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Guide

Guide to Reference and Standard Ionosphere Models

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Guide to Reference and Standard Ionosphere Models

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Abstract

This guide assists in the selection of ionospheric models for engineering design or scientific research. It describes the content of the models, uncertainties and limitations, technical basis, databases from which the models are formed, publication references, and sources of computer codes for 46 ionospheric models. The models cover the altitude range from the Earth's surface to approximately 10,000 kilometers. This guide is intended to assist communication and space system designers and developers, geophysicists, space physicists, and climatologists in understanding available models, comparing sources of data, and interpreting engineering and scientific results based on different ionospheric models.

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Foreword

This *Guide to Reference and Standard Ionosphere Models* is sponsored by the American Institute of Aeronautics and Astronautics (AIAA) as part of its Standards Program.

The proliferation of ionospheric models and the lack of documentation have hindered general knowledge of their availability as well as their relative strengths, weaknesses, and limitations. The intent of this guide is to compile, in one reference, practical information about known and available ionospheric models—those that describe the physical properties and practical effects of the ionosphere as a function of altitude, latitude, and other key parameters. At this writing, the included models are those intended for general purpose, scientific, or aerospace applications and therefore extend to heights ranging from 50 to 10,000 km. Dynamical models of the ionosphere are included in this guide, as the dynamics are essential to many applications.

The guide summarizes the principal features of the models:

- Model content
- Model uncertainties and limitations
- Basis of the model
- Database or model input parameters
- Publication references
- Dates of development, authors, and sponsors
- Model codes and sources.

The models are grouped according to whether they describe primarily global, regional, or special properties.

There is limited information on standard deviations from the mean values or frequencies of occurrence of some of the variables described by these models. This limits quantitative assessments of uncertainties. Correlation distances for electron densities, and statistics on scintillation are well defined. These and other statistics are discussed in the body of the guide. Candidates for inclusion in this guide have been solicited by means of advertisements in publications including announcements at national and international meetings of URSI, IAGA, AGU, COSPAR, AIAA, and scientific community newsletters. This collection of models is not exhaustive. It is hoped that future editions will include additional models from the international community.

We are indebted to those authors who submitted their models for inclusion, to those who offered valuable advice, to Jared Fulgham for notable assistance, and to the editors/reviewers: W. Kent Tobiska (Editor), Robert W. Schunk, Herbert C. Carlson, and Ludger Scherliess.

The first revision was prepared and approved in 1998. The second revision was initiated in 2010 and approved in March 2014 by the AIAA Atmospheric and Space Environments Committee on Standards (ASE CoS). At the time this document was balloted, the AIAA Atmospheric and Space Environments CoS included the following members:

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NOTE The cooperation of all those who provided input, both for the updates and new entries, is sincerely appreciated. Without their contributions, this significant revision of the *AIAA Guide to Reference and Standard Ionosphere Models* would not have been possible.

The ASE CoS acknowledges the following individuals who contributed to this guide: William H. Bauman, Craig D. Fry, Mike Newchurch, Fred Proctor, Andrew Shapiro, and John Wise.

This 2014 revision of *Guide to Reference and Standard Ionosphere Models* contains updated information on several models relative to information on references, sources, and so forth. In addition, a few of the models in the previous edition that are now obsolete have been replaced with updated versions. The model for which updated information is provided is the NCAR Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM).

Some new models that have been added include the following:

1. The Assimilative Mapping of Ionospheric Electrodynamics (AMIE)
2. Global Assimilation of Ionospheric Measurements–Full Physics (GAIM-FP)
3. Global Assimilation of Ionospheric Measurements–Gauss-Markov (GAIM-GM)
4. JPL/USC GAIM: The Jet Propulsion Laboratory/University of Southern California Global Assimilative Ionospheric Model
5. Ionosphere Forecast Model (IFM)
6. Ionosphere-Plasmasphere Model (IPM)

