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Space environment (natural and artificial) — The Earth's ionosphere model — International reference ionosphere (IRI) model and extensions to the plasmasphere

Environnement spatial (naturel et artificiel) — Modèle de l'ionosphère de la Terre — Modèle de l'ionosphère internationale de référence (IRI) et extensions à la plasmasphère

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Foreword

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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).

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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 16457:2014), which has been technically revised.

The main changes are as follows:

— adding a description of the newly developed real-time IRI (Clause 9);

— replacing one of the plasmaspheric extension models (GPID) that is no longer available with the option to extrapolate the standard IRI to plasmaspheric altitudes;

— providing more detail and newer references for the IMAGE/RPI and IZMIRAN plasmaspheric extensions of IRI.

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

The purpose of this document is to identify a set of management guidelines for dealing with space systems engineering activities and is intended to define the minimum existing processes on the subject seeking to reach an international agreement on the topic.

Guided by the knowledge gained from empirical data analysis, this document provides guidelines for specifying the global distribution of electron density, electron temperature, ion temperature, ion composition, and total electron content through the Earth's ionosphere and plasmasphere. The model recommended for the representation of these parameters in the ionosphere is the international reference ionosphere (IRI).

IRI is an international project sponsored by the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI). These organizations formed a working group in the late 1960s to produce an empirical standard model of the ionosphere based on all available data sources. The IRI Working Group consists of more than 60 international experts representing different countries and different measurement techniques and modelling communities. The group meets annually to discuss improvements and additions to the model. As a result of these activities several steadily improved editions of the model have been released [18],[19],[20],[5],[6],[1],[2],[3],[53],[72],[73]. The homepage of the IRI project at http://irimodel.org/ provides access to the computer code (FORTRAN) of the latest version of the model and to earlier versions and to links to several related sites that use IRI for various applications.

For a given location over the globe, time, and date, IRI describes the monthly averages of electron density, electron temperature, ion temperature, and the percentage of O^+, H^+, He^+, N^+, NO^+, O_2^+, and cluster ions in the altitude range from 50 km to 1 500 km. In addition, IRI provides the electron content by numerically integrating over the electron density height profile within user-provided integral boundaries. IRI is a climatological model describing monthly average conditions. The major data sources for building the IRI model are the worldwide network of ionosondes, the powerful incoherent scatter radars, the topside sounders and in situ instruments flown on several satellites and rockets. This document also presents several empirical and semi-empirical models that can be used to extend the IRI model to plasmasphere altitudes.

One advantage of the empirical approach is that it solely depends on measurements and not on the evolving theoretical understanding of the processes that determine the electron and ion densities and temperatures in the Earth's ionosphere. A physical model can help to find the best mathematical functions to represent variations of these parameters with altitude, latitude, longitude, time of day, day of year, and solar and magnetic activity.

IRI is recommended for international use by COSPAR and URSI. The IRI model is updated and improved as new data and new sub-models become available. This document provides a common framework of the international standard of the Earth's ionosphere and plasmasphere for the potential users.

Space environment (natural and artificial) — The Earth's ionosphere model — International reference ionosphere (IRI) model and extensions to the plasmasphere

1 Scope

This document provides guidance to potential users for the specification of the global distribution of ionosphere densities and temperatures, as well as the total content of electrons in the height interval from 50 km to 1 500 km. It includes and explains several options for a plasmaspheric extension of the model, embracing the geographical area between latitudes of 80°S and 80°N and longitudes of 0°E to 360°E, for any time of day, any day of year, and various solar and magnetic activity conditions.

A brief introduction to ionospheric and plasmaspheric physics is given in Annex A. Annex B provides an overview over physical models, because they are important for understanding and modelling the physical processes that produce the ionospheric plasma.

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
ionosphere
region of the Earth's atmosphere in the height interval from 50 km to 1 500 km containing weakly ionized cold plasma

3.2
plasmasphere
torus of cold, relatively dense (> 10 cm^{-3}) plasma of mostly H^+ in the inner magnetosphere, which is trapped on the Earth's magnetic field lines and co-rotates with the Earth

Note 1 to entry: Cold plasma is considered to have an energy of between a few electronvolts and a few dozen electronvolts.

3.3
plasmapause
outward boundary of the *plasmasphere* (3.2) located at between two and six Earth radii from the centre of the Earth and formed by geomagnetic field lines where the plasma density drops by a factor of 10 or more across a range of L-shells of as little as 0,1

Note 1 to entry: The L-shell is a parameter describing a particular set of planetary magnetic field lines, often describing the set of magnetic field lines which cross the Earth's magnetic equator at a number of Earth-radii equal to the L-value, e.g. “L = 2” describes the set of the Earth's magnetic field lines which cross the Earth's magnetic equator two Earth radii from the centre of the Earth.

3.4
solar activity
series of processes occurring in the Sun's atmosphere which affect the interplanetary space and the Earth

Note 1 to entry: The level of solar activity is characterized by indices.

3.5
ionospheric storm
storm lasting about a day, documented by depressions and/or enhancements of the ionospheric electron density during various phases of the storm

Note 1 to entry: Ionospheric storms are the ultimate result of solar flares or coronal mass ejections, which produce large variations in the particle and electromagnetic radiation that hit Earth's magnetosphere and *ionosphere* (3.1), as well as large-scale changes in the global neutral wind, composition and temperature.

3.6
sunspot number
R
daily index of sunspot activity defined as $k(10\ g + s)$ where s is the number of individual spots, g is the number of sunspot groups, and k is an observatory factor

Note 1 to entry: R is alternatively called Ri or Rz or SSN.

Note 2 to entry: R12 is 12-month running mean of monthly sunspot number.

Note 3 to entry: In 2014 the calculation scheme for the officially distributed sunspot number was changed[68] with the result that the new sunspot number (SSN2) is about a factor of 1,45 larger than the old one (SSN1).

3.7
F10.7
solar radio flux at 10,7 cm wavelength measured at the ground daily at noon

Note 1 to entry: Besides this 'observed' F10.7 index there is also an 'adjusted' F10.7 index that is adjusted to 1AU. Often used averages are the 81-day (3 solar rotations) running mean and the 12-month running mean.

3.8
Lyman-α index
solar activity (3.4) index based on daily measured solar emission at 121,6 nm (H Lyman-α line)

3.9
MGII index
solar activity (3.4) index based on core-to-wing ratio of the magnesium ion h and k lines at 279,56 nm and 280,27 nm

3.10
Kp index
planetary three-hour index of geomagnetic activity characterizing the disturbance in the Earth's magnetic field over three-hour universal time (UT) intervals[87]

Note 1 to entry: The index scale is uneven quasi-logarithmic and assigned to successive 3 h UT intervals giving eight values per UT day, and ranges in 28 steps from 0 (quiet) to 9 (disturbed).

3.11
ap index
three-hour UT amplitude index of geomagnetic variation equivalent to the *Kp index* (3.10)

Note 1 to entry: It is expressed in 1 nT to 400 nT.

3.12
total electron content
TEC
integral number of electrons in the unitary area column from a lower altitude boundary to an upper boundary

Note 1 to entry: Typically, the integral is taken from the lower boundary of the *ionosphere* (3.1) to the *plasmapause* (3.3)

Note 2 to entry: It is expressed in units of 10^{16} electrons m^{-2} (TECU).

3.13
TECg
TEC-based global index
global ionospheric index based on GNSS-derived TEC-noon measurements at the network of IGS stations

Note 1 to entry: See References [70] and [82] for more information on IGS stations.

3.14
GEC
global electron content
integral of *TEC* (3.12) over the whole globe based on GNSS-derived TEC measurements

3.15
IG
ionosphere global index
ionosphere-effective *sunspot number* (3.6)[56] that is obtained by adjusting the CCIR maps[7] to global ionosonde measurements of the F2 plasma critical frequency foF2

Note 1 to entry: IG12 is 12-month running mean of monthly ionosphere-effective sunspot number.

