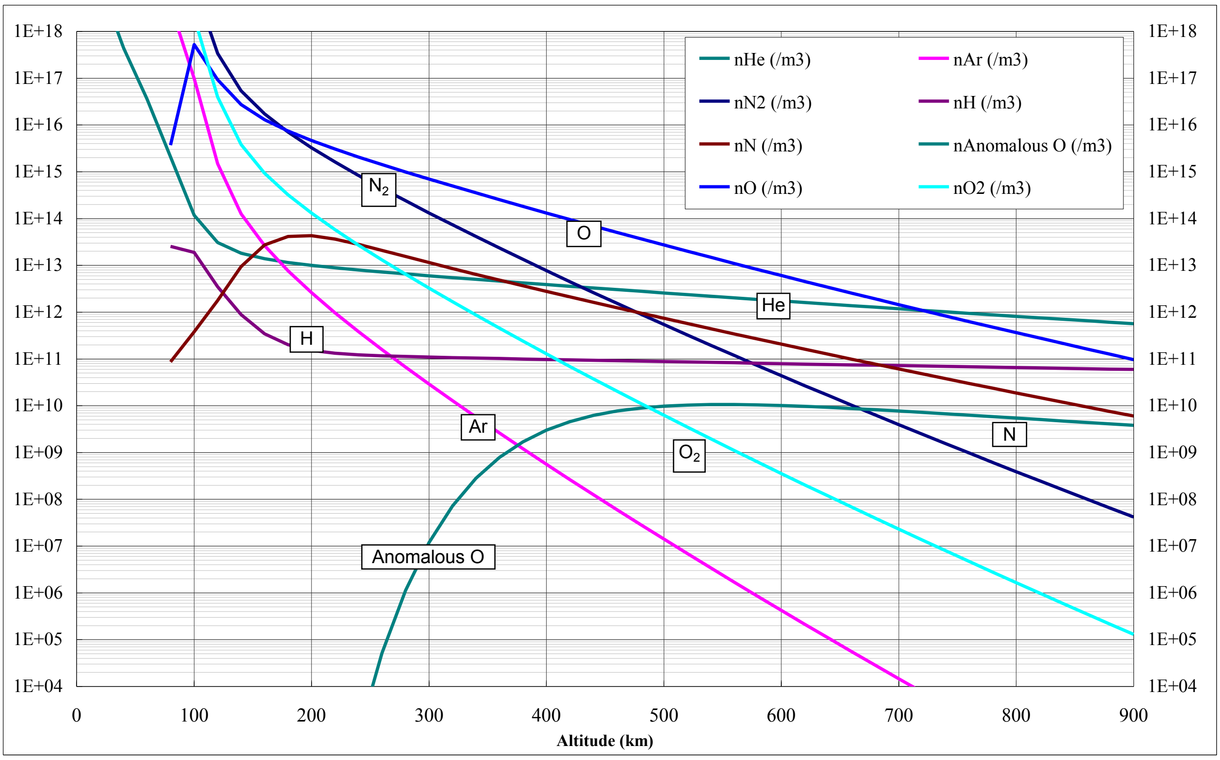

Figure 2 — NRLMSISE-00 mean concentration of atmosphere constituents for moderate solar and geomagnetic activity

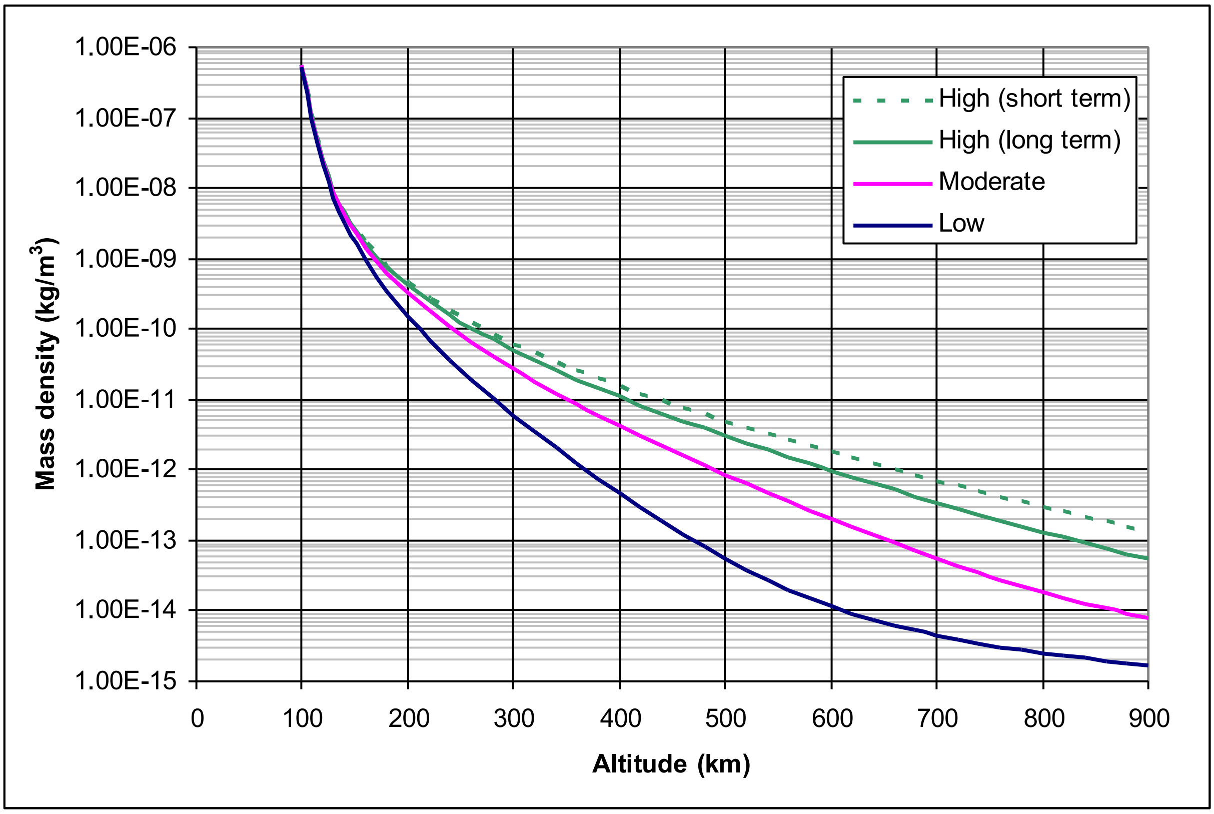

Figure 3 — JB2008 mean air density with altitude for low, moderate, and high long- and short-term solar and geomagnetic activity

Table 1 — Altitude profiles of the atmosphere constituents for low solar and geomagnetic activities