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7. Ionosphere-Polar Wind Model (IPWM)
8. Ionosphere-Polar Wind-PIC (IPW-PIC)
9. Thermosphere-Ionosphere Forecast Model (TIFM)
10. NRL SAMI2/SAMI3 Models
11. Texas Reconfigurable Ionosphere-Plasmasphere-Logarithmic Data Assimilator (TIPL-DA)
12. Weimer Electric Potential, Current, and Joule Heating Models
13. Incoherent Scatter Radar Ionospheric Models (ISRIMs)
14. Probabilistic Topside Ionosphere Model
15. PBMOD Time-Dependent Model of the Global Low-Latitude Ionosphere and Radio Scintillation

NOTE Every attempt has been made to obtain information from modelers in the community. However, ASETC CoS is aware that new models may have recently been developed and older models exist but may not have been incorporated into this document. We appreciate any information that could lead to reporting of models that are not included here.

The AIAA Atmospheric and Space Environments Committee on Standards (W. Kent Tobiska, Chairperson) approved this document for publication in March 2014.

The AIAA Standards Executive Council (Laura McGill, Chairperson) accepted this document for publication in April 2014.

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1 Scope

This guide describes the content of the models, uncertainties and limitations, technical basis, databases from which the models are formed, publication references, and sources of computer codes for 46 ionospheric models (see Table 1). The models cover the altitude range from the Earth's surface to approximately 10,000 km. It is intended to assist communication and space system designers and developers, geophysicists, space physicists, and climatologists in understanding available models and comparing sources of data, and interpreting engineering and scientific results based on different ionospheric models.

Table 1 — Summary of reference and standard ionospheres

Model (Page No.)	Geographic Region	Altitude Range (km)	Parameters	Species Included	Temporal Variation	Output Data Pre-sentation	Principal Application
USU (5)	global	90–1000	N_e, N_i, T_e, $T_{i\|\|}$, $T_{i\perp}$, u_e, u_i	NO^+, O_2^+, N_2^+, N^+, O^+, H^+	10–100 sec	3D grid	scientific studies
NCAR/ TIE-GCM (7)	global	97–500	T_n, T_i, T_e, neutrals U, V, W	CO_2, O, O_2, $N(^4S)$, $N(^2D)$, O^+, O_2^+, NO^+, $N_e(cm^{-3})$	120 sec	tables, plots	scientific studies
CTIM (10)	global	80–10,000	N_e, N_i neutrals U, V, W T_n, T_e, T_i	O^+, H^+, NO^+, $O_2N_2^+$, N^+, O, O_2^+, N_2, NO, $N(^2D)$, $N(^4S)$	1–6 min	tables, plots	scientific studies
CTIP (12)	global	80–10,000	N_e, N_i neutrals U, V, W T_n, T_e, T_i, T_e	O^+, H^+, NO^+, O_2^+, N_2^+, N^+, O, O_2, N_2, NO, N(2D), N(4S)	1–15 min	tables, plots	scientific studies
GTIM (13)	global	90–22,000	N_e, N_i	NO^+, O_2^+, O^+, H^+, He^+	diurnal with resolution of 15 min	tables, plots	theoretical climatology and development of parametric models such as PIM
PIM (15)	global	90–22,000	N_e, TEC, f_0F_2, h_mF_2, f_0E, h_mE	O^+, NO^+, O_2	diurnal with resolution of 30 min	tables	theoretical climatology, systems design
IRI (17)	global	N_e: 50–2000 T: 120–3000 N_i: 100–2000	N_e, T_e, T_i, N_i	O^-, H^+, He^-, NO, O_2^-, N_2^- cluster	diurnal (LT, UT, solar zenith angle), seasonal solar cycle	tables, interactive on WWW	spacecraft instrument design, satellite tracking, radio wave propagation, altimeter data analysis ray-tracing, education, etc.
EMI (20)	global coverage (lat)	50–4000	H^+, He^+, N_2^+, NO^+	N^+, O^+, O_2^+, N_e	diurnal seasonal solar activity	figures, tables	scientific studies
SUPIM (22)	global	90–22,000	N_e, N_i, T_e, T_i	O^+, O_2^+, NO^+, H^+, He^+	diurnal with resolution of 15 min	tables	theoretical studies and climatology
FLIP (25)	mid-lat	90–22,000	N_e, N_i, T_e, T_i	H^+, He^+, O^+, N^+, NO^+, O_2^+, $^+(^2D)$, $O^+(^2P)$, $N(^2D)$, $N(S^4)$, NO, $O(^1D)$, N_2(vib)	diurnal 1–30 min resolution	tables, plots	mid-latitude ionosphere-plasmasphere single ground comparison