Note 2 to entry: See Reference [56] for the ionosphere-effective sunspot number and Reference [7] for the CCIR maps.

4 Abbreviated terms

ELF	extremely low frequency (less than 3 kHz)
BeiDou	BeiDou Navigation Satellite System
GALILEO	European Global Satellite Navigation System
GLONASS	Global Orbiting Navigation Satellite System
GNSS	Global Navigation Satellite System (e.g. GPS, GLONASS, GALILEO and others)
GPS	Global Positioning System
HF	high frequency (3 MHz to 30 MHz)
IRI	international reference ionosphere
LF	low frequency (30 kHz to 300 kHz)
MF	medium frequency (300 kHz to 3 MHz)
UHF	ultra high frequency (300 MHz to 3 000 MHz)
VHF	very high frequency (30 MHz to 300 MHz)
VLF	very low frequency (3 kHz to 30 kHz)

5 General considerations

This model for the representation of the ionospheric and plasmaspheric plasma parameters is important to a wide spectrum of applications. Electromagnetic waves travelling through the ionized plasma at the Earth's environment experience retardation and refraction effects. A remote sensing technique relying on signals traversing the ionosphere and plasmasphere therefore needs to account for the ionosphere-plasmasphere influence in its data analysis. Applications can be found in the disciplines of altimetry, radio astronomy, satellite communication, navigation and orbit determination.

Radio signals, transmitted by modern communication and navigation systems, can be heavily disturbed by space weather hazards. Thus, severe temporal and spatial changes of the electron density in the ionosphere and plasmasphere can significantly degrade the signal quality of various radio systems which even can lead to a complete loss of the signal. Model-based products providing specific space weather information, in particular now- and fore-cast of the ionospheric state, serve for improvement of the accuracy and reliability of impacted communication and navigation systems.

For high frequency radio communication, a good knowledge of the heights and plasma frequencies of the reflective layers of the ionosphere and the plasmasphere is critical for continuous and high-quality radio reception. High frequency communication remains of great importance in many remote locations of the globe. The model helps to estimate the effect of charged particles on technical devices in the Earth's environment and defines the ionosphere-plasmasphere operational environment for existing and future systems of radio communication, radio navigation, and other relevant radio technologies in the medium and high frequency ranges.

6 Applicability

There are a multitude of operational usages for ionospheric models, of which the most important are outlined in this clause. Operators of certain navigational satellite systems such as GPS (USA), GLONASS (Russia), BeiDou (China) and GALILEO (Europe)[1)] require ionospheric predictions to mitigate losses of navigation signal phase and/or amplitude lock, as well as to maintain accurate orbit determination for all its satellites. Users of global navigation satellite systems need precise ionospheric models to increase the accuracy and to reduce the precise positioning convergence time[57][58]. Radio and television operators using LF, MF, HF, VHF, UHF satellite or ground stations require ionospheric parameters for efficient communications and for reducing interferences. Space weather forecasters have a great need for accurate ionospheric models to support their customers with reliable and up-to-the-minute space weather information. Ionospheric models are also used in the aeronautical and space system industries and by governmental agencies performing spacecraft design studies. Here the models help to estimate surface charging, sensor interference and satellite anomaly conditions.

Users also apply ionospheric models to mitigate problems with HF communications, HF direction finding, radar clutter and disruption to ELF/VLF communications with underwater vehicles. Insurance companies estimating the cost of protecting human health in space and satellites make use of ionospheric models. Scientists using remote sensing measurement techniques in astronomy, biology, geology, geophysics and seismology require parameter estimates for compensating the effects of the ionosphere on their observations. An ionospheric model can be also used to evaluate tomographic, radio occultation, and other similar techniques, by providing the ground-truth background model for test runs. Amateur radio operators, as well as students and teachers in space research and applications, also use ionosphere parameters. This document may be also applied for ray-path calculations to assess the performance of a particular ground-based or space-borne system. Monthly medians of ionospheric parameters are useful for HF circuit and service planning, while maps for individual days and hours aid frequency management and retrospective studies.

7 Model description

The first version of the IRI model, IRI-1979, and its mathematical build-up is described in References [18], [19] and [20]. The most detailed description of the model and the mathematical formulas and methods used is given in a 155-page report about IRI-1990[2]. The next significant updates of the model were introduced with IRI-1995[5], IRI-2000[3], IRI-2007[53],[54], IRI-2012[71],[72] and IRI-2016[73]. The latest version of the model is available from http://irimodel.org.

IRI-related research efforts and applications of the IRI model are presented and discussed during annual IRI workshops1), with each workshop focusing on a specific modelling topic. Papers from these workshops have been published in dedicated issues of the journal Advances in Space Research2). Reviews of IRI and other ionospheric models can be found in References [4], [51], [52] and [54].

8 Model content and inputs

The IRI model uses a modular approach combining sub-models for the different parameters in different altitude and/or time regimes. Examples of such sub-models are:

— International Telecommunication Union ITU-R (former CCIR) model for the F2 layer critical frequency foF2 (directly related with the F2 peak electron density, in m^{-3}) and for the propagation factor M(3000)F2 (inversely correlated with the peak height, in km)[7]; IRI recommends use of the CCIR model above continental areas and recommends use of the URSI model[55] above ocean areas, because the URSI model produces better results than the CCIR model in these areas; Instead of the CCIR-recommended sunspot number IRI uses the global ionosphere index IG[56] because it gives better results especially at high solar activities;

— COSPAR international reference atmosphere (CIRA) model (NRL-MSISE-00[38]) for the neutral temperature;

— STORM model for storm-time updating of the F2 layer peak density[9];

— International geomagnetic reference field (IGRF) model of the International Association of Geomagnetism and Aeronomy (IAGA) for the magnetic coordinates (https://www.ngdc.noaa.gov/IAGA/vmod/).

The IRI model requires the following indices as input parameters:

— R12, the 12-month running mean of sunspot number R;

— F10.7, the daily index and 81-day and 12-month running mean;

— IG12, the 12-month running mean of global ionosphere index IG;

— ap indices, the 3-hourly planetary magnetic indices for the prior 33 hours.

These indices can either be found automatically from the indices files that are included with the IRI software package and that are updated quarterly, or the user can provide his/her own input values for these indices. For R12 and IG12, the indices file starts from January 1958 and include indices prediction for one to two years into the future. For ap index, the values start from January 1960 and include no predictions.

In addition, model users have the options to use measured peak parameters to update the IRI profile, including the F2, F1, and E layer critical frequencies (or electron densities), the F2 peak height (or M(3000)F2 propagation factor), the E peak height, and the bottomside thickness and shape parameters B0 and B1. In this way, real-time IRI predictions can be obtained if the real-time peak parameters are available.

The total electron content (TEC) is obtained by numerical integration from the model's lower boundary (65 km during daytime and 80 km during night time) to the user-specified upper boundary.

1) Information about past and future workshops can be found on the IRI homepage (http://irimodel.org), which also provides access to the final report from each workshop and to a bibliography of IRI-related papers and issues of Advances in Space Research.

2) A list of IRI issues of Advances in Space Research is available at http://irimodel.org/docs/asr_list.html.

9 Real-time IRI

Various data-assimilation techniques and indices-updating algorithms have been used to bring IRI closer to the observed conditions in either real-time or retrospective mode[74]-[81]. The most advanced system developed by Galkin et al.[79] uses the global database of ionosonde measurements of the Global Ionospheric Radio Observatory (GIRO) to provide real-time inputs of foF2, hmF2, B0 and B1 for IRI.

10 Plasmasphere extension of the IRI model

10.1 General

The models described in 10.2 to 10.5 have been proposed as plasmasphere extension of the IRI model.

10.2 Extrapolation of IRI profiles

With the version of the IRI model available at http://irimodel.org, a user is given the option to increase the upper boundary for TEC computations to up to 20 000 km (GPS satellite altitude). Above 2 000 km a simple extrapolation is used employing the IRI topside function.

