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Space environment (natural and artificial) — Earth's atmosphere from ground level upward

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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.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

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

This second edition cancels and replaces the first edition (ISO 14222:2013), which has been technically revised.

The main changes are as follows:

— updated formulae, references to models, indices and links to websites;

— this document now applies to the Earth's atmosphere from ground level upward through the exosphere.

Any feedback or questions on this document should be directed to the user’s national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

This document provides guidance for determining the properties of the Earth’s atmosphere from ground level upward to the exosphere.

In the atmospheric regions up to approximately 100 km, a detailed knowledge of the average structure of the atmosphere as a function of geographic location, time in the year and solar activity is critical for the design of aircraft, balloon payloads, rocket launch activities and many other facets of modern society. The maximum departures from average conditions also need to be understood in order to provide a margin of safety in design and in operations. These features are included in this document.

A good knowledge of temperature, total density, concentrations of gas constituents, and pressure in the region above about 100 km is important for many space missions exploiting the low-earth orbit (LEO) regime below approximately 2 500 km altitude. In addition to the causes of variation of the atmosphere up to 100 km, geomagnetic processes may seriously affect the structure and dynamics of the thermosphere. 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 manoeuvring 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 atmosphere and internationally accepted empirical models that specify the details of the atmosphere are included in this document. The annexes and references provide a detailed description the details of those models. The purpose is to create a standard method for specifying Earth's atmosphere properties (density, temperature, wind etc.) at all altitudes from ground level upward, including the low Earth orbit regime now widely-used for space systems and space operations.

The details of those models are included in Annex A.

Annex B provides a detailed description of the electromagnetic radiation and solar and geomagnetic indices.

Space environment (natural and artificial) — Earth's atmosphere from ground level upward

1 Scope

This document specifies the structure and properties of the Earth's atmosphere from ground level upward. It provides internationally accepted empirical models that specify the details of the atmosphere. It also refers to widely-accepted physical models providing insight into the physical and chemical processes driving the response of the atmosphere.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

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

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
homosphere
region of the atmosphere that is well mixed

Note 1 to entry: The major species proportional concentrations are independent of height and location.

Note 2 to entry: This region extends from 0 km to ~100 km and includes the temperature-defined regions of the *troposphere* (3.2) (surface up to ~6 km to 18 km altitude), the *stratosphere* (3.3) (~6 km to 18 km up to 50 km altitude), the *mesosphere* (3.4) (~50 km up to about 90 km altitude), and the lowest part of the *thermosphere* (3.5) (~90 km to 125 km).

3.2
troposphere
lowest layer of the Earth's atmosphere

Note 1 to entry: It is also where nearly all weather conditions occur.

Note 2 to entry: The troposphere contains approximately 75 % of the atmosphere's mass and 99 % of the total mass of water vapour and aerosols. The average height of the tropopause is 18 km (11 mi; 59 000 ft) in the tropics, 17 km (11 mi; 56 000 ft) in the middle latitudes, and 6 km (3.7 mi; 20 000 ft) in the polar regions in winter. The global average height of the tropopause is 13 km.

Note 3 to entry: The lowest part of the troposphere, where friction with the Earth's surface influences air flow, is called the planetary boundary layer. The boundary layer is typically a few hundred metres to 4 km deep depending on the landform, latitude, season and time of day. The upper boundary of the troposphere is the tropopause, which is the border between the troposphere and *stratosphere* (3.3). The tropopause is an inversion layer, where the air temperature ceases to decrease with height and remains constant through its thickness.

3.3
stratosphere
second major layer of Earth’s atmosphere, immediately above the *troposphere* (3.2) and below the *mesosphere* (3.4)

Note 1 to entry: The stratosphere is stratified (layered) in temperature, with warmer layers higher and cooler layers closer to the Earth; this increase of temperature with altitude is a result of the absorption of the Sun's ultraviolet radiation by the ozone layer. This is in contrast to the *troposphere* (3.2), near the Earth's surface, where temperature decreases with altitude. The border between the *troposphere* (3.2) and stratosphere, the tropopause, marks where this temperature inversion begins. Near the equator, the stratosphere starts at as high as 18 km, around 17 km at midlatitudes, and at about 6 km at the poles. Temperatures range from an average of −51 °C near the tropopause to an average of −15 °C near the stratopause [the boundary with the *mesosphere* (3.4)]. Stratospheric temperatures also vary within the stratosphere as the seasons change, reaching particularly low temperatures in the polar night (winter). Winds in the stratosphere can far exceed those in the *troposphere* (3.2), reaching near 60 m/s in the Southern polar vortex.