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Table 1 — Summary of reference and standard ionospheres (*cont.*)

Model (Page No.)	Geographic Region	Altitude Range (km)	Parameters	Species Included	Temporal Variation	Output Data Pre-sentation	Principal Application
GAIM-FP (28)	global	90–30,000	N_mE, h_mE, N_mF_2, h_mF_2, N_i, E_i, U_n, O/N_2, TEC	NO^+, O_2^+, N_2^+, O^+, H^+, He^+	1-15 min	3D grid	scientific studies
GAIM-GM (30)	global	90–1400	N_mE, h_mE, N_mF_2, h_mF_2, N_e, TEC	NO^+, O_2^+, N_2^+, O^+, H^+	15 min	3D grid	scientific studies
JPL/USC GAIM (33)	global	40–80	H_mF_2, N_mF_2	O^+, H^+, He^+	5–12 min	3D grid	scientific studies
IFM (35)	global	90–1500	N_mE, h_mE, N_mF_2, h_mF_2, N_i	NO^+, O_2^+, N_2^+, O^+, H^+	1 min	3D grid	scientific studies
IPM (37)	global	90–30,000	N_mE, h_mE, N_mF_2, h_mF_2, N_i, TEC	NO^+, O_2^+, N_2^+, O^+, He^+, H^+	1 min	3D grid	scientific studies
IPWM (39)	global	90–9000	T_e, T_i, N_i	NO^+, O_2^+, N_2^+, O^+, H^+	1 min	3D grid	scientific studies
IPW-PIC (41)	global	90–1200	N_i, T_e, T_i	NO^+, O_2^+, N_2^+, O^+, H^+	1 min	3D grid	scientific studies
TIFM (43)	global	90–500	N_n, U_n, T_n	N_2, O_2, O	1 min	3D grid	scientific studies
SAMI2/ SAMI3 (45)	global/ mid-lat	85-20,000	N_e, N_i, TEC, U_i, T_e, T_i	H^+, He^+, N^+, O^+, N_2^+, NO^+, O_2^+	30 sec–15 min	3D plotting	scientific studies
TRIPL-DA (46)	global	user specified, 100–22,000	N_e at every grid point	ions only	user specified, > input data stream	3D mapping	scientific studies
IDA4D (48)	global	100–20,000 user selectable; often only E- and F-regions used	N_e		~5 min	graphical or data files of 3D distribution	scientific studies, radio propagation applications, concept of operations tool for mission planning applications
ISRIMs (51)	≈35–55° sub-auroral	100–500	N_e, T_e, T_i		1–3 hr	tables, plots	scientific studies
PTIM (54)	global, single altitude of 800 km +/– 1 scale height	830–860	mode, median, and mean densities, probability of reaching a given density	electrons only	climate model only	probability of observing a given electron density level	Estimating both typical and extreme electron density values at a common LEO orbit
Algebraic (56)	global	60–90		21 positive ions 8 negative ions	diurnal	tables, plots	scientific studies
Numerical Chem. (58)	global	60–90		36 positive ions 19 negative ions	diurnal	tables, plots	scientific studies

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Table 1 — Summary of reference and standard ionospheres (*cont.*)