10.3 Global core plasma model (GCPM)

GCPM-2000[10] is an empirical description of thermal plasma densities in the plasmasphere, plasmapause, magnetospheric trough and polar cap. GCPM-2000 uses the Kp index and is coupled to IRI in the transition region 500 km to 600 km[3)].

10.4 IMAGE/RPI plasmasphere model

The IMAGE/RPI plasmasphere model[15] is based on more than 700 density profiles along field lines derived from active sounding measurements made by the radio plasma imager (RPI)[21] on the IMAGE satellite between June 2000 and July 2005. The measurements cover all magnetic local times and vary from L = 1,6 to L = 4 spatially. The resulting model depends not only on L-shell but also on magnetic latitude and can be applied to specify the electron densities in the plasmasphere between 2 000 km altitude and the plasmapause (the plasmapause location itself is not included in this model). A comparison of this model with other diffusive equilibrium models was published in Reference [22]. A power profile model as function of magnetic activity was developed from RPI observations for the polar cap region[17].

10.5 IZMIRAN plasmasphere model

The IZMIRAN[4)] plasmasphere model[8],[11],[13] is an empirical model based on whistler and satellite observations. IRI-Plas model presents global vertical analytical profiles of electron density and temperature in the plasmasphere smoothly fitted to the IRI Ne(h) and Te(h) profiles at the altitude of the topside half peak density (400 km to 600 km for electron density and 400 km for electron temperature) and extended towards the plasmapause (up to 36 000 km). For the smooth fitting of the two models, the shape of the IRI topside electron density profile is modified using ISIS-1, ISIS-2 and IK-19[5)] satellite inputs[12]. The plasmasphere model depends on solar activity and magnetic activity. The latest version of IRI-Plas model includes dependence on eight solar and ionospheric proxy indices (SSN, R12, F10.7,

3) A FORTRAN code implementation of GCPM that includes all regions except the polar cap is available at https://plasmasphere.nasa.gov/models/.

4) IZMIRAN: Institute of Terrestrial Magnetism, Ionosphere and Radio Waves Propagation, Russian Academy of Sciences.

5) ISIS: International Satellites for Ionospheric Studies; IK-19: Intercosmos-19 satellite.

Lyman-α index, MGII index, TECg, GEC and IG)[69],[70],[81]-[84][6]. IRI-Plas applies the new global model GMF2 that provides foF2 and hmF2 global maps based on the re-calibrated sunspot numbers SSN[86].

11 Accuracy of the model

The IRI model has been built to represent the monthly average behavior of space plasma. Efforts are underway to also include a quantitative description of the monthly variability in IRI. As variability measure, either the relative standard deviation or upper/lower quartiles and deciles will be used.

The accuracy of the IRI electron density model is typically (given here as standard deviation divided by monthly median in %)[88]:

— 50 % to 80 % at heights from 65 km to 95 km;

— 5 % to 15 % at heights from 100 km to 200 km during daytime;

— 15 % to 30 % at heights from 100 km to 200 km during night time;

— 15 % to 25 % at heights from 200 km to 1 000 km at low and middle dip latitudes (< 60°);

— 50 % to 80 % at heights from 200 km to 1 000 km at high dip latitudes (> 60°).

6) Source code for this IRI-Plas ionosphere-plasmasphere version is available from the IZMIRAN web site https://ftp.izmiran.ru/pub/izmiran/SPIM/ and IRI-Plas online is available at http://www.ionolab.org/.

Annex A
(informative)

Brief introduction to ionosphere and plasmasphere physics

The ionosphere and plasmasphere are conductive, ionized regions of the Earth's atmosphere consisting of free electrons and ions. The ionosphere and plasmasphere are embedded within the Earth's magnetic field and thus are constrained by interactions of the ionized particles with the magnetic field. The ionization levels in this near-Earth space plasma are controlled by solar extreme ultraviolet (EUV) radiation and particle precipitation. The dynamics of the neutral atmosphere plays a significant role in causing movement of the ionized particles by collisions with neutral atoms and molecules from the surrounding thermosphere. The ionosphere extends in altitude from about 65 km to about 1 500 km and exhibits significant variations with local time, altitude, latitude, longitude, solar cycle, season, and geomagnetic activity. At middle and low latitudes, the ionosphere is contained within a region of closed field lines, whereas at high latitudes the geomagnetic field can reconnect with the interplanetary magnetic field and thus open the ionosphere to the driving force of the solar wind.

Plasma flowing upwards from the oxygen-dominated ionosphere is constrained to move along the Earth's magnetic field lines co-rotating with Earth and comprising the hydrogen-dominated plasmasphere extended up to a few Earth radii[25],[26]. The O^+/H^+ transition height where the ion gas consists of an equal percentage of both ions is often taken as the boundary between the ionosphere and plasmasphere. These two regions of the upper atmosphere are strongly coupled through diffusion and resonant charge exchange reactions between O^+ and H^+. At quiet conditions, H^+ in the plasmasphere typically diffuses down to the topside ionosphere at night and undergoes resonant charge exchange reactions with atomic oxygen to produce O^+ (downward flux). The O^+ produced in this way can make a significant contribution to the maintenance of the night-time ionosphere, and works in combination with the meridional component of the neutral wind. The depleted night-time plasmasphere can be refilled during the day through the reverse process; that is, the O^+ ions flow up from the ionosphere, exchange charges with the neutral hydrogen atoms to produce protons, and the protons are then stored in the plasmasphere (upward flux). During geomagnetically disturbed conditions the plasmaspheric plasma can be eroded by the enhanced magnetospheric electric fields, and consequently, the flux becomes upward both during the day and night, due to the reduced plasmaspheric pressure, to refill the empty plasmaspheric flux tubes. While the low-latitude flux tubes refill relatively quickly due to their small volumes, most of the mid-latitude flux tubes are always in a partially depleted state, since the average time between consecutive geomagnetic storms is not long enough for the upflowing ionospheric flux to completely refill the flux tubes.

Terrestrial HF communications rely entirely on reflections from the ionized layers in the upper atmosphere, but the ionosphere acts also as a hindrance because it distorts ground-to-space and spacecraft-to-spacecraft radio links. Although empirical models of the ionosphere are now accessible via electronic networking, most of them are far from reliable in predicting the average ionospheric conditions, not to mention their limitations in forecasting the ionospheric "space weather". In particular, a reliable and standard ionosphere-plasmasphere model is required for calibration of trans-ionospheric signals of the high-altitude GPS and GLONASS satellites at 20 200 km above the Earth. On the other hand, GNSS are also benefiting ionospheric modelling because they provide measurements of TEC between ground receiver and satellite transmitter if the system operates on two or more frequencies. This is the case because TEC can be deduced from the difference in delay at the different frequencies.

Due to the high temporal and spatial variability of the space plasma surrounding the Earth and due to the requirements of its specification for the design and operation of space vehicles, remote sensing, reliable communication and navigation, modelling of the ionosphere and plasmasphere is an important research focus within the worldwide space science communities. Among these efforts the IRI plays an outstanding part and is widely used by space agencies and scientists and engineers worldwide. It is recommended for international use by COSPAR and URSI.

Annex B
(informative)

Physical models

Physical models typically use a numerical iterative scheme to solve the Boltzmann equations for the ionospheric gas including the continuity, energy, and momentum equations[53]. They are solved along field-lines of the Earth magnetic field where the field is represented either by a simple tilted dipole or a multipole model like the IGRF. The equations are either solved self-consistently along a full flux tube or the plasmaspheric flux is provided as a top boundary condition. The effects of the geomagnetic field on the transport of the ionospheric plasma are introduced by the magnetic dip (I) and declination (D) angles from IGRF.