3.4
mesosphere
layer of the Earth’s atmosphere that is directly above the *stratosphere* (3.3) and directly below the *thermosphere* (3.5)

Note 1 to entry: In the mesosphere, temperature decreases as the altitude increases. This characteristic is used to define its limits: it begins at the top of the *stratosphere* (3.3) (sometimes called the stratopause), and ends at the mesopause, which is the coldest part of Earth's atmosphere with temperatures frequently below −143 °C. The exact upper and lower boundaries of the mesosphere vary with latitude and with season (higher in winter and at the tropics, lower in summer and at the poles), but the lower boundary is usually located at heights from 50 km to 65 km above the Earth's surface and the upper boundary (mesopause) is usually around 85 km to 100 km.

Note 2 to entry: The *stratosphere* (3.3) and the mesosphere are collectively referred to as the “middle atmosphere”, which spans heights from approximately 10 km to 100 km. The mesopause, at an altitude of 80 km to 90 km, separates the mesosphere from the *thermosphere* (3.5) – the second-outermost layer of the Earth's atmosphere. This is also approximately the same altitude as the turbopause. Below the turbopause, different chemical species are well mixed due to turbulent eddies. Above this level the atmosphere becomes non-uniform; also, above the turbopause, the scale heights of different chemical species differ by their molecular masses.

3.5
thermosphere
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 km to 600 km altitude, depending on solar and geomagnetic activity levels)

Note 1 to entry: At its lower boundary with the *mesosphere* (3.4), the composition is close to that found at ground level. In the upper thermosphere, the composition is usually mainly atomic oxygen.

3.6
exosphere
region of the atmosphere that extends from the top of the *thermosphere* (3.5) outward

3.7
NRLMSIS 2.0
Naval Research Laboratory mass spectrometer, incoherent scatter radar extended model
model that describes the neutral temperature and species densities in Earth's atmosphere from ground level upward, including the *troposphere* (3.2), *stratosphere* (3.3), *mesosphere* (3.4), *thermosphere* (3.5) and *exosphere* (3.6)

Note 1 to entry: 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 to entry: It is valid for use from ground level to the *exosphere* (3.6). Two indices are used in this model: $F_{10,7}$ (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)

Note 3 to entry: See References [1] and [2].

3.8
Earth GRAM 2016
Earth GLOBAL reference atmosphere models
models which have been produced on behalf of NASA to describe the terrestrial atmosphere from ground level upward for operational purposes

Note 1 to entry: Earth GRAM 2016 is now available as an open-source C++ computer code that can run on a variety of platforms including PCs and UNIX stations. The software provides a model that offers values for atmospheric parameters such as density, temperature, winds, and constituents for any month and at any altitude and location within the Earth's atmosphere. An earlier version, Earth GRAM 2010 is available in FORTRAN.

Note 2 to entry: Earth GRAM 2016 includes the *troposphere* (3.2), *stratosphere* (3.3), *mesosphere* (3.4), *thermosphere* (3.5) and *exosphere* (3.6).

Note 3 to entry: These models now include options for NRLMSIS 2.0, HWM-14 and JB2008.

Note 4 to entry: See https://software.nasa.gov/software/MFS-32780-2.

Note 5 to entry: 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 6 to entry: It is valid for use from ground level to the *exosphere* (3.6). Two indices are used in this model: $F_{10,7}$ (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)

Note 7 to entry: See References [3] and [4].

3.9
JB2008
Jacchia-Bowman 2008 model
model that describes the neutral temperature and the total density in Earth's *thermosphere* (3.5) and *exosphere* (3.6)

Note 1 to entry: See https://spacewx.com/jb2008/.