Model (Page No.)	Geographic Region	Altitude Range (km)	Parameters	Species Included	Temporal Variation	Output Data Pre-sentation	Principal Application
Solar EUV and Chemistry (62)	global	90–120	N_i^+, N_i^-, N_e neutrals	5 negative ions 4 positive ions	steady state	global	90–120
AFRL B-F-P (65)	mid-lat	100–250	N_e, N_i, T_e	O^+, N_2^+, O_2^+, O, N_2, O_2	steady state	tables, plots	mid-latitude daytime E- and F1-regions of ionosphere
Electron-Proton Aurora (67)	high lat >60°	90–600	N_e, N_i, N_2^+ (3914Å) N_2 (3371Å) LBH (1325, 1354, 1383, 1493Å) OI (1356 Å) Lα (1216Å) Hβ (4861Å) Hα (6563Å)	H^+, H, O, N_2, O_2	steady state	tables, plots	auroral ionosphere: ionization of emission yields
Two-cell convection (70)	high lat	150–2000	electrostatic potential	N/A	directly IMF input driven	tables	ionosphere convection flow applications
Heppner-Maynard (72)	high lat >45° geo-magnetic	100–150	electric potential	N/A	statistical k_p-dependent	point values, plots	modeling
Millstone Hill (75)	high lat	150–2000	electrostatic potential	N/A	either of 3 indices: precipitation, K_p or IMF B_Y/B_Z	tables	ionosphere convection flow
APL (77)	global	100–500	V_I (electric potential)	N/A	2 min	velocity maps	scientific modeling studies
Weimer (80)	high-lat	300-1000	V (electric potential), Ψ (mag-netic scalar potential)	N/A	diurnal and polar tilt angle, at epic	tables, plots, mapping	scientific studies
AMIE (83)	global high lat	mapped to 110	V_I ,**E, I, J,** Σ_p, Σ_H, JH	N/A	indices or IMF	plots, mapping	ionosphere convection, input to ionospheric models, scientific studies
HWM (86)	global	7–500	neutral atm wind	horizontal neutral wind	diurnal seasonal solar and magnetic activity	tables	wind climatology
Empirical T_e (88)	global	140–4000	T_e (N_e dependent)	T_e, N_e	latitude local time	tables	climatological model testing
Empirical T_e, T_i (90)	global coverage (lat)	50–4000	T_e, T_I	T_e, T_I	diurnal seasonal solar activity	figures, tables	scientific studies
PEMIC (93)	high lat	85–220	N_e, N_I, σ_p, σ_H, Σ_p, Σ_H	NO^+, O_2^+, N_2^+, O^+	sec	tables, plots	scientific studies

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Table 1 — Summary of reference and standard ionospheres (*cont.*)

Model (Page #)	Geographic Region	Altitude Range (km)	Parameters	Species Included	Temporal Variation	Output Data Pre-sentation	Principal Application
EMC (94)	high-lat >50° geo-magnetic	110	Σ_p, Σ_H	e^- ions	hr	tables, figures	input to ionospheric models, scientific studies
AEIF (96)	high-lat >50° geo-magnetic	110	Σ_p, Σ_H	e^- ions	hr	tables, figures	input to ionospheric models, scientific studies
WBMOD (98)	global	150–1000	plasma irregularity strength & spectrum	N_e	diurnal seasonal solar cycle	tables, plots	eng specs, climatology of scintillation at VHF and above
PBMOD (101)	low-lat	90–2000	S4 scintillation	O^+, H^+, NO^+, O_2^+, N_2^+	at epic	tables, plots	scientific studies
FIRST (104)	global		S4 scintillation				forecasting
HF/VHF (106)	high-lat	F-layer maximum	foF_2 MLAT/MLT boundaries	N_e	15 min to several hr	graphs, formulae	input to global ionospheric models
GPS TEC (108)	global	N/A	TEC, ionospheric delay at GPS frequencies	N/A	diurnal	tables	single frequency GPS users
CPI TEC (110)	global	N/A	TEC, ionosphere delay at GPS frequencies	O^+, H^+, He^+, NO^+, O_2^+	diurnal	tables	single frequency GPS users, TEC climatology, TEC variability studies

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2 USU Time-Dependent Model of the Global Ionosphere

2.1 Model Content

The USU ionospheric model describes the three-dimensional, time-dependent evolution of the global ionosphere at altitudes between 90 and 1000 km. The numerical model yields density distributions for electrons and six ion species (NO^+, O_2^+, N_2^+, O^+, N^+, H^+) as a function of latitude, longitude, and altitude on a prespecified spatial grid. The model also calculates the isotropic electron temperature and the ion temperatures both parallel and perpendicular to the geomagnetic field on the same spatial grid. The model outputs the global density and temperature distributions at specified times.