The ionosphere is strongly coupled with the neutral atmosphere, chemically as well as dynamically. In addition to the effects of the neutral wind, the neutral atmosphere significantly affects the ionospheric plasma density distribution through neutral composition and temperature. The neutral composition is a crucial factor not only for the production and loss of the plasma, but also for the diffusion of the ionospheric plasma through the neutral atmosphere. The neutral temperature effect on the ionosphere usually comes from the changes of the neutral densities caused by the neutral temperature change. Below the F-region peak, chemical equilibrium prevails and the plasma density profile is largely controlled by the neutral composition through the production and loss. As altitude increases, plasma diffusion becomes important and well above the F-region peak, the plasma density profile is primarily determined by diffusion. However, the diffusion of the plasma through the neutral atmosphere strongly depends on the neutral densities, mainly the O density in the topside ionosphere, via collisions between the plasma and the neutrals.

A physical model requires several input parameters, including the neutral densities and temperature, neutral wind, and plasma temperatures. For these inputs, empirical models are adopted. In assimilative mode of operation, up to six free model parameters should be adjusted to measurements within physically reasonable ranges, and this cannot be reached straightforward under certain conditions.

Utah State University has been developing the global assimilation of ionospheric measurements (GAIM) models that specify and forecast the state of the ionosphere. There are two models; the Gauss Markov (GAIM-GM) and full physics (GAIM-FP) models[27],[29],[59]-[63]. GAIM-GM uses a physics-based ionosphere model and a Kalman filter as a basis for assimilating a diverse set of measurements. The physics-based model is the ionosphere forecast model (IFM), which is global, covers altitudes from 90 km to 1 400 km, and takes account of five ion species (NO+, O2+, N2+, O+, H+). However, the main output of the model is a 3-D electron density distribution. GAIM-FP uses a physics-based model of the ionosphere-plasmasphere system and an ensemble Kalman filter as a basis for assimilating the measurements. The physics-based model is the ionosphere plasmasphere model (IPM), which is global, covers the ionosphere and plasmasphere from 90 km to 30 000 km, and takes account of six ion species (NO+, O2+, N2+, O+, H+, He+). The primary output of GAIM-FP is a 3-D plasma density distribution. However, the model also provides the self-consistent drivers of the ionosphere-plasmasphere system (e.g. neutral winds and composition and electric fields).

The University of Southern California and the Jet Propulsion Laboratory (USC/JPL) physics model[30],[31],[28] is derived from the Sheffield University Plasmasphere Ionosphere Model, SUPIM[32]. In physical models, such as SUPIM, the time-dependent equations of continuity, momentum (ignoring the time variation and inertial terms in the momentum equation), and energy balance are solved along eccentric-dipole magnetic field lines for the densities, field-aligned fluxes and temperatures of the ions and the electrons. Its application relies on accurate estimates of the solar EUV, **E** x **B** drift, neutral wind, and neutral densities. The ion momentum equation is further broken into a field-parallel and field perpendicular component. The velocity component perpendicular to the magnetic field is considered to be due entirely to **E** x **B** and is an input driver. The parallel component of velocity also has input drivers due to neutral winds and electron and ion temperatures. Thus, in the USC/JPL system the only state variable solved for is the O^+ density; the rest are input drivers to the system.

The coupled thermosphere ionosphere model (CTIM)[33] was developed by coupling a self-consistent thermosphere physical model with the Sheffield University high latitude ionospheric model[64]. As with many of the theoretical models, the global atmosphere is divided into a series of elements in geographic latitude, longitude, and pressure (or altitude). Each grid point rotates with Earth to define a non-inertial frame of reference in an Earth-centred coordinate system. The magnetospheric input is provided by statistical models of auroral precipitation[34] and electric fields[35],[65]. Both inputs are keyed to a hemispheric power index (PI), based on the TIROS/NOAA auroral particle measurements or use solar wind density and magnetic field measurements. A recent upgrade of this model included a self-consistent plasmasphere and low latitude ionosphere models[32] in the coupled thermosphere-ionosphere-plasmasphere model (CTIP)[36]. The effects of $\mathbf{E} \times \mathbf{B}$ drift at lower latitudes are incorporated by the inclusion of a low-latitude physical electric field dynamo model[66]. The new ionosphere-plasmasphere component of CTIP solves the coupled equations of continuity, momentum and energy to calculate the densities, field-aligned velocities and temperatures of the ions O+ and H+ and the electrons, along a total of 800 independent flux-tubes arranged in magnetic longitude and L value (20 longitudes and 40 L values). CTIPe includes a more fully coupling of electrodynamics into the model. It is used at NOAA's Space Weather Prediction Center (SWPC) to study thermosphere-ionosphere phenomena in order to develop nowcasting and forecasting algorithms for space weather (https://www.swpc.noaa.gov/products/ctipe-total-electron-content-forecast).

The field line interhemispheric plasma (FLIP) model[37],[67] is a first-principles, one-dimensional, time-dependent, chemical, and physical model of the ionosphere and plasmasphere. It couples the local ionosphere to the overlying plasmasphere and conjugate ionosphere by solving the ion continuity and momentum, ion and electron energy, and photoelectron equations along entire magnetic flux tubes. The interhemispheric solutions yield densities and fluxes of H^+, O^+, He^+, and N^+ as well as the electron and ion temperatures. The neutral densities, temperature, and wind are supplied by the empirical NRLMSISE-00[38] and HWM[39],[89] models. During quiet times the error in the inputs for the solar EUV flux, MSIS neutral parameters, reaction rates, and cross sections are typically about 20 %. During ionospheric storms uncertainties can be much larger. The set of nonlinear, second-order, partial differential equations for continuity, momentum, and energy is transformed into finite difference equations and solved by a Newton-Raphson iterative scheme. The current FLIP model is primarily a mid-latitude model but it can include convection electric fields, which are important at equatorial and auroral latitudes.

As described in the previous paragraphs driver inputs must be obtained from empirical models including the following: thermospheric densities from the NRLMSISE-00 model[38], neutral winds from the horizontal wind model (HWM)[39],[89], solar EUV[40], electric fields[35],[41]-[43],[65], and electron energy precipitation flux[34]. The interested reader can refer to Reference [30] and references therein. In this 2003 model validation experiment, only vertical drift at the geomagnetic equator was simulated and estimated, while all the other inputs were held at their empirical values. The vertical drift was parameterized by nine coefficients at different local times

The open geospace general circulation model (OpenGGCM) is a global model of the magnetosphere-ionosphere system. It solves the magneto-hydrodynamic (MHD) equations in the outer magnetosphere and couples via field aligned current (FAC), electric potential, and electron precipitation to an ionosphere potential solver and the CTIM[44]. This code coupling enables studies of the global energy budget of the magnetosphere-ionosphere-thermosphere system. The CTIPe model is a non-linear, coupled thermosphere-ionosphere-plasmasphere physically based numerical code that includes a self-consistent electrodynamics scheme for the computation of dynamo electric fields. The model consists of four distinct components which run concurrently and are fully coupled. Included are a global thermosphere, a high-latitude ionosphere, a mid and low-latitude ionosphere/plasmasphere and an electrodynamical calculation of the global dynamo electric field[45].

The thermospheric general circulation model (TGCM) of the National Center for Atmospheric Research (NCAR) was extended to include a self-consistent aeronomic scheme of the thermosphere and ionosphere[46]. The model now calculates total temperature, instead of perturbation temperature about some specified global mean, global distributions of N(2D), N(S) and NO, and a global ionosphere with distributions of O^+, NO^+, O2+, N•+, N^+, electron density, and ion temperature as well as the usual fields of winds, temperature and major composition. Mutual couplings between the thermospheric neutral gas and ionospheric plasma occur at each model time step and at each point of the geographic grid. Steady state results for this first Eulerian model of the ionosphere are presented for solar minimum equinox conditions. The calculated thermosphere and ionosphere global structure agrees reasonably well with the structure of these regions obtained from empirical models. This suggests that the major physical and chemical processes that describe the large-scale structure of the thermosphere and ionosphere have been identified and a self-consistent aeronomic scheme, based on first principles, can be used to calculate thermospheric and ionospheric structure considering only external sources. Global empirical atmospheric models, such as the mass spectrometer/incoherent scatter models (e.g. Reference [38]), were used to specify atmospheric properties for ionospheric model. Equations describing the ionosphere and thermosphere are both solved on the TGCM geographic grid. Ion drift for the ionospheric calculation is obtained from the empirical model[47] for low- and mid-latitudes and the empirical model[48] for high latitudes. Consideration of displaced geomagnetic and geographic poles is included. Results for solar minimum equinox conditions are presented that show good agreement with MSIS-86[38]. The self-consistent model requires only specifications of external sources as solar EUV and UV fluxes, aurora particle precipitation, ionospheric convection pattern, and the amplitudes and phases of semi-diurnal tides from the lower atmosphere.