H (km)	n_{HE} (m^{-3})	n_O (m^{-3})	n_{N2} (m^{-3})	n_{O2} (m^{-3})	n_{AR} (m^{-3})	n_H (m^{-3})	n_N (m^{-3})	$n_{Anomal\ O}$ (m^{-3})	T(K)	ρ ($kg.m^{-3}$)
0	1.17E+20	0.00E+00	1.74E+25	4.67E+24	2.08E+23	0.00E+00	0.00E+00	0.00E+00	3.00E+02	1.07E+00
20	9.46E+18	0.00E+00	1.41E+24	3.78E+23	1.69E+22	0.00E+00	0.00E+00	0.00E+00	2.06E+02	8.68E-02
40	4.05E+17	0.00E+00	6.04E+22	1.62E+22	7.23E+20	0.00E+00	0.00E+00	0.00E+00	2.57E+02	3.72E-03
60	3.29E+16	0.00E+00	4.90E+21	1.31E+21	5.86E+19	0.00E+00	0.00E+00	0.00E+00	2.45E+02	3.01E-04
80	1.89E+15	3.01E+15	2.73E+20	7.27E+19	3.25E+18	2.65E+13	6.64E+10	2.28E-51	2.06E+02	1.68E-05
100	1.17E+14	4.78E+17	1.02E+19	2.38E+18	1.04E+17	2.70E+13	3.10E+11	2.24E-37	1.71E+02	6.18E-07
120	2.50E+13	7.23E+16	3.11E+17	4.36E+16	1.36E+15	6.07E+12	1.19E+12	1.41E-27	3.53E+02	1.88E-08
140	1.50E+13	2.12E+16	4.89E+16	4.45E+15	1.09E+14	2.17E+12	6.16E+12	2.44E-19	5.21E+02	3.08E-09
160	1.16E+13	9.37E+15	1.38E+16	1.06E+15	1.88E+13	1.09E+12	1.61E+13	1.12E-12	6.05E+02	9.49E-10
180	9.61E+12	4.88E+15	4.76E+15	3.34E+14	4.23E+12	7.31E+11	2.20E+13	1.45E-07	6.48E+02	3.70E-10
200	8.21E+12	2.73E+15	1.80E+15	1.15E+14	1.08E+12	5.94E+11	2.02E+13	1.20E-03	6.70E+02	1.63E-10
220	7.12E+12	1.59E+15	7.14E+14	4.11E+13	2.98E+11	5.32E+11	1.51E+13	1.22E+00	6.82E+02	7.80E-11
240	6.21E+12	9.42E+14	2.93E+14	1.51E+13	8.62E+10	4.98E+11	1.04E+13	2.43E+02	6.88E+02	3.97E-11

260	5.45E+12	5.66E+14	1.23E+14	5.66E+12	2.59E+10	4.75E+11	6.85E+12	1.40E+04	6.92E+02	2.13E-11
280	4.78E+12	3.44E+14	5.27E+13	2.16E+12	8.02E+09	4.57E+11	4.50E+12	3.08E+05	6.94E+02	1.18E-11
300	4.21E+12	2.10E+14	2.30E+13	8.42E+11	2.54E+09	4.41E+11	2.96E+12	3.26E+06	6.95E+02	6.80E-12
320	3.71E+12	1.30E+14	1.01E+13	3.33E+11	8.22E+08	4.27E+11	1.96E+12	1.96E+07	6.96E+02	4.01E-12
340	3.28E+12	8.05E+13	4.54E+12	1.33E+11	2.71E+08	4.13E+11	1.30E+12	7.64E+07	6.96E+02	2.41E-12
360	2.90E+12	5.02E+13	2.06E+12	5.42E+10	9.06E+07	4.00E+11	8.74E+11	2.13E+08	6.96E+02	1.47E-12
380	2.56E+12	3.15E+13	9.43E+11	2.23E+10	3.07E+07	3.87E+11	5.88E+11	4.60E+08	6.96E+02	9.14E-13
400	2.27E+12	1.99E+13	4.37E+11	9.29E+09	1.06E+07	3.75E+11	3.98E+11	8.15E+08	6.96E+02	5.75E-13
420	2.01E+12	1.26E+13	2.04E+11	3.91E+09	3.66E+06	3.64E+11	2.70E+11	1.24E+09	6.96E+02	3.66E-13
440	1.78E+12	8.06E+12	9.61E+10	1.66E+09	1.29E+06	3.53E+11	1.85E+11	1.69E+09	6.96E+02	2.35E-13
460	1.58E+12	5.17E+12	4.56E+10	7.13E+08	4.55E+05	3.42E+11	1.26E+11	2.09E+09	6.96E+02	1.53E-13
480	1.41E+12	3.33E+12	2.18E+10	3.09E+08	1.63E+05	3.32E+11	8.68E+10	2.42E+09	6.96E+02	1.01E-13
500	1.25E+12	2.15E+12	1.05E+10	1.35E+08	5.87E+04	3.22E+11	5.99E+10	2.66E+09	6.96E+02	6.79E-14
520	1.11E+12	1.40E+12	5.11E+09	5.92E+07	2.13E+04	3.12E+11	4.15E+10	2.81E+09	6.96E+02	4.63E-14
540	9.91E+11	9.14E+11	2.50E+09	2.62E+07	7.81E+03	3.03E+11	2.88E+10	2.88E+09	6.96E+02	3.21E-14
560	8.83E+11	5.99E+11	1.23E+09	1.17E+07	2.88E+03	2.94E+11	2.00E+10	2.88E+09	6.96E+02	2.28E-14
580	7.88E+11	3.94E+11	6.07E+08	5.24E+06	1.07E+03	2.85E+11	1.40E+10	2.83E+09	6.96E+02	1.65E-14
600	7.04E+11	2.60E+11	3.02E+08	2.36E+06	4.01E+02	2.77E+11	9.79E+09	2.74E+09	6.96E+02	1.23E-14
620	6.29E+11	1.73E+11	1.51E+08	1.07E+06	1.51E+02	2.69E+11	6.88E+09	2.63E+09	6.96E+02	9.37E-15
640	5.63E+11	1.15E+11	7.59E+07	4.90E+05	5.74E+01	2.61E+11	4.84E+09	2.50E+09	6.96E+02	7.33E-15
660	5.04E+11	7.67E+10	3.84E+07	2.25E+05	2.19E+01	2.54E+11	3.42E+09	2.37E+09	6.96E+02	5.88E-15
680	4.51E+11	5.14E+10	1.95E+07	1.04E+05	8.42E+00	2.46E+11	2.42E+09	2.23E+09	6.96E+02	4.83E-15
700	4.04E+11	3.45E+10	9.94E+06	4.84E+04	3.26E+00	2.39E+11	1.72E+09	2.09E+09	6.96E+02	4.04E-15
720	3.63E+11	2.33E+10	5.10E+06	2.26E+04	1.27E+00	2.33E+11	1.22E+09	1.96E+09	6.96E+02	3.44E-15
740	3.26E+11	1.58E+10	2.63E+06	1.06E+04	4.97E-01	2.26E+11	8.70E+08	1.83E+09	6.96E+02	2.98E-15
760	2.93E+11	1.07E+10	1.36E+06	5.00E+03	1.96E-01	2.20E+11	6.21E+08	1.70E+09	6.96E+02	2.61E-15
780	2.63E+11	7.28E+09	7.06E+05	2.37E+03	7.75E-02	2.14E+11	4.45E+08	1.59E+09	6.96E+02	2.31E-15
800	2.37E+11	4.97E+09	3.68E+05	1.13E+03	3.09E-02	2.08E+11	3.20E+08	1.48E+09	6.96E+02	2.06E-15
820	2.13E+11	3.40E+09	1.93E+05	5.41E+02	1.24E-02	2.02E+11	2.30E+08	1.38E+09	6.96E+02	1.85E-15
840	1.92E+11	2.33E+09	1.02E+05	2.60E+02	4.99E-03	1.97E+11	1.66E+08	1.28E+09	6.96E+02	1.67E-15
860	1.73E+11	1.61E+09	5.36E+04	1.26E+02	2.02E-03	1.91E+11	1.20E+08	1.19E+09	6.96E+02	1.51E-15
880	1.57E+11	1.11E+09	2.85E+04	6.09E+01	8.25E-04	1.86E+11	8.68E+07	1.11E+09	6.96E+02	1.38E-15
900	1.41E+11	7.67E+08	1.52E+04	2.97E+01	3.38E-04	1.81E+11	6.30E+07	1.03E+09	6.96E+02	1.26E-15

Table 2 — Altitude profiles of the atmosphere constituents for mean solar and geomagnetic activities