Numerous physical and chemical processes are contained in the model, including field-aligned diffusion, cross-field electrodynamic drifts, thermospheric winds, polar wind escape, energy-dependent chemical reactions, neutral composition changes, ion production due to EUV radiation and auroral electron precipitation, thermal conduction, diffusion-thermal heat flow, and a host of local heating and cooling mechanisms. The model also takes account of the offset between the geomagnetic and geographic poles.

Depending on the inputs, the global ionospheric model can describe different solar cycle, seasonal, and daily variations. It can describe different levels of sustained geomagnetic activity, as well as storm and substorm dynamics.

2.2 Model Uncertainties and Limitations

2.2.1 To a large extent, the reliability of the calculated ionospheric parameters depends on the accuracy to which the global inputs can be specified. The ionospheric model is most sensitive to the magnetospheric electric field and particle precipitation inputs at high latitudes, the thermospheric winds at mid-latitudes, and the equatorial (dynamo) electric fields at low latitudes.

2.2.2 The topside plasma scale heights can be significantly affected by the downward electron heat flux through the upper boundary, but this input is virtually unknown on a global scale.

2.2.3 Steep spatial gradients can lead to plasma instabilities and scintillations, but the ionospheric model does not take instabilities into account.

2.2.4 A supercomputer is needed for global simulations.

2.3 Basis of the Model

2.3.1 The USU model of the global ionosphere is based on a Euler-Lagrange hybrid numerical scheme. For the mid-high latitude region, the ion continuity, momentum, and energy equations are solved as a function of altitude using a fixed spatial grid, whereas for the equatorial region the ion equations are solved along the magnetic field (B) from one hemisphere to the conjugate hemisphere on a fixed spatial grid. In all latitudinal domains, the plasma flux tubes are allowed to convect through a moving neutral atmosphere in a direction perpendicular to B due to magnetospheric, co-rotational, and dynamo electric fields. The three-dimensional nature of the model is obtained by following many flux tubes of plasma while keeping track of their positions at all times. This approach has the advantage over a purely Eulerian scheme, which requires fixed grid points in latitude and longitude, because more flux tubes can be placed in the high-latitude regions where sharp horizontal gradients are expected, such as near the auroral oval and main trough.

2.3.2 The continuity, momentum, and energy equations correspond to a set of nonlinear, second-order, partial differential equations. The equations are first linearized in time, and then finite differences are used for the spatial and temporal derivatives. The resulting coupled algebraic equations are solved with standard matrix inversion techniques.

2.3.3 At the lower boundary (90 km), the different ion species are assumed to be in chemical equilibrium, and hence the boundary ion densities are obtained simply by equating local sources and sinks. Likewise, the ion and electron temperatures at the lower boundary are obtained by equating local heating and cooling rates.

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2.3.4 At the upper boundary (1000 km), a protonospheric exchange flux is specified for O^+, and the fluxes of the other ion species are assumed to be negligibly small. The upper boundary conditions on the ion and electron temperatures are specifications of the downward heat fluxes through this boundary.

2.3.5 A 4 km spatial step is used in the vertical direction, and the time step typically varies from 10 to 100 sec as a given flux tube follows a specified trajectory. The high-latitude region, above 50°N, is usually modeled with 500 flux tubes of plasma, if empirical plasma convection and particle precipitation patterns are used (climatology modeling). For storm and high-resolution studies, 1000–3000 flux tubes are used.