SAMI2[90] (Sami2 is Another Model of the Ionosphere) treats the dynamic plasma and chemical evolution of the seven most important ionospheric ion species (H^+, He^+, N^+, O^+, N_2^+, NO^+, and O_2^+) in the altitude range ~ 100 km to several thousand kilometers. The ion continuity and momentum equations are solved for all seven species and the temperature equation is solved for H^+, He^+, O^+, and the electrons. SAMI2 models the plasma along the Earth's dipole field from hemisphere to hemisphere, includes the E × B drift of a flux tube (both in altitude and in longitude), and includes ion inertia in the ion momentum equation for motion along the dipole field line. The neutral species are specified using the NRLMSISE-00 model[38] and the Horizontal Wind Model (HWM)[39],[89]. A recent study assimilating ionosonde data into SAMI2 was published by Kim et al.[91]. The NCAR Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM)[92] is a comprehensive, first-principles, three-dimensional, non-linear representation of the coupled thermosphere and ionosphere system that includes a self-consistent solution of the middle and low-latitude dynamo field. The model solves the three-dimensional momentum, energy and continuity equations for neutral and ion species at each time step, using a semi-implicit, fourth-order, centred finite difference scheme on each pressure surface in a staggered vertical grid. TIE-GCM is being improved and further developed by the NCAR group. Consult the model homepage at https://www.hao.ucar.edu/modeling/tgcm/tie.php for recent developments.

The Ground-to-topside model of Atmosphere and Ionosphere for Aeronomy (GAIA)[93] project couples atmospheric, ionospheric and electrodynamics models to successfully produce a numerical model that is capable of handling the entire global atmospheric region, ranging from the troposphere through the ionosphere. The GAIA model has been used to examine geomagnetic activity effects on longterm trends in the thermosphere and ionosphere[94] and has proven its real-time and forecast capabilities[93]. The most recent developments and publications of the GAIA projects can be found at https://gaia-web.nict.go.jp/index_e.html.

Plasmasphere thermosphere model (PTM) is a physical model developed to estimate ion and electron densities, temperatures, and velocities with time-dependent equations of continuity, momentum, and energy along dipole magnetic field lines at altitudes between 90 km and 10 Re[85]. The PTM, thermosphere model, and ion outflow model are made as functions of time, season, longitude, latitude, altitude, solar activity, and geomagnetic activity. These models are solved simultaneously. The input parameters to the models are solar and geomagnetic activities only. The boundary conditions are set at the altitude of 90 km, where the data from the mass spectrometer and incoherent scatter (MSIS) model are used[14]. The electron densities by the PTM show clearly a density gradient change at altitude of ~ 1 500 km in the polar region and plasmapause. The density gradient change at ~ 1 500 km altitude is corresponding to the transition height from O+ to H+. The variations of plasmapause location and plasma density and temperature within the plasmasphere, and the generation of plasma tail during geomagnetic storms and the refilling of plasmasphere are reproduced.

The models of the ionospheric plasma density distribution and TEC depend on a number of upper atmospheric and ionospheric parameters, such as the neutral density, neutral wind, neutral and plasma temperatures, plasmaspheric flux, and ion-neutral collision frequencies. In the numerical modelling of the ionosphere, these parameters are generally often only roughly known and can cause significant uncertainties in the model results[49]. The physical models are also tested for implementation in the ionosphere tomography though a numerical model is often derived to give a close approximation to the full theoretical calculations under all conditions[50]. The physical model can be used to determine the qualitative relationship, but we do not have to rely on the physical model to provide the quantitative dependence for operational use[9]. The physical models can match empirical models in accuracy provided accurate drivers are available, but their true value comes when combined with data in an optimal way (data assimilative scenario).

Physical models were assessed and evaluated in a series of studies[96]-[100] undertaken by NASA's Community Coordinated Modelling Center (CCMC) providing performance scores for these models with regard to specific events and data sources. IRI was the only empirical model included in these assessments and received excellent scores throughout.

Recent compilations of ionospheric and atmospheric models, including statistical and physical models were published by STEP[51], AIAA[52], NOVA[54], and AGU[92].

Bibliography

[1] Bilitza D., *International Reference Ionosphere - A Review.* In: Solar-Terrestrial Predictions - IV, (Hruska J., Shea M.A., Smart D.F., Heckman G., eds.)., **Vol. 3**, 1993, pp. 313–37

[2] Bilitza D. *International Reference Ionosphere 1990*, 155 pages, National Space Science Data Center, NSSDC/WDC-A-R&S 90-22, Greenbelt, Maryland, November 1990. Available at http://irimodel.org

[3] Bilitza D., International Reference Ionosphere 2000. Radio Sci. 2001, **36** (2) pp. 261–275

[4] Bilitza D., *Ionospheric Models for Radio Propagation Studies.* In: Review of Radio Science 1999-2002, 625 - 679. Oxford University Press, Oxford, 2002

[5] Bilitza D., Rawer K. International Reference Ionosphere, pp735-772, in: *The Upper Atmosphere -Data Analysis and Interpretation*, W. Dieminger, G. Hartmann and R. Leitinger (eds.), Springer-Verlag Berlin Heidelberg, 1996

[6] Bilitza D., Rawer K., Bossy L., Gulyaeva T.L., International Reference Ionosphere - past, present, and future: I. Electron density. Adv. Space Res. 1993, **13** (3) pp. 3–13

[7] CCIR Atlas of Ionospheric Characteristics. Comité Consultatif International des Radiocommunications Rept. 340, Geneva, 1990

[8] Chasovitin Yu.K., Gulyaeva T.L., Deminov M.G., Ivanova S.E. Russian Standard Model of Ionosphere (SMI). In *COST251TD(98)005*, RAL, UK, 161-172, 1998

[9] Araujo-Pradere E.A., Fuller-Rowell T.J., Codrescu M.V., STORM: An empirical storm-time ionospheric correction model, 1, Model description. Radio Sci. 2002, **37** (5) p. 1070. DOI:10.1029/2001RS002467

[10] Gallagher D.L., Craven P.D., Comfort R.H., Global Core Plasma Model. J. Geophys. Res. 2000, **105** (A8) pp. 18819–18833

[11] Gulyaeva T.L., Huang X., Reinisch B.W., The ionosphere-plasmasphere model software for ISO. Acta Geod. Geophys. Hung. 2002, **37** (2-3) pp. 143–152

[12] Gulyaeva T.L., Variation in the half width of the topside ionosphere according to the observations by space ionosondes ISIS 1, ISIS 2, and IK 19. Intern. J. Geomagn. and Aeronomy. 2003, **4** (3) pp. 201–207

[13] Gulyaeva T.L., and J.E. Titheridge Advanced specification of electron density and temperature in the IRI ionosphere-plasmasphere model. Adv. Space Res. 2006, **38** (11) pp. 2587–2595. DOI:10.1016/j.asr.2005.08.045

[14] Hedin A.E., Extension of the MSIS Thermospheric Model into the Middle and Lower Atmosphere. J. Geophys. Res. 1991, **96** p. 1159

[15] Ozhogin P., Tu J., Song P., Reinisch B. W. 2012), Field-aligned distribution of the plasmaspheric electron density: An empirical model derived from the IMAGE RPI measurements. *J. Geophys. Res*, 117A06225 doi:10.1029/2011JA017330