Note 2 to entry: 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 and NRLMSIS 2.0.

Note 3 to entry: It is valid for use from an altitude of 120 km to 2 500 km in the *exosphere* (3.6). Four solar indices and two geomagnetic activity indices are used in this model: $F_{10,7}$ (both tabular value one day earlier and the 81-day average centred on the input time); $S_{10,7}$ (both tabular value one day earlier and the 81-day average centred on the input time); $M_{10,7}$ (both tabular value five days earlier and the 81-day average centred on the input time); $Y_{10,7}$ (both tabular value five days earlier and the 81-day average centred on the input time); a_p (3 h tabular value); and D_st (1 h value) (a_p and D_st are both used as inputs to create a $\mathrm{d}T_c$ temperature change tabular value on the input time).

Note 4 to entry: See References [5] and [6].

3.10
HWM14
horizontal wind model
comprehensive empirical global model of horizontal winds in the atmosphere

Note 1 to entry: Reference values for the a_p index needed as input for the wind model are given in Annex A.

Note 2 to entry: HWM14 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 to entry: HWM14 thermospheric winds at high geomagnetic latitudes during geomagnetically quiet periods should be treated cautiously.

Note 4 to entry: See References [7] and [8].

3.11
DTM-2013

drag temperature model 2013

model that describes the neutral temperature and (major and some minor) species densities in the Earth’s atmosphere between an altitude of 120 km to approximately 1 500 km

Note 1 to entry: DTM-2013 is based on a large database going back to the early ‘70s, but it is mainly constructed with high-resolution CHAMP and GRACE accelerometer-inferred data and GOCE thruster-inferred densities.

Note 2 to entry: It is valid from an altitude of 120 km to approximately 1 500 km in the *exosphere* (3.6). Two indices are used in this model: F_{30} solar flux (both daily solar flux of the previous day and the average of the previous 81-days) and K_p (3 h value delayed by 3 h and the average of the last 24 h).

Note 3 to entry: The DTM model codes (DTM-2009 and DTM-2013) are available for download on the SWAMI project website (swami-h2020.eu/).

Note 4 to entry: See References [9] and [10].

3.12
reanalysis model

model that provides access to corrected data sets for any location and any time around the world

EXAMPLE *ERA5* (3.13) and *NCEP/NCAR reanalysis* (3.14).

Note 1 to entry: Reanalysis models provide specific data for locations and periods of interest (e.g. inter-comparison and calibration measurements) and can also be used to provide examples of extrema of atmospheric conditions, contrasting with the long-term averages represented by the empirical models described in 3.7 to 3.11.

3.13
ERA5

latest ECMWF (European Centre for Medium Range Weather Forecasting) meteorological reanalysis project

Note 1 to entry: The first ECMWF reanalysis product, ERA-15[11], generated reanalyses for approximately 15 years, from December 1978 to February 1994. The second product, ERA-40 (originally intended as a 40-year reanalysis) begins in 1957 (the International Geophysical Year) and covers 45 years to 2002. As a precursor to a revised extended reanalysis product to replace ERA-40, ECMWF released ERA-Interim, which covers the period from 1979 to present.

Note 2 to entry: ERA5[11],[12] is a new reanalysis product which has recently been released by ECMWF as part of Copernicus Climate Change Services.

Note 3 to entry: This product has higher spatial (horizontal) resolution (31 km) and covers the period from 1979 to present. Extension back to 1950 is now available.

Note 4 to entry: In addition to reanalysing all the old data, now using a consistent system, the reanalyses also make use of much archived data that was not available to the original analyses. This allows for the correction of many historical hand-drawn maps, where the estimation of features was common in areas of data sparsity. ERA5 also has the ability to create new maps of parameters at specific atmosphere levels that were not commonly used until more recent times.

Note 5 to entry: Accessing the data: The ERA5 data can be downloaded for research use from ECMWF's homepage (see https://apps.ecmwf.int/data-catalogues/era5/?class=ea) and the National Center for Atmospheric Research data archives. Both require registration.