H (km)	n_{HE} (m^{-3})	n_O (m^{-3})	n_{N2} (m^{-3})	n_{O2} (m^{-3})	n_{AR} (m^{-3})	n_H (m^{-3})	n_N (m^{-3})	$n_{Anomal\ O}$ (m^{-3})	T(K)	ρ ($kg.m^{-3}$)
0	1.26E+20	0.00E+00	1.88E+25	5.04E+24	2.25E+23	0.00E+00	0.00E+00	0.00E+00	3.00E+02	1.16E+00
20	1.02E+19	0.00E+00	1.52E+24	4.09E+23	1.82E+22	0.00E+00	0.00E+00	0.00E+00	2.06E+02	9.37E-02
40	4.38E+17	0.00E+00	6.53E+22	1.75E+22	7.81E+20	0.00E+00	0.00E+00	0.00E+00	2.57E+02	4.02E-03
60	3.55E+16	0.00E+00	5.29E+21	1.42E+21	6.33E+19	0.00E+00	0.00E+00	0.00E+00	2.45E+02	3.26E-04
80	2.07E+15	3.71E+15	3.00E+20	7.66E+19	3.56E+18	2.53E+13	8.61E+10	8.53E-51	1.98E+02	1.83E-05
100	1.16E+14	5.22E+17	9.60E+18	2.00E+18	9.71E+16	1.89E+13	3.76E+11	7.28E-37	1.88E+02	5.73E-07
120	3.08E+13	9.27E+16	3.36E+17	3.95E+16	1.49E+15	3.47E+12	1.77E+12	5.52E-27	3.65E+02	2.03E-08
140	1.83E+13	2.73E+16	5.38E+16	3.84E+15	1.26E+14	8.82E+11	9.45E+12	8.98E-19	6.10E+02	3.44E-09
160	1.39E+13	1.31E+16	1.72E+16	9.29E+14	2.64E+13	3.46E+11	2.73E+13	4.12E-12	7.59E+02	1.20E-09
180	1.16E+13	7.47E+15	7.08E+15	3.22E+14	7.67E+12	2.01E+11	4.18E+13	5.33E-07	8.53E+02	5.46E-10
200	1.00E+13	4.67E+15	3.27E+15	1.31E+14	2.61E+12	1.53E+11	4.31E+13	4.43E-03	9.11E+02	2.84E-10
220	8.91E+12	3.06E+15	1.62E+15	5.81E+13	9.73E+11	1.33E+11	3.64E+13	4.48E+00	9.49E+02	1.61E-10
240	8.00E+12	2.07E+15	8.36E+14	2.71E+13	3.84E+11	1.23E+11	2.82E+13	8.94E+02	9.73E+02	9.60E-11
260	7.24E+12	1.43E+15	4.44E+14	1.31E+13	1.58E+11	1.17E+11	2.10E+13	5.14E+04	9.88E+02	5.97E-11
280	6.59E+12	9.94E+14	2.40E+14	6.48E+12	6.69E+10	1.13E+11	1.56E+13	1.14E+06	9.98E+02	3.83E-11
300	6.01E+12	7.00E+14	1.32E+14	3.27E+12	2.90E+10	1.10E+11	1.15E+13	1.20E+07	1.00E+03	2.52E-11
320	5.50E+12	4.96E+14	7.35E+13	1.67E+12	1.28E+10	1.07E+11	8.60E+12	7.22E+07	1.01E+03	1.69E-11
340	5.04E+12	3.54E+14	4.13E+13	8.66E+11	5.75E+09	1.05E+11	6.45E+12	2.81E+08	1.01E+03	1.16E-11
360	4.62E+12	2.54E+14	2.35E+13	4.54E+11	2.61E+09	1.02E+11	4.86E+12	7.85E+08	1.01E+03	7.99E-12
380	4.24E+12	1.83E+14	1.34E+13	2.40E+11	1.20E+09	1.00E+11	3.68E+12	1.69E+09	1.01E+03	5.60E-12
400	3.90E+12	1.32E+14	7.74E+12	1.28E+11	5.61E+08	9.79E+10	2.79E+12	3.00E+09	1.02E+03	3.96E-12
420	3.59E+12	9.56E+13	4.50E+12	6.90E+10	2.64E+08	9.59E+10	2.13E+12	4.57E+09	1.02E+03	2.83E-12
440	3.30E+12	6.96E+13	2.63E+12	3.74E+10	1.25E+08	9.38E+10	1.63E+12	6.21E+09	1.02E+03	2.03E-12
460	3.04E+12	5.08E+13	1.55E+12	2.05E+10	6.00E+07	9.19E+10	1.25E+12	7.70E+09	1.02E+03	1.47E-12
480	2.80E+12	3.72E+13	9.15E+11	1.13E+10	2.90E+07	9.00E+10	9.59E+11	8.92E+09	1.02E+03	1.07E-12
500	2.58E+12	2.73E+13	5.44E+11	6.24E+09	1.41E+07	8.81E+10	7.39E+11	9.81E+09	1.02E+03	7.85E-13
520	2.38E+12	2.01E+13	3.26E+11	3.48E+09	6.90E+06	8.64E+10	5.71E+11	1.04E+10	1.02E+03	5.78E-13
540	2.20E+12	1.48E+13	1.96E+11	1.95E+09	3.40E+06	8.46E+10	4.42E+11	1.06E+10	1.02E+03	4.29E-13
560	2.03E+12	1.10E+13	1.18E+11	1.10E+09	1.69E+06	8.29E+10	3.43E+11	1.06E+10	1.02E+03	3.19E-13
580	1.88E+12	8.17E+12	7.19E+10	6.24E+08	8.42E+05	8.12E+10	2.67E+11	1.04E+10	1.02E+03	2.39E-13

600	1.74E+12	6.08E+12	4.38E+10	3.55E+08	4.23E+05	7.96E+10	2.08E+11	1.01E+10	1.02E+03	1.80E-13
620	1.61E+12	4.54E+12	2.68E+10	2.04E+08	2.13E+05	7.81E+10	1.62E+11	9.69E+09	1.02E+03	1.36E-13
640	1.49E+12	3.40E+12	1.65E+10	1.17E+08	1.08E+05	7.65E+10	1.27E+11	9.22E+09	1.02E+03	1.04E-13
660	1.38E+12	2.55E+12	1.02E+10	6.78E+07	5.52E+04	7.50E+10	9.91E+10	8.72E+09	1.02E+03	7.98E-14
680	1.28E+12	1.92E+12	6.33E+09	3.94E+07	2.83E+04	7.36E+10	7.78E+10	8.20E+09	1.02E+03	6.16E-14
700	1.18E+12	1.45E+12	3.94E+09	2.30E+07	1.46E+04	7.22E+10	6.11E+10	7.70E+09	1.02E+03	4.80E-14
720	1.10E+12	1.09E+12	2.46E+09	1.34E+07	7.54E+03	7.08E+10	4.81E+10	7.20E+09	1.02E+03	3.76E-14
740	1.02E+12	8.27E+11	1.54E+09	7.91E+06	3.92E+03	6.94E+10	3.80E+10	6.73E+09	1.02E+03	2.98E-14
760	9.45E+11	6.28E+11	9.72E+08	4.67E+06	2.05E+03	6.81E+10	3.00E+10	6.28E+09	1.02E+03	2.38E-14
780	8.78E+11	4.78E+11	6.14E+08	2.77E+06	1.07E+03	6.68E+10	2.37E+10	5.85E+09	1.02E+03	1.92E-14
800	8.16E+11	3.64E+11	3.89E+08	1.65E+06	5.65E+02	6.56E+10	1.88E+10	5.45E+09	1.02E+03	1.57E-14
820	7.58E+11	2.78E+11	2.47E+08	9.83E+05	2.99E+02	6.44E+10	1.49E+10	5.07E+09	1.02E+03	1.29E-14
840	7.05E+11	2.13E+11	1.58E+08	5.89E+05	1.59E+02	6.32E+10	1.19E+10	4.72E+09	1.02E+03	1.07E-14
860	6.56E+11	1.63E+11	1.01E+08	3.54E+05	8.47E+01	6.20E+10	9.45E+09	4.40E+09	1.02E+03	9.03E-15
880	6.11E+11	1.26E+11	6.47E+07	2.14E+05	4.53E+01	6.09E+10	7.54E+09	4.09E+09	1.02E+03	7.67E-15
900	5.69E+11	9.68E+10	4.16E+07	1.29E+05	2.44E+01	5.98E+10	6.02E+09	3.81E+09	1.02E+03	6.59E-15