2.4 Model Input Parameters

The ionospheric model requires several inputs. The main global inputs are the neutral densities, temperatures, and winds; the magnetospheric and equatorial electric field distributions; the auroral electron precipitation pattern; the downward electron heat flux through the upper boundary; and the protonospheric exchange flux. Typically, empirical or statistical models are used for the required atmospheric and magnetospheric inputs, but in this case the calculated ionospheric parameters pertain to the climatology of the region. For storm and substorm simulations, the temporal variation of the magnetospheric and atmospheric inputs must be specified.

2.5 Publication References

2.5.1 Schunk, R.W. (1988), A mathematical model of the middle and high latitude ionosphere, *Pure Appl. Geophys.* 127, 255–303.

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2.6 Dates of Development

1973 Original one-dimensional, mid-latitude, multi-ion (NO^+, O_2^+, N_2^+, O^+) model.

1975 High-latitude effects due to plasma convection and particle precipitation added for single plasma flux tubes.

1980 Updated chemical scheme and new ions (N^+ and H^+) are added.

1981 Plasma convection and particle precipitation patterns added so that multiple flux tubes can be followed.

1982 A more complete ion energy equation is added.

1983 Time-dependent plasma convection and particle precipitation patterns are included so that geomagnetic storms and substorms can be modeled.

1985 An equatorial ionospheric model is added so that the entire globe can be modeled.

1986 The complete electron energy equation is added.

1992 A grid system that allows for a high spatial resolution in a specified region is developed.

2.7 Model Codes and Sources

The model is in the form of a large Fortran code, but it is not user-friendly and is not available. However, the authors frequently run the model in collaborative studies with both experimentalists and other modelers.

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3 NCAR Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM)

3.1 Model Developers

R. G. Roble et al.
High Altitude Observatory
National Center for Atmospheric Research

3.2 Model Description

The National Center for Atmospheric Research (NCAR) Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM) 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 low-latitude electric 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, centered, finite difference scheme on each pressure surface in a staggered vertical grid. It has 29 constant pressure levels in the vertical, extending from approximately 97 km to 500 km in intervals of one-half scale height, and a 5° x 5° latitude-longitude grid, in its base configuration. The time step is 120 s.

3.3 Model Assumptions, Uncertainties, and Limitations

Hydrostatic equilibrium, constant gravity, steady-state ion and electron energy equations, and incompressibility on a constant pressure surface are assumed. Ion velocities are derived from the potential field created by combining the imposed magnetospheric potential with the low-latitude dynamo potential, then calculating ion velocities from **E** × **B** drifts, rather than solving the ion momentum equations explicitly. Some minor species are not currently included in the model, including H and He, their ions, and Ar. Several parameterizations are used in the TIE-GCM: an empirical model is used to specify photoelectron heating; the production of secondary electrons is included using an empirical model derived from two-stream calculations; the effects of mixing by gravity waves are included using an eddy diffusion formulation; and CO_2 is included by specifying a lower boundary condition, assuming that it is in diffusive equilibrium. The upper boundary conditions for electron heat transfer and electron number flux are empirical formulations. At the lower boundary, atmospheric tides are specified using the Global Scale Wave Model (GSWM).

3.4 Model Inputs

- Solar EUV inputs:

$F_{10.7}$ (current daily $F_{10.7}$ solar index) and $F_{10.7}A$ (81-day center-averaged $F_{10.7}$ solar index)

- Particle precipitation:

Hemispheric Power in GW, obtained from 3-hour K_p index

- Ionospheric electric fields at high latitudes:

Provided by Heelis model (or Weimer model, in the future)

- Inputs for Heelis model:

Cross-polar cap potential in kV, obtained from 3-hour K_p index

Hemispheric Power in GW, obtained from 3-hour K_p index

Optional (not implemented): y-component of the interplanetary magnetic field (B_Y) in nT

- Inputs for Weimer model:

Interplanetary magnetic field, B_Y and B_Z, in nT

Solar wind density and speed, r and v, in cm^{-3} and km s^{-1}

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- Inputs for lower boundary**:**

Diurnal and semi-diurnal migrating tides, specified by the GSWM

3.5 Model Outputs

Primary time-dependent output fields, specified in latitude, longitude, and pressure level:

Geopotential height: Height of pressure surfaces (cm)

Temperatures: Neutral, ion, electron (K)

Neutral winds: zonal, meridional (cm^{-3}), vertical (s^{-1})

Composition: O, O_2, NO, N(^{4}S), N(^{2}D) (mass mixing ratios—dimensionless)

Ion and electron densities: O^+, O_2^+, Ne (cm^{-3}) *(NO^+ is calculated from $N_e - (O^+ + O_2^+)$)*

Electric potential: (V)

NOTE Other fields are available as secondary histories, which can be set as needed.