[16] Huang X., Reinisch B.W., Bilitza D., IRI in Windows Environment. Adv. Space Res. 2001, **27** (1) pp. 127–131

[17] Nsumei P.A., Huang X., Reinisch B.W., Song P., Vasyliunas V.M., Green J.L. et al., Electron Density Distribution Over the Northern Polar Region Deduced from IMAGE/RPI Sounding. J. Geophys. Res. 2003, **108** p. A2

[18] Rawer K., Bilitza D., Ramakrishnan S., International Reference Ionosphere, International Union of Radio Science. URSI, Brussels, Belgium, 1978

[19] Rawer K., Bilitza D., Ramakrishnan S., Goals and status of the International Reference Ionosphere. Rev. Geophys. 1978, **16** pp. 177–181

[20] Rawer K., Lincoln J.V., Conkright R.O., eds. International Reference Ionosphere – IRI 79. Rept. UAG-82, WDC-A for STP. NOAA, Boulder:1981

[21] Reinisch B.W., Haines D.M., Bibl K., Cheney G., Galkin I.A., Huang X. et al., The Radio Plasma Imager investigation on the IMAGE spacecraft. Space Sci. Rev. 2000, **91** pp. 319–359

[22] Ozhogin P., Song P., Tu J., Reinisch B.W., Evaluating the diffusive equilibrium models: Comparison with the IMAGE RPI field-aligned electron density measurements. J. Geophys. Res. Space Physics. 2014, **119** pp. 4400–4411 doi:10.1002/2014JA019982

[23] Webb P.A., Essex E.A., An ionosphere-plasmasphere global electron density model. Phys. Chem Earth (C). 2000, **25** (4) pp. 301–306

[24] Webb P.A., Essex E.A., A dynamic global model of the plasmasphere. J. Atmos. Sol. Terr. Phys. 2004, **66** (12) pp. 1057–1073. DOI:10.1016/j.jastp.2004.04.001

[25] Carpenter D.L., Park C.G., On what ionospheric workers should know about the plasmapause – plasmasphere. Rev. Geophys. Space Phys. 1973, **11** pp. 133–154

[26] Kotova G.A., The Earth's Plasmasphere: current state of research. Geomagn. Aeron. 2007, **47** (4) pp. 1–16

[27] Scherliess L., Schunk R.W., Sojka J.J., Thompson D.C. Development of a physics-based reduced state Kalman filter for the ionosphere. *Radio Sci.* 2004, 39RS1S04. DOI:10.1029/2002RS002797

[28] Wang C., Hajj G., Pi X., Rosen I.G., Wilson B., Development of the Global Assimilative Ionospheric Model. Radio Sci. 2004, **39**. DOI:10.1029/2002RS002854

[29] Schunk R.W. et al. Global assimilation of ionospheric measurements (GAIM). *Radio Sci.* 2004, 39RS1S02. DOI:10.1029/2002RS002794

[30] Pi X., Wang C., Hajj G.A., Rosen G., Wilson B.D., Bailey G.J., Estimation of ExB drift using a global assimilative ionospheric model: An observation system simulation experiment. J. Geophys. Res. 2003, **108** (A2) p. 1075. DOI:10.1029/2001JA009235

[31] Hajj G.A., Wilson B.D., Wang C., Pi X., Rosen I.G. Data assimilation of ground GPS total electron content into a physics-based ionospheric model by use of the Kalman filter. *Radio Sci.* 2004, 39RS1S05. DOI:10.1029/2002RS002859

[32] Bailey G.J., Balan N., Su Y.Z., The Sheffield University plasmasphere ionosphere model—A review. J. Atmos. Sol. Terr. Phys. 1997, **59** pp. 1541–1552

[33] Fuller-Rowell T.J., Rees D., Quegan S., Moffett R.J., Codrescu M.V., Millward G.H., In: STEP Handbook of Ionospheric Models. (Schunk R.W., ed.). Utah State Univ, 1996

[34] Fuller-Rowell T.J., Evans D.S., Height-integrated Pedersen and Hall conductivity patterns inferred from the TIROS-NOAA satellite data. J. Geophys. Res. 1987, **92** pp. 7606–7618

[35] Foster J.C., Holt J.M., Musgrove R.G., Evans D.S., Geophys. Res. Lett. 1986, **13** pp. 656–659

[36] Millward G.H., Moffett R.J., Quegan S., Fuller-Rowell T.J., *A Coupled Thermosphere Ionosphere-Plasmasphere Model, CTIP.* In: STEP Handbook of Ionospheric Models, (Schunk R.W., ed.). Utah State University, 1996

[37] Richards P.G., *The Field Line Interhemispheric Plasma Model.* In: Solar-Terrestrial Energy Program: Handbook of Ionospheric Models, (Schunk R.W., ed.). 1996, pp. 207.

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

[39] Hedin A.E. et al., Empirical wind model for the upper, middle and lower atmosphere. J. Atmos. Terr. Phys. 1996, **58** pp. 1421–1447

[40] Tobiska W.K., Revised solar extreme ultraviolet flux model. J. Atmos. Terr. Phys. 1991, **53** pp. 1005–1018

[41] Fejer B.G., Low latitude electrodynamic plasma drifts: A review. J. Atmos. Terr. Phys. 1991, **53** pp. 677–693

[42] Heppner J.P., Maynard N.C., Empirical high-latitude electric field models. J. Geophys. Res. 1987, **92** pp. 4467–4489

[43] Scherliess L., Fejer B.G., Radar and satellite global equatorial F region vertical drift model. J. Geophys. Res. 1999, **104** pp. 6829–6842

[44] Raeder J., Larson D., Li W., Kepko E.L., Fuller-Rowell T., Open GGCM Simulations for the THEMIS Mission. Space Sci. Rev. 2008, **141** (1-4) pp. 535–555

[45] Fedrizzi M., Fuller-Rowell T.J., Codrescu M.V. Global Joule heating index derived from thermospheric density physics-based modeling and observations. *Space Weather*. 2012, 10S03001. DOI:10.1029/2011SW000724

[46] Roble R.G., Ridley E.C., Richmond A.D., A Coupled Thermosphere/Ionosphere general circulation model. Geophys. Res. Lett. 1988, **15** (12) pp. 1325–1328

[47] Richmond A.D., Blanc M., Emery B.A., Wand L.H., Fejer B.G., Woodman R.F. et al., An Empirical Model of Quiet-Day Ionospheric Electric Fields at Middle and Low Latitudes. J. Geophys. Res. 1980, **85** (A9) pp. 4658–4664. DOI:10.1029/JA085iA09p04658

[48] Heelis R.A., Lowell J.K., Spiro R.W., A Model of the High-Latitude Ionospheric Convection Pattern. J. Geophys. Res. 1982, **87** (A8) pp. 6339–6345. DOI:10.1029/JA087iA08p06339

[49] Jee G., Schunk R.W., Scherliess L., On the sensitivity of total electron content (TEC) to upper atmospheric / ionospheric parameters. J. Atmos. Terr. Phys. 2005, **67** (11) pp. 1040–1052

[50] Bust G.S., Mitchell C.N. History, current state, and future directions of ionospheric imaging. *Rev. Geophys.* 2008, 46RG1003. DOI:10.1029/2006RG000212

[51] Shunk R.W., ed. Solar-Terrestrial Energy Program, STEP Handbook of Ionospheric Models. Utah State University, 1996

[52] AIAA, Guide to Reference and Standard Ionosphere Models, ANSI/AIAA G-034-1998. American Institute of Aeronautics and Astronautics, Reston, Virginia, 1998

[53] Bilitza D., Reinisch B.W., International Reference Ionosphere 2007: Improvements and new parameters. Adv. Space Res. 2008, **42** (4) pp. 599–609. DOI:10.1016/j.asr.2007.07.048