Table 3.3 — Altitude profiles of the atmosphere constituents for high long term solar and geomagnetic activities

H (km)	n_{HE} (m^{-3})	n_O (m^{-3})	n_{N2} (m^{-3})	n_{O2} (m^{-3})	n_{AR} (m^{-3})	n_H (m^{-3})	n_N (m^{-3})	$n_{Anomal\ O}$ (m^{-3})	T(K)	ρ ($kg.m^{-3}$)
0	1.41E+20	0.00E+00	2.10E+25	5.65E+24	2.52E+23	0.00E+00	0.00E+00	0.00E+00	3.00E+02	1.29E+00
20	1.14E+19	0.00E+00	1.71E+24	4.57E+23	2.04E+22	0.00E+00	0.00E+00	0.00E+00	2.06E+02	1.05E-01
40	4.90E+17	0.00E+00	7.31E+22	1.96E+22	8.74E+20	0.00E+00	0.00E+00	0.00E+00	2.57E+02	4.49E-03
60	3.98E+16	0.00E+00	5.92E+21	1.59E+21	7.09E+19	0.00E+00	0.00E+00	0.00E+00	2.45E+02	3.64E-4
80	2.34E+15	4.36E+15	3.39E+20	8.15E+19	4.02E+18	2.51E+13	1.23E+11	2.04E-50	1.93E+02	2.03E-05
100	1.21E+14	5.70E+17	9.71E+18	1.72E+18	9.73E+16	1.43E+13	5.38E+11	1.57E-36	2.02E+02	5.64E-07
120	3.61E+13	1.15E+17	3.72E+17	3.37E+16	1.62E+15	2.13E+12	3.08E+12	1.36E-26	3.80E+02	2.22E-08
140	2.09E+13	3.51E+16	6.07E+16	3.02E+15	1.43E+14	3.93E+11	1.76E+13	2.12E-18	7.10E+02	3.93E-09
160	1.59E+13	1.86E+16	2.17E+16	6.80E+14	3.51E+13	1.24E+11	5.84E+13	9.74E-12	9.16E+02	1.54E-09
180	1.34E+13	1.15E+16	1.00E+16	2.29E+14	1.21E+13	6.34E+10	1.02E+14	1.26E-06	1.05E+03	7.87E-10
200	1.17E+13	7.72E+15	5.24E+15	9.68E+13	4.91E+12	4.52E+10	1.18E+14	1.05E-02	1.14E+03	4.57E-10
220	1.05E+13	5.42E+15	2.93E+15	4.65E+13	2.18E+12	3.83E+10	1.09E+14	1.06E+01	1.19E+03	2.86E-10
240	9.62E+12	3.93E+15	1.71E+15	2.42E+13	1.03E+12	3.51E+10	9.18E+13	2.11E+03	1.23E+03	1.87E-10

260	8.85E+12	2.90E+15	1.03E+15	1.32E+13	5.02E+11	3.34E+10	7.39E+13	1.22E+05	1.25E+03	1.27E-10
280	8.19E+12	2.17E+15	6.30E+14	7.43E+12	2.52E+11	3.23E+10	5.87E+13	2.68E+06	1.27E+03	8.87E-11
300	7.60E+12	1.64E+15	3.91E+14	4.28E+12	1.30E+11	3.15E+10	4.65E+13	2.84E+07	1.28E+03	6.31E-11
320	7.07E+12	1.25E+15	2.46E+14	2.51E+12	6.77E+10	3.08E+10	3.70E+13	1.71E+08	1.29E+03	4.56E-11
340	6.59E+12	9.53E+14	1.56E+14	1.49E+12	3.59E+10	3.02E+10	2.95E+13	6.65E+08	1.30E+03	3.34E-11
360	6.16E+12	7.32E+14	1.00E+14	8.94E+11	1.93E+10	2.97E+10	2.36E+13	1.85E+09	1.30E+03	2.47E-11
380	5.75E+12	5.65E+14	6.44E+13	5.41E+11	1.05E+10	2.91E+10	1.90E+13	4.00E+09	1.30E+03	1.85E-11
400	5.38E+12	4.37E+14	4.18E+13	3.30E+11	5.75E+09	2.86E+10	1.54E+13	7.10E+09	1.30E+03	1.40E-11
420	5.04E+12	3.39E+14	2.73E+13	2.03E+11	3.18E+09	2.82E+10	1.24E+13	1.08E+10	1.30E+03	1.06E-11
440	4.72E+12	2.64E+14	1.79E+13	1.26E+11	1.78E+09	2.77E+10	1.01E+13	1.47E+10	1.31E+03	8.13E-12
460	4.42E+12	2.06E+14	1.18E+13	7.84E+10	1.00E+09	2.72E+10	8.21E+12	1.82E+10	1.31E+03	6.26E-12
480	4.14E+12	1.62E+14	7.85E+12	4.91E+10	5.66E+08	2.68E+10	6.69E+12	2.11E+10	1.31E+03	4.84E-12
500	3.89E+12	1.27E+14	5.23E+12	3.10E+10	3.23E+08	2.64E+10	5.47E+12	2.32E+10	1.31E+03	3.76E-12
520	3.65E+12	9.97E+13	3.50E+12	1.96E+10	1.85E+08	2.60E+10	4.48E+12	2.45E+10	1.31E+03	2.94E-12
540	3.43E+12	7.86E+13	2.36E+12	1.25E+10	1.07E+08	2.55E+10	3.67E+12	2.51E+10	1.31E+03	2.31E-12
560	3.22E+12	6.21E+13	1.59E+12	8.01E+09	6.21E+07	2.51E+10	3.02E+12	2.51E+10	1.31E+03	1.82E-12
580	3.02E+12	4.92E+13	1.08E+12	5.15E+09	3.62E+07	2.48E+10	2.48E+12	2.47E+10	1.31E+03	1.43E-12
600	2.84E+12	3.91E+13	7.34E+11	3.33E+09	2.13E+07	2.44E+10	2.04E+12	2.39E+10	1.31E+03	1.14E-12
620	2.67E+12	3.11E+13	5.02E+11	2.16E+09	1.25E+07	2.40E+10	1.69E+12	2.29E+10	1.31E+03	9.06E-13
640	2.52E+12	2.48E+13	3.44E+11	1.41E+09	7.41E+06	2.36E+10	1.39E+12	2.18E+10	1.31E+03	7.23E-13
660	2.37E+12	1.98E+13	2.37E+11	9.19E+08	4.41E+06	2.33E+10	1.15E+12	2.06E+10	1.31E+03	5.79E-13
680	2.23E+12	1.58E+13	1.63E+11	6.03E+08	2.63E+06	2.29E+10	9.57E+11	1.94E+10	1.31E+03	4.65E-13
700	2.10E+12	1.27E+13	1.13E+11	3.97E+08	1.58E+06	2.26E+10	7.94E+11	1.82E+10	1.31E+03	3.75E-13
720	1.98E+12	1.02E+13	7.86E+10	2.63E+08	9.50E+05	2.22E+10	6.60E+11	1.70E+10	1.31E+03	3.03E-13
740	1.87E+12	8.21E+12	5.48E+10	1.74E+08	5.74E+05	2.19E+10	5.50E+11	1.59E+10	1.31E+03	2.46E-13
760	1.76E+12	6.62E+12	3.83E+10	1.16E+08	3.48E+05	2.16E+10	4.58E+11	1.48E+10	1.31E+03	2.00E-13
780	1.66E+12	5.35E+12	2.68E+10	7.74E+07	2.12E+05	2.13E+10	3.82E+11	1.38E+10	1.31E+03	1.63E-13
800	1.57E+12	4.33E+12	1.88E+10	5.19E+07	1.29E+05	2.10E+10	3.20E+11	1.29E+10	1.31E+03	1.34E-13
820	1.48E+12	3.51E+12	1.33E+10	3.48E+07	7.93E+04	2.07E+10	2.67E+11	1.20E+10	1.31E+03	1.10E-13
840	1.40E+12	2.85E+12	9.39E+09	2.35E+07	4.87E+04	2.04E+10	2.24E+11	1.12E+10	1.31E+03	9.06E-14
860	1.32E+12	2.32E+12	6.65E+09	1.59E+07	3.01E+04	2.01E+10	1.88E+11	1.04E+10	1.31E+03	7.50E-14
880	1.25E+12	1.89E+12	4.72E+09	1.07E+07	1.86E+04	1.98E+10	1.58E+11	9.67E+09	1.31E+03	6.23E-14
900	1.18E+12	1.54E+12	3.36E+09	7.30E+06	1.16E+04	1.95E+10	1.33E+11	9.01E+09	1.31E+03	6.00E-14