3.6 Additional Information

The TIE-GCM is a community model that can be run on a variety of computational platforms. The model source code is provided under the auspices of an open-source academic research license. Standard runs are available from the HAO/NCAR web site, and runs-on-request can also be generated at the NASA Community Coordinated Modeling Center (CCMC). For additional information, see these web pages:

TIE-GCM web page: http://www.hao.ucar.edu/modeling/tgcm

User Guide: http://www.hao.ucar.edu/modeling/tgcm/doc/userguide

Documentation: http://www.hao.ucar.edu/modeling/tgcm/doc/tiegcm_modeldes.pdf

Release Notes: http://www.hao.ucar.edu/modeling/tgcm/download/files/tiegcm1.9x_release.html

Post-Processing: http://www.hao.ucar.edu/modeling/tgcm/download/files/tgcmproc29_idl.tar.gz

NOTE Registration at the main web page is required in order to access the /tgcm/download area.

3.7 References

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3.8 Developer Contacts

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4 Coupled Thermosphere-Ionosphere Model (CTIM)

The Coupled Thermosphere-Ionosphere Model (CTIM) has evolved from an integration of a neutral thermospheric code and a high- and mid-latitude ionosphere model. The neutral thermospheric model was originally developed by Fuller-Rowell and Rees (1980) at University College London (UCL); the ionospheric model originated from Sheffield University (Quegan et al., 1982). A complete description is provided in Fuller-Rowell et al. (1996). A recent upgrade of this model, including a self-consistent plasmasphere and low-latitude ionosphere, is described in the section on CTIP.

4.1 Thermosphere Model

The thermospheric code simulates the time-dependent structure of the wind vector, temperature, and density of the neutral thermosphere by numerically solving the non-linear primitive equations of momentum, energy, and continuity. The global atmosphere is divided into a series of elements in geographic latitude, longitude, and pressure. Each grid point rotates with Earth to define a non-inertial frame of reference in a spherical polar coordinate system. Latitude resolution is 2° and longitude is 18°. Each longitude slice sweeps through local time with a 1 min time step. In the vertical direction, the atmosphere is divided into 15 levels in logarithm of pressure, from a lower boundary of 1 Pa at 80 km altitude, to an altitude above 500 km.

The momentum equation is nonlinear and the solution describes the horizontal and vertical advection, curvature and Coriolis effects, pressure gradients, horizontal and vertical viscosity, and ion drag. The nonlinear energy equation is solved self-consistently with the momentum equation; it describes three-dimensional advection and the exchange between internal, kinetic, and potential energy. The solutions also describe horizontal and vertical heat conduction by both molecular and turbulent diffusion, heating by solar UV and EUV radiation, cooling by infrared radiation, and Joule heating.

Time-dependent major species composition equations are solved including the evolution of O, O_2, and N_2, under chemistry, transport, and mutual diffusion (Fuller-Rowell et al., 1994). The time-dependent variables of southward and eastward wind, total energy density, and concentrations of O, O_2, and N_2 are evaluated at each grid point by an explicit, time-stepping numerical technique. After each iteration, the vertical wind, the temperature, the density, and the heights of pressure surfaces are derived. The parameters can be interpolated to fixed heights for comparison with experimental data.

4.2 Ionosphere Model

The equations for the neutral thermosphere are solved self-consistently with a high- and mid-latitude ionospheric convection model (Quegan et al., 1982). The ionosphere is computed self-consistently with the thermosphere poleward of 23° latitude in both hemispheres. In this coupled model, the ionospheric Lagrangian frame has been modified to be more compatible with the Eulerian frame by the use of semi-Lagrangian technique (Fuller-Rowell et al., 1987, 1988).