Note 6 to entry: A Python web API can be used to download a subset of parameters for a selected region and time period.

Note 7 to entry: ERA5 is a *reanalysis model* (3.12).

3.14
NCEP/NCAR reanalysis
continually updated globally gridded data set that represents the state of the Earth's atmosphere, incorporating observations and numerical weather prediction (NWP) model output from 1948 to present

Note 1 to entry: It is a joint product from the National Center for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR).

Note 2 to entry: Accessing the data: The data is available for free download from the NOAA Earth System Research Laboratory[13] and NCEP.[14]-[18] It is distributed in Netcdf and GRIB files, for which a number of tools and libraries exist.

Note 3 to entry: It is available for download through the NCAR CISL Research Data Archive on the NCEP/NCAR Reanalysis main data page[16].

Note 4 to entry: Since then, NCEP-DOE reanalysis 2[17] and the NCEP CFS reanalysis[18] have been released.

Note 5 to entry: The former focuses in fixing existing bugs with the NCEP/NCAR reanalysis system – most notably surface energy and usage of observed precipitation forcing to the land surface, but otherwise uses a similar numerical model and data assimilation system. The latter is based on the NCEP Climate Forecast System[18].

Note 6 to entry: See https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html.

Note 7 to entry: NCEP/NCAR reanalysis is a *reanalysis model* (3.12).

3.15
SET HASDM density database
database which is used for scientific studies through a SQL database with open community access

Note 1 to entry: The information content of the database originated from the highly accurate densities used to create the NORAD satellite catalogue and produced by the US Air Force through its High Accuracy Satellite Drag Model (HASDM) system.

Note 2 to entry: The historical database covers the period from January 1, 2000 through December 31, 2019. Data records exist every 3 h during solar cycles 23 and 24.

Note 3 to entry: The database has a grid size of 10° × 15° (latitude, longitude) with 25 km altitude steps between 175 km to 825 km.

Note 4 to entry: A description of the source of the database, its validation, its information content and its accessibility are provided by Reference [19].

Note 5 to entry: See https://spacewx.com/hasdm/.

3.16
first principles atmospheric models
models that use the physical inputs in terms of energy and momentum to the formulae describing the behaviour of the atmosphere and as such describe the self-consistent evolution of the whole atmosphere responding to external forcing from the Sun, the oceans, the magnetosphere and solar wind

Note 1 to entry: They include interactions, calculated self-consistently, with the Earth's ionosphere at higher altitudes (upper *mesosphere* (3.4), *thermosphere* (3.5)).

Note 2 to entry: See References [20] to [28].

3.17
WAM
whole atmosphere model
model developed in collaboration with the NOAA Space Weather Prediction and Environmental Modeling Centers (SWPC and EMC) by vertical extension of the operational Global Forecast System (GFS) model over the last decade

Note 1 to entry: The model has demonstrated remarkable performance in simulating climatology and daily variability of the upper atmosphere and ionosphere driven from below. Coupled to ionosphere-electrodynamics models, it not only reproduced dramatic variations of ionospheric plasma drifts and density distribution observed during sudden stratospheric warmings but also demonstrated predictive capability with lead times up to 2 weeks. WAM has reached a level of maturity to be implemented into operations at the National Weather Service (NWS).

Note 2 to entry: Within the same timeframe NWS also plans to substantially upgrade GFS to the Next Generation Global Prediction System (NGGPS). Specific capabilities of NGGPS include in particular a nonhydrostatic dynamical core and the ability to directly simulate important processes such as tropospheric convection at very high resolution globally and without the need for parameterization. This opens an opportunity for development of the Next Generation WAM (NGWAM). Specific requirements for extension of NGGPS into NGWAM will be discussed and capabilities of the new models in application to the upper atmosphere and ionosphere dynamics, simulation and prediction presented.

Note 3 to entry: See References [20]to [23].

3.18
CTIPe
coupled thermosphere ionosphere plasmasphere electrodynamics model
model that consists of four distinct components: a global *thermosphere* (3.5) model; a high-latitude ionosphere model; a mid and low-latitude ionosphere/plasmasphere model; an electrodynamical calculation of the global dynamo electric field, with all four components running concurrently and fully coupled with respect to energy, momentum and continuity

Note 1 to entry: See References [24] to [28].