Table 4 — Reference values for intermediate- and short-term solar variability

	Case 1: Intermediate-term (81 days)			Case 2: Short-term (27 days high activity)			Case 3: Short-term (27 days low activity)		
Daily	Low	Moderate	High	Low	Moderate	High	Low	Moderate	High
$F_{10.7}$	65	120	225	90	165	280	80	105	145
$S_{10.7}$	60	120	215	105	135	185	85	100	120
$M_{10.7}$	60	115	215	95	135	185	80	95	115
$Y_{10.7}$	50	115	180	110	150	185	90	110	135

NOTE 1 Reference index values are provided in Table 3.4 for intermediate-term variability that includes more than one solar rotation (>27 days) but for not more than a half solar cycle (<6 years). The 81-day smoothed minimum, mean, and maximum values rounded to the nearest unit of 5 for solar cycle 23 are used for reference low, moderate, and high intermediate-term examples, respectively.

NOTE 2 Daily (short-term) solar variability reference values for less than a solar rotation (27 days) are also provided in Table 3.4 as rounded numbers to the nearest unit of 5. The period of October 14 to November 9, 2003 in solar cycle 23 is used as a reference period when highly variable activity occurred; these are conditions appropriate to the rise of a solar cycle or large events that occur during the decline of a solar cycle. A second period is provided from January 7 to February 2, 2005 when lower variable activity occurred; these are conditions appropriate approaching or leaving the minimum of a solar cycle. In short-term periods, higher values have been measured than those given in Table 3.4, e.g., F10.7 = 380 over a day. However, empirical atmosphere density models are not developed for such high index values and their use will lead to large and unknown errors.

NOTE 3 In Table 3.4, the example Cases 1, 2, and 3 should use the low, moderate, and high solar activity levels for that Case only as one complete set of inputs into JB2008. The 81-day value should be set to the moderate Case value for each proxy or index. Values from different Case examples should not be mixed. If a single daily value from one Case and one solar activity level is desired, the 81-day index should be set to the moderate value for each index.

3.1.7 JB2008 Long-term Solar Cycle Variability

Tables 3.5 and 3.6 are provided for estimating solar cycle variability in the four solar indices. The example of solar cycle 23, a moderate cycle, is used. In these tables, the actual monthly minimum, mean, and maximum value of each index or proxy is given. Table 3.5 reports monthly values for the $F_{10.7}$, F_{81} proxy and the $S_{10.7}$, S_{81} index. Table 3.6 reports monthly values for the $M_{10.7}$, M_{81} proxy and the $Y_{10.7}$, Y_{81} index.

The ranges of maximum and minimum values are not the confidence values since they are the actual measurements. Smaller solar cycles will tend to produce a smaller monthly range and larger solar cycles will tend to produce a larger monthly range. Solar cycle 23 is considered a moderate cycle by recent historical standards.

The tabled values should be used as provided for periods of up to a solar cycle if no forecasts are available. If daily values are required, the monthly values can be interpolated to daily resolution. Figure 3.6 shows all four proxies and indices with their monthly minimum, mean, and maximum values. Monthly $F_{10.7}$ forecasts that include confidence bounds are provided by the NASA Marshall Space Flight Center (http://sail.msfc.nasa.gov/) and by the NOAA SWPC (http://www.swpc.noaa.gov/). Daily forecasts for $F_{10.7}$, F_{81}, $S_{10.7}$, S_{81}, $M_{10.7}$, M_{81}, $Y_{10.7}$, and Y_{81} out to 5 solar rotations (137-days) are provided by Space Environment Technologies (http://spacewx.com "Innovations:SET Space Weather Forecasts" menu link).

Table 3.5 — Reference values for long-term solar cycle variability in the F10.7, F81 proxy and S10.7, S81 index

Month	$F10_{min}$	$F10_{mean}$	$F10_{max}$	$F81_{min}$	$F81_{mean}$	$F81_{max}$	$S10_{min}$	$S10_{mean}$	$S10_{max}$	$S81_{min}$	$S81_{mean}$	$S81_{max}$
0	72	74	77	74	76	78	74	78	82	78	79	79
1	71	74	81	74	74	74	74	77	82	78	78	78
2	70	73	76	74	74	74	73	78	83	78	79	79
3	69	74	81	74	74	74	74	80	86	79	80	81
4	71	75	85	72	73	74	78	83	91	81	81	81
5	68	72	77	72	72	73	78	81	87	81	81	82
6	67	71	80	73	74	77	75	80	87	82	83	86
7	71	79	96	78	82	86	80	89	100	86	90	94
8	85	96	119	86	88	91	97	100	103	94	96	99
9	79	85	91	91	92	93	92	98	103	99	100	102
10	86	100	118	93	95	96	97	105	120	102	102	103
11	85	99	117	96	97	97	95	104	114	103	104	105
12	81	93	108	94	95	96	92	104	110	103	104	105
13	83	93	107	95	99	103	93	103	110	104	106	108
14	90	109	133	103	106	108	97	110	123	109	111	113
15	88	108	141	109	110	110	101	117	131	114	115	116
16	87	107	133	106	107	109	103	114	125	116	116	117
17	96	108	122	108	109	111	108	119	128	116	117	117
18	99	114	129	112	119	127	118	118	118	117	118	119
19	109	136	179	127	130	133	118	118	118	118	118	118
20	116	138	177	130	132	133	118	118	118	118	119	122
21	103	117	135	128	130	132	118	120	130	122	125	131
22	115	140	168	132	136	140	123	139	158	131	136	140
23	129	150	184	140	143	147	140	147	159	139	141	142
24	110	141	178	142	145	147	128	136	143	138	139	140

25	99	142	205	135	139	143	115	138	159	137	138	139
26	102	126	156	127	130	135	119	139	154	137	138	139
27	98	117	141	127	130	134	111	132	151	139	141	144
28	127	149	178	134	144	154	130	153	168	145	152	159
29	139	170	210	155	161	167	154	171	192	160	165	170
30	130	166	206	164	166	169	156	172	200	169	170	171
31	123	171	248	155	159	166	146	169	194	161	164	170
32	107	136	163	153	156	159	136	151	184	158	160	162
33	122	165	200	160	165	169	149	159	168	160	162	165
34	143	192	249	169	176	181	157	177	193	165	169	170
35	130	170	217	166	174	178	144	169	192	169	172	173
36	126	158	211	163	167	172	142	167	200	170	171	173
37	138	173	227	172	179	186	155	177	194	174	179	183
38	178	208	234	185	189	192	173	193	213	183	187	189
39	158	184	223	187	191	195	179	192	214	188	189	191
40	127	185	262	181	183	187	165	183	212	184	186	188
41	148	180	202	184	191	196	165	185	206	185	191	195
42	148	202	262	181	185	187	176	207	234	193	196	197
43	131	163	194	174	180	184	162	189	213	187	192	195
44	133	182	232	170	171	173	166	181	197	181	183	187
45	140	168	203	173	176	179	166	183	197	181	182	183
46	144	179	205	171	173	176	157	185	224	182	183	184
47	135	174	201	172	174	176	156	184	209	182	183	184
48	152	167	184	160	165	172	172	178	185	175	179	183
49	130	147	170	155	161	167	158	170	184	171	174	176
50	130	178	274	165	168	170	155	175	218	174	174	176
51	123	178	258	169	170	172	152	178	215	173	174	174
52	129	148	185	160	165	171	151	165	186	170	172	174
53	133	174	221	150	153	160	162	176	190	165	167	170
54	115	131	150	151	154	158	142	156	168	166	166	167
55	120	163	199	158	173	187	143	168	180	167	173	181
56	183	234	285	188	203	218	174	199	230	182	191	200
57	171	208	248	218	220	222	192	207	222	201	204	206