[54] Gulyaeva T., Bilitza D., *Towards an ISO Standard Earth Ionosphere and Plasmasphere Model.* In: New Developments in the Standard Model, (Larsen R.J., ed.). NOVA, Hauppauge, New York, 2012, pp. 1–39. Available at https://ftp.izmiran.ru/pub/izmiran/SPIM/NOVA2012GulyaevaBilitza.pdf

[55] Rush C., Fox M., Bilitza D., Davies K., McNamara L., Stewart F., and M. PoKempner. Ionospheric Mapping – An Update of foF2 Coefficients. Telecommunication Journal. 1989, **56** pp. 179–182

[56] Liu R.Y., Smith P.A., King J.W., A New Solar Index Which Leads to Improved foF2 Predictions Using the CCIR Atlas. Telecommunication Journal. 1983, **50** (8) pp. 408–414

[57] Allain D.J., Mitchell C.N., Ionospheric delay corrections for single-frequency GPS receivers over Europe using tomographic mapping. GPS Solut. 2008. DOI:10.1007/s10291-008-0107-y

[58] Juan J.M., Hernández-Pajares M., Sanz J., Ramos-Bosch P., Aragón-Àngel A., Orús R. et al. Enhanced Precise Point Positioning for GNSS Users. *IEEE Trans. Geosci. Rem. Sens.* 2012. DOI:10.1109/TGRS.2012.2189888

[59] Schunk R.W., Scherliess L., Sojka J.J., Thompson D.C., USU global ionospheric data assimilation models. Proc. SPIE. 2004, **5548** pp. 327–336. DOI:10.1117/12.562448

[60] Schunk R.W., Scherliess L., Sojka J.J., Thompson D.C., Zhu L., An operational data assimilation model of the global ionosphere, Proceedings of the 2005 Ionospheric Effects Symposium, pp. 512-518, (ed. J. M. Goodman), JMG Associates Ltd., 2005

[61] Schunk R.W., Scherliess L., Sojka J.J., Thompson D.C., Zhu L. Ionospheric weather forecasting on the horizon. *Space Weather*. 2005, 3S08007. DOI:10.1029/2004SW000138

[62] Scherliess L., Schunk R.W., Sojka J.J., Thompson D.C., Zhu L. The USU GAIM Gauss-Markov Kalman Filter Model of the Ionosphere: Model Description and Validation. *J. Geophys. Res.* 2006, 111A11315. DOI:10.1029/2006JA011712

[63] Scherliess L., Thompson D.C., Schunk R.W., Data assimilation models: A 'new' tool for ionospheric science and applications, The Dynamic Magnetosphere. IAGA Special Sopron Book Series. 2011, **2** pp. 329–339. DOI:10.1007/978-94-007-0501-2_18

[64] Quegan S., Bailey G.J., Moffett R.J., Heelis R.A., Fuller-Rowell T.J., Rees D. et al., A theoretical study of the distribution of ionization in the high-latitude ionosphere and plasmasphere: first results on the mid-latitude trough and the light ion trough. J. Atmos. Terr. Phys. 1982, **44** p. 619

[65] Weimer D.R. Improved ionospheric electrodynamics models and application to calculating Joule heating rates. *J. Geophys. Res.* 2005, 110A05306. DOI:10.1029/2004JA010884

[66] Richmond A.D., Roble R.G., Electrodynamic effects of thermospheric winds from the NCAR thermospheric general circulation model. J. Geophys. Res. 1987, **92** pp. 12365–12376

[67] Richards P.G., Buonsanto M.J., Reinisch B.W., Holt J., Fennelly J.A., Scali J.L. et al., On the relative importance of convection and temperature on the behavior of the ionosphere in North America during January, 6-12, 1997. J. Geophys. Res. 2000, **105** pp. 12763–12776

[68] Clette F., Svalgaard L., Vaquero J.M., Cliver E.W., Revisiting the sunspot number: a 400-year perspective on the solar cycle. Space Sci. Rev. 2014, **186** pp. 35–103

[69] Gulyaeva T.L., Modification of the solar activity indices in the International Reference Ionosphere IRI and IRI-Plas models due to recent revision of sunspot number time series. Solar-Terr. Phys. 2016, **2** pp. 87–98. DOI:10.12737/20872

[70] Gulyaeva T.L., Arikan F., Sezen U., Poustovalova L.V., Eight proxy indices of solar activity for the International Reference Ionosphere and Plasmasphere model. J. Atmos. Sol. Terr. Phys. 2018. DOI:10.1016/j.jastp.2018.03.025

[71] Bilitza D., Altadill D., Zhang Y., Mertens C., Truhlik V., Richards P. et al., The International Reference Ionosphere 2012 – a model of international collaboration. J. Space Weather Space Climate. 2014, **4** (A07) pp. 1–12. DOI:10.1051/swsc/2014004

[72] Bilitza D., The International Reference Ionosphere – Status 2013. Adv. Space Res. 2015, **55** (8) pp. 1914–1927. DOI:10.1016/j.asr.2014.07.032

[73] Bilitza D., Altadill D., Truhlik V., Shubin V., Galkin I., Reinisch B. et al., International Reference Ionosphere 2016: From ionospheric climate to real-time weather predictions. Space Weather. 2017, **15** pp. 418–429. DOI:10.1002/2016SW001593

[74] Bilitza D., Bhardwaj S., Koblinsky C., Improved IRI predictions for the GEOSAT time period. Adv. Space Res. 1997, **20** (9) pp. 1755–1760. DOI:10.1016/S0273-1177(97)00585-1

[75] Komjathy A., Langley R., Bilitza D., Ingesting GPS-derived TEC data into the International Reference Ionosphere for single frequency radar altimeter ionospheric delay corrections. Adv. Space Res. 1998, **22** (6) pp. 793–802. DOI:10.1016/S0273-1177(98)00100-8

[76] Hernandez-Pajares M., Juan J., Sanz J., Bilitza D., Combining GPS measurements and IRI model values for Space Weather specification, Adv. Space Res., 29(6), 949–958, DOI:10.1016/S0273-1177(02)00051-0,2002

[77] Pezzopane M., Pietrella M., Pignatelli A., Zolesi B., Cander L.R. Assimilation of autoscaled data and regional and local ionospheric models as input sources for real-time 3-D International Reference Ionosphere modeling. *Radio Sci.* 2011, 46RS5009. DOI:10.1029/2011RS004697

[78] Yue X. et al. Global 3-D ionospheric electron density reanalysis based on multi-source data assimilation. *J. Geophys. Res.* 2012, 117A09325. DOI:10.1029/2012JA017968

[79] Galkin I.A., Reinisch B.W., Huang X., Bilitza D. Assimilation of GIRO data into a real-time IRI. *Radio Sci.* 2012, 47RS0L07. DOI:10.1029/2011RS004952

[80] Ssessanga N., Kim Y.H., Kim E., Kim J., Regional optimization of the IRI-2012 output (TEC, foF2) by using derived GPS-TEC. J. Korean Phys. Soc. 2015, **66** (10) pp. 1599–1610. DOI:10.3938/jkps.66.1599

[81] Gulyaeva T.L., Arikan F., Hernandez-Pajares M., Stanislawska I., GIM-TEC adaptive ionospheric weather assessment and forecast system. J. Atmosph. Solar-Terr. Phys. 2013, **102** pp. 329–340. DOI:10.1016/j.jastp.2013.06.011

[82] Gulyaeva T., Arikan F., Poustovalova L., Sezen U., TEC Proxy Index of Solar Activity for the International Reference Ionosphere IRI and its Extension to Plasmasphere IRI-Plas Model. Int. J. Sci. Eng. Applied Sci., 2017, **3**, 5, 144-150. Available at https://ijseas.com/volume3/v3i5ijseas20170519.pdf/