4 Symbols and abbreviated terms

a_p	the 3 h planetary geomagnetic index given in nT
A_p	the daily planetary geomagnetic index given in nT
CIRA	COSPAR international reference atmosphere
COSPAR	Committee on Space Research
D_{st}	the hourly disturbance storm time ring current index given in nT
F_{10}	the $F_{10,7}$ solar proxy given in units of solar flux, $\times 10^{-22}$ W m^{-2}
F_{30}	the solar energy proxy that is used in the DTM-2013; it corresponds to the solar radio flux emitted by the Sun at 1,000 megaHertz (30 cm wavelength)
M_{10}	the $M_{10,7}$ solar proxy given in units of solar flux, $\times 10^{-22}$ W m^{-2}
S_{10}	the $S_{10,7}$ solar index given in units of solar flux, $\times 10^{-22}$ W m^{-2}
SET	Space Environment Technologies
URSI	International Union of Radio Science
Y_{10}	the $Y_{10,7}$ solar index given in units of solar flux, $\times 10^{-22}$ W m^{-2}

5 General concept and assumptions

5.1 Earth's atmosphere model use

5.1.1 General

NOTE 1 ISO/TR 11225 provides an extensive listing of many empirical and first principles atmospheric models used since before the beginning of the space age up through the modern era.

The NRLMSIS 2.0[1],[2] should be used for calculating both the neutral temperature and the detailed composition of the atmosphere from ground level upward.

The Earth GRAM 2016[3],[4] should be used for calculating the total atmospheric density from ground level upward.

The JB2008 model[5],[6] should be used for calculating the total atmospheric density from 120 km to the exosphere.

The HWM14[7],[8] should be used for horizontal winds from ground level upward.

The DTM-2013[9],[10] should be used for calculating the total atmospheric density above an altitude of 120 km, for example as used in determining satellite drag in low Earth orbit.

For altitudes below 120 km, NRLMSIS 2.0[1],[2], Earth-GRAM 2016[3],[4], ECMWF ERA5[11],[12], NCEP/NCAR reanalysis[13]-[18] or WAM[20]-[23] should be used for calculating the total air density.

The SET HASDM[19] density database should be used as a baseline reference for solar cycles 23 and 24 thermospheric densities with a time cadence of 3 h, an altitude range of 175 km to 825 km in 25 km steps and a latitude/longitude bin size of 10° × 15°.

WAM[20]-[23] should be used primarily for scientific analysis of specific events, from ground level upward.

CTIPe[24]-[28] should be used for investigations of atmospheric and Ionospheric parameters above approximately 100 km, when the response to specific solar and geomagnetic conditions and events is under investigation.

NOTE 2 This usage follows the advice of the CIRA Working Group, sponsored by COSPAR and URSI, following the resolution of the COSPAR Assembly in Montreal in July 2008.

5.1.2 Application guidance

a) The NRLMSIS 2.0 model for species densities should not be mixed with the JB2008, Earth GRAM 2016 or DTM-2013 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 Annex A 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 Annex A 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 Annex A, the daily and 81-day averaged solar activities given in Annex A 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 NRLMSIS 2.0, Earth GRAM 2016, JB2008, and DTM-2013 can only predict large scale and slow variations, on the order of 1 000 km (given by the highest harmonic component) and 3 h.

Spacecraft can often encounter density variations with smaller temporal and spatial scales. This is partly since the spacecraft are in motion (for example, +100 % or −50 % in 30 s) and partly because smaller-scale disturbances certainly do 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 Annex A.

NOTE 3 The $F_{10,7}$ 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 Annex A and in References [1] to [4].

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 D_{st} values can be used corresponding to low, moderate or high solar activities.

5.2 Earth wind model use

The HWM14[7],[8] should be used from ground level upward.

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 Annex A.

NOTE 2 The $F_{10,7}$ 81-day average solar activity can also be estimated by averaging three successive monthly predicted values as given in Annex A.