58	170	213	271	214	220	226	182	201	232	204	206	209
59	206	236	275	223	224	225	197	211	232	207	209	212
60	189	227	261	217	223	227	197	219	235	211	212	213
61	188	205	246	201	206	216	199	205	218	202	206	211
62	166	179	204	186	193	201	181	191	196	191	196	202
63	147	190	226	181	183	186	171	189	203	183	187	191
64	157	178	191	161	172	181	161	180	194	171	177	183
65	131	149	179	159	162	165	150	163	183	164	166	170
66	129	174	242	163	168	175	144	161	181	163	165	167
67	135	184	241	176	181	183	149	172	202	167	170	172
68	138	176	221	174	178	182	153	174	198	170	172	173
69	136	167	183	164	170	174	150	164	180	163	166	170
70	137	169	199	162	165	169	149	162	176	160	163	166
71	114	157	213	148	157	162	135	164	177	154	158	161
72	115	144	189	136	143	148	133	149	172	144	150	154
73	102	125	150	129	133	136	111	135	151	134	138	143
74	89	132	160	126	127	129	102	131	153	126	130	133
75	99	126	158	121	123	126	109	128	149	123	125	126
76	92	116	149	122	124	126	104	123	142	124	125	126
77	106	129	193	125	126	127	107	125	139	125	126	127
78	99	128	157	122	126	128	108	127	134	125	126	126
79	107	122	137	117	119	122	114	124	136	123	124	125
80	94	112	137	115	122	132	106	121	135	122	123	126
81	92	151	279	129	135	141	110	129	185	123	125	127
82	91	141	210	137	138	140	100	128	153	123	124	126
83	86	115	143	121	126	140	92	118	143	117	119	123
84	87	114	135	111	113	120	96	109	126	111	113	117
85	95	107	122	108	110	111	101	109	120	109	111	112
86	90	112	129	105	107	108	101	114	125	109	111	112
87	88	101	117	102	104	105	99	109	117	108	109	110
88	85	100	118	97	99	102	99	104	111	102	105	107
89	82	97	119	97	104	108	93	102	109	102	103	104
90	78	119	175	106	110	112	89	105	125	103	104	105

91	83	110	149	107	112	115	88	105	118	103	105	106
92	88	103	131	102	105	107	93	103	112	102	103	105
93	87	106	140	106	107	108	92	105	122	104	104	105
94	95	114	141	106	106	107	103	108	113	104	104	104
95	85	95	111	99	103	106	92	97	106	99	101	103
96	83	102	145	97	99	100	86	98	119	95	97	98
97	75	97	122	93	97	99	76	94	109	92	94	95
98	74	90	114	90	91	93	76	88	101	88	90	91
99	77	86	106	91	92	93	81	86	92	88	89	90
100	82	100	126	93	95	99	85	92	100	89	90	91
101	77	94	116	94	96	99	82	89	98	90	91	92
102	71	96	130	91	93	95	76	92	107	89	89	90
103	75	91	111	89	91	95	72	88	103	87	88	90
104	72	91	119	85	86	89	74	87	101	84	85	87
105	72	77	83	83	84	85	70	78	83	80	82	84
106	77	86	102	83	85	86	76	80	84	80	81	82
107	85	91	106	86	87	88	79	86	93	82	83	83
108	77	83	94	81	83	86	76	83	89	80	81	83
109	74	77	79	78	79	80	72	76	79	77	78	80
110	72	75	86	79	80	82	71	74	78	77	78	80
111	76	89	101	82	82	83	78	84	92	79	80	82
112	72	81	93	81	82	83	72	83	92	80	81	82
113	72	77	86	76	78	81	73	76	82	76	78	80
114	70	76	87	76	77	78	70	74	82	74	75	76
115	70	79	89	77	78	79	69	73	79	74	74	75
116	70	78	87	78	78	78	67	75	82	74	74	74
117	70	74	80	78	79	81	66	72	78	74	74	75
118	77	86	97	81	83	84	73	77	81	74	74	75
119	72	84	103	84	84	85	68	75	90	75	75	75
120	76	83	92	79	81	84	72	75	80	73	73	74
121	73	78	90	75	77	79	68	72	77	71	72	73
122	69	72	76	73	74	75	64	69	73	68	69	71
123	68	72	87	73	73	75	63	67	71	68	68	69

124	67	74	87	74	74	75	66	68	71	68	69	69
125	65	74	87	72	73	75	61	70	79	68	68	69
126	66	72	79	70	71	72	62	67	70	65	66	68
127	67	69	72	68	69	70	62	64	66	63	64	65
128	65	67	71	68	68	68	60	61	65	62	62	63
129	66	68	69	68	68	70	59	62	66	61	61	62
130	67	70	72	70	72	74	59	60	63	61	62	63
131	71	79	94	74	75	75	60	65	71	63	64	65
132	70	74	80	72	74	75	60	67	76	64	64	65
133	70	71	73	72	72	72	61	64	67	63	64	64
134	68	73	89	71	72	72	60	64	72	63	63	63
135	67	70	78	70	71	71	63	66	71	63	63	63
136	66	68	72	67	68	70	60	63	68	62	62	63
137	65	66	67	66	67	67	59	61	63	61	61	62
138	65	66	67	66	66	66	58	61	64	61	61	61
139	65	66	68	66	66	67	59	60	62	60	61	61
140	65	67	69	67	67	68	59	61	63	61	61	61
141	66	68	72	68	68	68	60	63	65	61	62	62
142	67	69	71	69	69	69	60	62	65	61	62	62
143	68	69	71	69	69	69	60	61	63	61	62	62

Table 3.6 — Reference values for long-term solar cycle variability in the M10.7, M81 proxy and Y10.7, Y81 index

Month	$M10_{min}$	$M10_{mean}$	$M10_{max}$	$M81_{min}$	$M81_{mean}$	$M81_{max}$	$Y10_{min}$	$Y10_{mean}$	$Y10_{max}$	$Y81_{min}$	$Y81_{mean}$	$Y81_{max}$
0	65	72	76	72	73	74	62	66	73	69	71	74
1	62	71	75	72	72	73	63	70	84	69	69	71
2	66	73	80	73	73	74	61	71	80	71	72	72
3	67	75	86	74	75	76	63	74	87	72	73	74
4	72	78	87	76	76	77	64	76	92	72	73	75
5	70	76	86	76	76	77	65	71	86	72	72	73
6	68	75	85	76	77	80	63	70	91	73	75	80
7	73	82	99	80	84	88	65	85	104	81	87	92