[83] Sezen U., Gulyaeva T., Arikan F. Online Computation of International Reference Ionosphere Extended to Plasmasphere (IRI-Plas) Model for Space Weather. *Geodesy and Geodynamics*. 2018, **9** (5) pp. 347–357. Available at https://doi.org/10.1016/j.geog.2018.06.004

[84] Sezen U., Gulyaeva T., Arikan F., Performance of solar proxy options of IRI-Plas model for equinox seasons. J. Geophys.Res. Space Phys. 2018, **123** (2) pp. 1441–1456. DOI:10.1002/2017JA024994

[85] Seki K., Miyoshi Y., Ebihara Y. et al., Theory, modeling, and integrated studies in the Arase (ERG) project. Earth Planets Space. 2018, **70** p. 17. DOI:10.1186/s40623-018-0785-9

[86] Shubin V.N., Gulyaeva T.L., Solar forcing on the ionosphere: Global model of the F2 layer peak parameters driven by re-calibrated sunspot numbers. Acta Astronaut. 2021, **179** pp. 197–208. Available at https://doi.org/10.1016/j.actaastro.2020.10.029

[87] MATZKA J., STOLLE C. YMAZAKI Y., BRONKALLA O., MORSCHHAUSER A. The geomagnetic Kp index and derived indices of geomagnetic activity. Space Weather. 2021. Available at https://doi.org/10.1029/2020sw002641

[88] ARIKAN F., SEZEN U., GULYAEVA T. Comparison of IRI-2016 F2 layer model parameters with ionosonde measurements, J. Geophys. Res. - Space Physics,2019, 124 pp., 8092-8109., 2019. Available at https://doi.org/10.1029/2019JA027048, 2019

[89] DROB, D. P., EMMERT, J. T., MERIWETHER, J. W., MAKELA, J. J., DOORNBOS, E., CONDE, M., et al. An update to the Horizontal Wind Model (HWM): The quiet time thermosphere. Earth and Space Science, 2015, 2 pp. 301–319. Available at https://doi.org/10.1002/2014EA000089

[90] HUBA, J. D., JOYCE, G., & FEDDER, J. A., Sami2 is Another Model of the Ionosphere (SAMI2): A new low-latitude ionosphere model. Journal of Geophysical Research, 2000, **105**(A10) pp. 23,035–23,053. Available at https://doi.org/10.1029/2000JA000035

[91] KIM, J. H., KIM, Y. H., SSESSANGA, N., JEONG, S. H., MOON, S. I., KWAK, Y. S., & YUN, J. Y., Regional ionosphere specification by assimilating ionosonde data into the SAMI2 model. Advances in Space Research, 2019, **64**(7) pp. 1343– 1357. Available at https://doi.org/10.1016/j.asr.2019.06.036

[92] HUBA J., R. SCHUNK, AND G. KHAZANOV (eds.), Modeling the Ionosphere-Thermosphere System, American Geophysical Union Geophysical Monograph Series, 2014, DOI: 10.1002/9781118704417

[93] QIAN, L., A. G. BURNS, B. A. EMERY, B. FOSTER, G. LU, A. MAUTE, A. D. RICHMOND, R. G. ROBLE, S. C. SOLOMON, AND W. WANG, The NCAR TIE-GCM: A community model of the coupled thermosphere/ionosphere system, in: Modeling the Ionosphere-Thermosphere System, AGU Geophysical Monograph Series, 2014

[94] TAO, C., H. JIN, Y. MIYOSHI, H. SHINAGAWA, H. FUJIWARA, M. NISHIOKA, AND M. ISHIIM, Numerical forecast of the upper atmosphere and ionosphere using GAIA, Earth Planets Space, 2020, **72**:178. Available at https://doi.org/10.1186/s40623-020-01307-x

[95] LIU, H., C. TAO, H. JIN, AND T. ABE, Examining geomagnetic activity effects on CO2-driven trend in the thermosphere and ionosphere using ideal model experiments with GAIA, J. Geophys. Res.: Space Phys., 2021, **126**, 1. Available at https://doi.org/10.1029/2020JA028607

[96] SHIM, J. S., M. KUZNETSOVA, L. RASTÄTTER, M. HESSE, D. BILITZA, M. CODRESCU, B. EMERY, B. FOSTER, T. FULLERROWELL, J. HUBA, A. J. MANNUCCI, A. RIDLEY, L. SCHERLIESS, R. W. SCHUNK, P. STEPHENS, D. C. THOMPSON, L. ZHU, D. ANDERSON, J. L. CHAU, J. J. SOJKA, and B. RIDEOUT, CEDAR Electrodynamics Thermosphere Ionosphere 1 (ETI) Challenge for Systematic Assessment of Ionosphere/ Thermosphere Models 1: NmF2, hmF2, and Vertical Drift Using Ground Based Observations, Space Weather, 2011, **9**, S12003, DOI:10.1029/2011SW000727

[97] SHIM J. S. M. KUZNETSOVA, L. RASTÄTTER, M. HESSE, D. BILITZA, M. BUTALA, M. CODRESCU, B. A. EMERY, B. FOSTER, T. J. FULLER-ROWELL, J. HUBA, A. J. MANNUCCI, X. PI, A. RIDLEY, L. SCHERLIESS, R. W. SCHUNK, J. J. SOJKA, P. STEPHENS, D. C. THOMPSON, D. WEIMER, L. ZHU and E. SUTTON, CEDAR Electrodynamics Thermosphere Ionosphere (ETI) Challenge for systematic assessment of ionosphere/thermosphere models: Electron density, neutral density, NmF2, and hmF2 using space based observations, *Space Weather*, 2012, **10**, S10004, doi:10.1029/2012SW000851, 2012

[98] SHIM, *J. S., KUZNETSOVA, M., RASTÄTTER, L., BILITZA, D., BUTALA, M., CODRESCU, M., EMERY, B. A., FOSTER, B., FULLER-ROWELL, T. J., HUBA, J., MANNUCCI, A. J., PI, X., RIDLEY, A., SCHERLIESS, L., SCHUNK, R. W., SOJKA, J. J., STEPHENS, P., THOMPSON, D. C., WEIMER, D., ZHU, L., ANDERSON, D., CHAU, J. L. and SUTTON, E., Systematic Evaluation of Ionosphere/Thermosphere (IT) Models*, in: Modeling the Ionosphere-Thermosphere System (eds HUBA J., SCHUNK R., KHAZANOV G., John Wiley & Sons, Ltd, Chichester, UK. DOI: 10.1002/9781118704417.ch13, 14 March 2014

[99] SHIM, J. S., L. RASTÄTTER, M. KUZNETSOVA, D. BILITZA, M. CODRESCU, A. J. COSTER, B. A. EMERY, M. FEDRIZZI, M. FÖRSTER, T. J. FULLER-ROWELL, L. C. GARDNER, L. GONCHARENKO, J. HUBA, S. E. MCDONALD, A. J. MANNUCCI, A. A. NAMGALADZE, X. PI, B. E. PROKHOROV, A. J. RIDLEY, L. SCHERLIESS, R. W. SCHUNK, J. J. SOJKA L. ZHU. CEDAR-GEM challenge for systematic assessment of Ionosphere/thermosphere models in predicting TEC during the 2006 December storm event. Space Weather, 2017, **15** pp. 1238–1256. Available at https://doi.org/10.1002/2017SW001649

[100] SHIM, J. S., TSAGOURI, I., GONCHARENKO, L., RASTAETTER, L., KUZNETSOVA, M., BILITZA, D., M. CODRESCU A. J. COSTER S. C. SOLOMON M. FEDRIZZI M. FÖRSTER T. J. FULLER-ROWELL L. C. GARDNER J. HUBA A. A. NAMGALADZE B. E. PROKHOROV A. J. RIDLEY L. SCHERLIESS R. W. SCHUNK J. J. SOJKA L. ZHu. Validation of ionospheric specifications during geomagnetic storms:

TEC and foF2 during the 2013 March storm event. Space Weather, 2018, **16** pp. 1686–1701. Available at https://doi.org/10.1029/2018SW002034

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