NOTE 3 The use of the HWM14 model at high geomagnetic latitudes and for disturbed geomagnetic periods necessitates caution in the interpretation of model results.

5.3 Robustness of standard

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

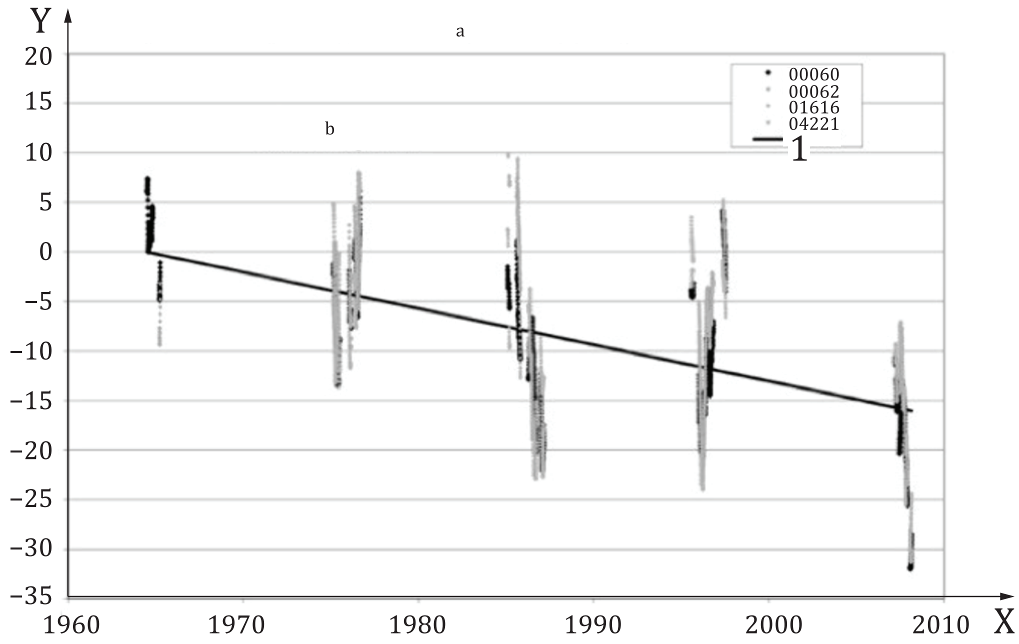
There are subtle differences between the recommended models.

These reflect differences between the selection of the very many data sources used in these models, although these generally overlap or may even be identical in many cases. However, the weighting applied to the individual data sets may differ. The mathematical formulation of the various empirical models is also distinct.

Differences between the model's predictions for specific location and conditions are generally small compared with the variability of the atmosphere. Users may find that one specific model is more convenient for their specific application than another. Users should, however, be very careful not to mix and merge atmospheric parameters from one model with those from another distinct model.

5.4 Long-term changes of the atmosphere

As the result of increasing levels of CO_2 and CH_4 in the Earth's atmosphere, the mean temperature of the troposphere and stratosphere have warmed, due to the increased thermal blanketing effect. At higher levels – the mesopause and lower thermosphere, the thermal effect is reversed since increased mixing ratios of these thermally-active gases are free to radiate to cold space. The result is a cooling of the upper mesosphere and lower thermosphere and the consequent changes in the thermal and density structure of the middle and upper thermosphere. These effects are highlighted in Figure 1[29].



Key

X year

Y dT_c (K)

1 formula

[a] Change in 81-day exospheric temperature, dT_c, at 400 km for F10B = 68-73.

[b] Slope = −3,7 degree per decade + −0,1.

= −3,1 % density per decade.

Figure 1 — Changes in temperature at solar minimum at 400 km altitude over 4 solar cycles

These changes of the temperature atmosphere (and consequently density) of the thermosphere are under detailed scrutiny. There are the significant effects on orbital drag (decreased) and the lifetime of artificial satellites and orbital debris (increased). The embedded ionosphere is also affected (for example a reduction in the height of f_0F_2 (height of the maximum of the F_2 region). It is intended that these effects should be analysed in detail and presented in a systematic way in a future revision of this document.