8	81	94	101	88	90	92	96	103	110	92	94	98
9	85	91	98	92	93	95	68	90	100	98	100	102
10	84	98	121	95	96	97	98	112	125	101	103	104
11	84	100	120	97	98	99	91	106	120	104	105	106
12	85	99	114	97	98	99	77	101	114	102	103	104
13	85	96	107	98	99	102	91	102	116	103	106	111
14	83	103	117	103	106	109	102	115	131	111	114	118
15	94	113	147	109	111	112	105	120	136	118	120	121
16	90	110	129	112	113	114	107	122	138	120	121	122
17	99	115	139	115	117	119	113	122	129	122	123	125
18	111	128	150	119	125	130	117	127	137	125	130	134
19	122	135	148	130	132	134	132	142	162	135	136	138
20	121	137	151	132	134	135	130	140	154	138	139	139
21	109	126	137	131	133	135	123	132	138	138	139	141
22	116	137	169	134	136	138	129	148	162	141	143	145
23	126	146	175	137	139	140	142	149	158	145	148	149
24	109	138	166	137	138	140	126	149	171	146	147	148
25	102	134	172	134	135	138	123	144	167	142	144	147
26	109	130	159	130	132	134	117	136	157	137	138	142
27	97	121	157	131	132	135	115	131	143	137	139	141
28	117	145	175	135	142	150	140	151	172	141	147	152
29	135	163	197	151	156	160	152	159	175	153	156	159
30	132	162	191	159	160	162	140	159	177	158	159	160
31	129	162	202	152	155	161	140	162	181	155	157	159
32	121	142	175	150	152	154	135	147	164	154	155	156
33	131	153	167	153	156	158	144	157	165	156	158	160
34	141	170	195	158	161	164	151	170	184	160	162	163
35	125	159	191	162	165	167	140	158	173	158	161	163
36	129	162	209	163	164	166	138	156	175	157	158	160
37	131	167	193	166	170	174	148	162	174	160	163	166
38	156	185	213	174	178	181	163	173	182	165	166	167
39	164	186	213	178	180	183	153	163	178	165	167	168
40	141	172	210	173	176	179	139	163	188	163	164	165

41	145	174	197	174	181	184	152	164	174	164	168	171
42	156	196	236	181	185	187	152	177	194	167	168	169
43	131	177	220	177	182	183	144	161	176	164	166	168
44	150	173	196	173	174	176	150	164	178	163	163	164
45	153	175	200	173	174	176	153	165	175	164	166	168
46	137	179	211	173	174	176	149	170	183	166	166	167
47	126	174	203	172	174	176	149	164	181	164	165	167
48	148	172	188	165	170	176	154	161	167	156	159	163
49	127	156	179	159	162	165	137	148	162	155	157	160
50	137	158	216	157	159	164	140	166	204	159	160	161
51	116	163	204	158	159	162	144	163	203	161	161	162
52	125	154	173	161	161	163	137	150	167	156	158	161
53	147	171	194	159	161	163	147	162	175	152	153	155
54	133	152	172	159	160	161	133	145	153	153	154	157
55	133	157	182	161	166	173	135	160	177	157	162	167
56	172	194	223	173	184	194	167	181	191	167	172	177
57	176	202	234	194	198	201	162	173	182	175	176	177
58	168	192	207	200	202	206	164	175	191	175	176	179
59	196	212	232	203	207	212	171	182	203	179	179	180
60	195	219	243	211	213	214	173	181	188	179	180	180
61	192	207	230	202	206	211	171	177	185	177	177	179
62	176	188	202	190	195	202	166	174	186	176	177	178
63	167	188	212	185	187	190	166	179	190	176	176	177
64	157	184	210	173	180	185	167	175	182	168	172	176
65	143	167	190	166	169	172	153	161	175	167	167	167
66	139	164	201	165	167	169	150	169	188	166	168	170
67	134	174	214	169	173	175	156	175	195	170	171	172
68	144	177	207	174	175	176	151	166	177	168	170	171
69	145	168	190	165	170	173	152	166	180	164	166	168
70	140	163	185	161	165	169	152	166	181	163	165	167
71	130	164	193	153	159	163	135	162	182	155	160	163
72	128	149	182	143	149	154	137	151	167	146	151	155
73	109	130	163	132	137	142	116	138	152	138	142	145

74	94	131	172	126	129	132	113	137	154	135	136	138
75	106	130	158	123	125	126	114	136	161	132	133	134
76	94	122	147	124	125	128	105	130	145	133	134	136
77	103	126	151	127	128	131	122	138	163	135	136	137
78	113	134	150	129	130	131	122	138	152	135	137	137
79	118	129	141	126	128	130	131	135	146	132	134	135
80	106	123	145	125	127	130	118	130	142	131	134	138
81	102	133	187	126	129	133	110	144	185	136	138	141
82	92	134	175	128	129	131	113	142	177	138	139	140
83	84	121	159	121	123	128	100	129	151	128	132	138
84	88	112	152	112	115	120	101	123	143	122	124	128
85	91	108	127	109	111	112	106	117	123	118	120	121
86	90	110	126	107	109	110	108	120	130	115	117	118
87	95	108	122	107	108	109	100	113	135	113	115	116
88	95	104	113	101	104	107	101	111	122	109	111	113
89	87	101	116	101	103	105	94	110	123	109	112	114
90	79	106	142	102	105	106	90	118	143	113	116	118
91	83	106	135	105	107	108	96	119	146	117	120	121
92	85	105	131	103	106	108	96	117	136	114	115	117
93	94	108	131	106	107	109	94	111	131	113	115	116
94	99	112	129	107	107	108	107	121	130	113	114	116
95	87	102	116	101	104	107	100	110	122	111	113	115
96	83	98	117	97	99	101	90	110	134	105	108	111
97	74	96	121	94	96	97	76	101	117	100	103	105
98	72	90	113	91	92	94	77	96	118	97	98	99
99	75	88	101	91	92	94	82	95	109	98	100	101
100	92	98	109	93	94	96	93	109	124	101	104	107
101	79	93	107	94	95	97	87	104	116	105	106	108
102	71	95	123	92	93	95	75	106	126	101	103	105
103	72	94	118	90	92	94	79	99	121	97	101	104
104	72	90	105	87	89	91	74	99	115	90	93	98
105	71	81	93	85	86	88	60	77	89	86	88	90
106	76	84	91	84	85	87	81	90	104	86	87	89

107	80	92	107	86	87	87	90	97	108	86	89	91
108	75	86	102	82	85	86	62	82	98	76	81	86
109	72	78	86	79	80	82	53	66	77	72	74	76
110	70	76	81	80	81	83	62	72	88	74	77	82
111	77	88	108	83	84	86	82	91	104	82	84	87
112	69	87	106	84	85	86	74	87	101	85	86	87
113	72	79	87	80	81	84	68	81	91	80	82	86
114	70	79	91	78	78	80	59	78	95	80	80	81
115	67	77	83	77	78	79	63	82	97	79	81	82
116	66	77	92	75	76	78	66	80	93	77	78	80
117	63	72	83	74	75	76	58	69	84	78	78	79
118	63	77	86	74	75	76	72	87	97	79	81	83
119	62	76	89	76	77	77	61	83	106	80	83	84
120	67	77	88	74	75	76	69	81	90	72	76	80
121	67	74	84	71	73	74	56	64	86	66	69	72
122	64	68	74	69	69	71	59	63	70	62	64	66
123	62	68	80	69	69	71	55	65	89	65	66	68
124	64	70	80	70	71	72	57	69	83	68	69	70
125	62	73	89	71	71	72	55	69	87	65	67	70
126	61	70	76	68	69	71	56	64	81	61	63	65
127	60	66	70	66	67	68	56	59	64	58	59	61
128	60	64	67	65	65	66	54	57	61	56	57	58
129	61	64	67	65	65	67	52	55	58	56	56	57
130	62	65	70	68	70	72	55	57	60	58	60	60
131	63	80	94	72	72	72	54	66	86	58	59	60
132	61	67	77	68	71	72	46	52	61	52	56	58
133	64	68	74	66	67	67	49	51	55	51	52	53
134	64	67	71	66	67	67	49	55	72	52	53	53
135	62	66	71	66	66	66	47	51	66	52	52	52
136	63	65	70	65	65	66	48	50	53	49	50	52
137	62	63	65	63	64	64	47	48	50	48	49	49
138	60	62	65	62	63	63	46	48	49	48	48	48
139	61	62	63	62	62	62	47	47	48	47	47	48

140	60	62	63	62	62	62	46	47	48	47	47	48
141	61	63	65	62	62	62	47	48	49	48	48	48
142	60	62	65	62	62	62	46	48	49	47	47	48
143	60	61	64	62	62	62	46	47	49	47	47	47

3.1.8 JB2008 Long-Term 25-Year Solar Variability

As a guide for orbit lifetime planning and debris mitigation purposes, it is often useful to have a 25-year estimate of atmosphere density variability that is driven by solar indices. The following procedure is recommended for producing a consistent, repeatable estimate of long-term 25-year JB2008 thermospheric densities:

1) Determine the relative starting point in the solar cycle for the proxies and indices from Tables 3.5 and 36; the most useful index for this is the F_{81} mean value in Table 3.5; the start may be at the beginning, rise, maximum, decline, or end of a cycle; for example, to plan a mission with a spacecraft launch in 2012 and to estimate its 25-year lifetime, the assumption would be made that the mission start is approximately at the maximum of cycle 24; an appropriate date in cycle 23 would be selected such as Month 60 where the F_{81} mean value is 223; the F_{81} mean value can be used a generalized indicator of solar cycle phases;
2) Form a consecutive set of monthly proxy and index values by concatenating onto Tables 3.5 and 3.6 the Month 0 line of the Tables starting in place of Month 124; although solar cycles are often thought of as 11-year cycles, there is actually a range of cycle periods and this method results in an acceptable solar cycle length of 124 months (10 years, 4 months) where the discontinuity between the end of one cycle and the start of another cycle is minimized; the cycle start in the table data set is Month 0, the peak is Month 60, and the cycle end is Month 123 when the table is used to create multiple cycles; it is typical for a solar cycle to have a faster rise to maximum and a slower decline to minimum; the solar cycle minimum is the lowest average value following the peak of the cycle; this method has a slight high flux bias by excluding the lowest solar activity conditions and favours shorter solar cycles; and
3) Repeat this process for as many months, years, or solar cycles as are needed.

3.1.9 JB2008 Altitude Profiles of Total Air Density

Table 3.7 shows the JB2008 altitude profiles of total density r [kg m^{-3}] for low ($F10.7 = F10.7_{avg}$ = 65, $S10.7 = S10.7_{avg}$ = 60, $M10.7 = M10.7_{avg}$ = 60, $Y10.7 = Y10.7_{avg}$ = 60, A_p = 0, Dst = -15), moderate ($F10.7 = F10.7_{avg}$ = 140, $S10.7 = S10.7_{avg}$ = 125, $M10.7 = M10.7_{avg}$ = 125, $Y10.7 = Y10.7_{avg}$ = 125, A_p = 15, Dst = -15), high long-term ($F10.7 = F10.7_{avg}$ = 250, $S10.7 = S10.7_{avg}$ = 220, $M10.7 = M10.7_{avg}$ = 220, $Y10.7 = Y10.7_{avg}$ = 220, A_p = 45, Dst = -100), and high short-term ($F10.7 = 300$, $F10.7_{avg}$ = 250, $S10.7 = 235$, $S10.7_{avg}$ = 220, $M10.7 = 240$, $M10.7_{avg}$ = 220, $Y10.7 = Y10.7_{avg}$ = 220, A_p = 240, Dst = -300) solar and geomagnetic activity.

Table 7 — Altitude profiles of total density for low, moderate, and high long-and short-term solar and geomagnetic activity

H (km)	Low activity	Moderate activity	High activity (long term)	High activity (short term)
100	5.31E-07	5.47E-07	5.44E-07	5.43E-07
120	2.18E-08	2.40E-08	2.45E-08	2.46E-08
140	3.12E-09	3.98E-09	4.32E-09	4.45E-09
160	9.17E-10	1.36E-09	1.54E-09	1.60E-09
180	3.45E-10	6.15E-10	7.40E-10	7.77E-10
200	1.47E-10	3.17E-10	4.10E-10	4.38E-10
220	6.96E-11	1.77E-10	2.46E-10	2.70E-10
240	3.54E-11	1.05E-10	1.56E-10	1.77E-10
260	1.88E-11	6.47E-11	1.04E-10	1.21E-10
280	1.03E-11	4.12E-11	7.12E-11	8.57E-11
300	5.86E-12	2.69E-11	5.00E-11	6.22E-11
320	3.40E-12	1.80E-11	3.59E-11	4.60E-11
340	2.02E-12	1.23E-11	2.61E-11	3.45E-11
360	1.22E-12	8.48E-12	1.93E-11	2.63E-11
380	7.46E-13	5.95E-12	1.44E-11	2.02E-11
400	4.63E-13	4.22E-12	1.09E-11	1.57E-11
420	2.92E-13	3.02E-12	8.32E-12	1.23E-11
440	1.87E-13	2.18E-12	6.40E-12	9.69E-12
460	1.21E-13	1.59E-12	4.96E-12	7.70E-12
480	8.04E-14	1.17E-12	3.87E-12	6.16E-12
500	5.44E-14	8.60E-13	3.04E-12	4.95E-12
520	3.77E-14	6.39E-13	2.40E-12	4.01E-12
540	2.68E-14	4.77E-13	1.91E-12	3.25E-12
560	1.96E-14	3.58E-13	1.52E-12	2.66E-12
580	1.47E-14	2.71E-13	1.22E-12	2.18E-12
600	1.14E-14	2.06E-13	9.82E-13	1.79E-12
620	9.10E-15	1.57E-13	7.93E-13	1.48E-12
640	7.41E-15	1.20E-13	6.43E-13	1.23E-12
660	6.16E-15	9.28E-14	5.22E-13	1.02E-12
680	5.22E-15	7.19E-14	4.25E-13	8.49E-13
700	4.50E-15	5.60E-14	3.47E-13	7.09E-13
720	3.93E-15	4.40E-14	2.84E-13	5.94E-13
740	3.48E-15	3.48E-14	2.34E-13	4.98E-13
760	3.10E-15	2.79E-14	1.92E-13	4.19E-13
780	2.79E-15	2.26E-14	1.59E-13	3.54E-13
800	2.53E-15	1.85E-14	1.32E-13	2.99E-13
820	2.30E-15	1.53E-14	1.10E-13	2.54E-13
840	2.11E-15	1.28E-14	9.21E-14	2.16E-13
860	1.94E-15	1.08E-14	7.72E-14	1.84E-13
880	1.78E-15	9.27E-15	6.50E-14	1.57E-13
900	1.65E-15	8.01E-15	5.49E-14	1.35E-13

3.1.10. Useful Internet References for Indices

a) Indices glossary: http://www.sec.noaa.gov/info/glossary.html

b) F10.7 daily values at DRAO website: http://hia-iha.nrc-cnrc.gc.ca/drao/icarus_e.html

c) F10.7, Kp, Ap, Dst, Solar Wind Speed, IMF archive values at Space Physics Interactive Data Resource (SPIDR): http://spidr.ngdc.noaa.gov/spidr/index.jsp

d) F10, S10, M10, Y10, Dst, ap and source code at JB2008 website:

http://sol.spacenvironment.net/~JB2008/

e) F10.7 predictions at NASA Marshall Space Flight Center's: http://sail.msfc.nasa.gov

f) http://sol.spacenvironment.net/

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[3] Drob, D. P., et al., "An empirical model of the Earth's horizontal wind fields: HWM07", *J. Geophys. Res.*, *113*, A12304, doi:10.1029/2008JA013668, (2008).

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

[6] "Guide to Reference and Standard Atmosphere Models", AIAA G-003C-2010. American Institute of Aeronautics and Astronautics, Reston, VA, (2010).

[7] ASTE E 490 – 00, "Solar constant and zero air mass solar spectral irradiance tables", ASTM, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, (2000).