Transport under the influence of the magnetospheric electric field is explicitly treated, assuming $\mathbf{E} \times \mathbf{B}$ drifts and collisions with the neutral particles. The densities of atomic ions H^+ and O^+ and the ion temperature are evaluated over the height range from 100 to 10,000 km, including horizontal transport, vertical diffusion, and the ion-ion and ion-neutral chemical processes. Below 400 km, the additional contribution from the molecular ion species N_2^+, O_2^+, and NO^+, and atomic ion N^+ are included. The ion temperature is calculated under the assumption of thermal balance between heat gained from the electron gas, ion-neutral frictional heating, and heat lost to the neutral gas.

4.3 Common Inputs

The magnetospheric input to the model is based on the statistical models of auroral precipitation and electric fields described by Fuller-Rowell and Evans (1987) and Foster et al. (1986), respectively. Both inputs are keyed to a hemispheric power index (PI), based on the TIROS/NOAA auroral particle measurements, and are mutually consistent in this respect. The PI index runs from 1 to 10 to cover various levels of geomagnetic activity; the relationship between PI and K_p can be found in Foster et al. (1986). Alternative electric field and auroral precipitation models can easily be incorporated into the model.

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The (2,2), (2,3), (2,4), (2,5), and (1,1) propagating tidal modes are imposed at 97 km altitude (Fuller-Rowell et al., 1991); amplitude and phase can be prescribed. Ionization rates from the EUV flux are evaluated from reference spectra for high and low solar activity on the basis of the Atmospheric Explorer (AE) measurements.

4.4 Publication References

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4.5 Contacts

The model is available for collaborations. Please contact Tim Fuller-Rowell, Space Environment Center, 325 Broadway, Boulder, CO 80303; tel. 303-497-5764; e-mail: Tim.Fuller-Rowell@noaa.gov; or Mihail Codrescu, Space Environment Center, 325 Broadway, Boulder, CO 80303; tel. 303-497-6763; e-mail: Mihail.Codrescu@noaa.gov.

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5 Coupled Thermosphere-Ionosphere-Plasmasphere Model (CTIP)

5.1 Model content

The Coupled Thermosphere-Ionosphere-Plasmasphere model (CTIP) is an enhanced version of the CTIM model described elsewhere in this guide. The new enhanced version is identical to CTIM, but includes a fully coupled model of the Earth's mid- and low-latitude ionosphere and plasmasphere, where CTIM relies on an empirical description.

5.2 Basis of the Model

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). The effects of $\mathbf{E} \times \mathbf{B}$ drift at lower latitudes are incorporated by the inclusion of an empirical low-latitude electric field model. Full three-dimensional routines are used to interpolate parameters between the thermosphere and ionosphere-plasmasphere grids.

Recent developments of the CTIP model have included changing the mid- and low-latitude ionosphere/plasmasphere component such that the basic equations are now solved in a Eulerian (rather than Lagrangian) framework. This is a subtle change that allows ionospheric $\mathbf{E} \times \mathbf{B}$ convection to take any form. (Previous incarnations required flux-tubes to return to their geographic starting positions during a 24 hr simulation.) In addition the resolution of the ionosphere, in the height-latitude plane, has been significantly increased, such that the equatorial ionosphere, between altitudes of 200 and 1300 km, is modeled with a vertical resolution of 20 km. The new resolution represents a threefold increase in the number of individual flux-tubes solved within the model, necessary in order to correctly simulate (in particular) the dusk sector ionospheric response to the "pre-reversal enhancement" low-latitude electric field.

The CTIP model is thus a fully dynamic coupled model of the global thermosphere and ionosphere and has recently been used to study the mid-latitude ionospheric F2-layer annual and semi-annual variations (Millward et al., 1996a). A full description of the mathematical basis of the model has been given by Millward et al. (1996b).

5.3 Publication References

5.3.1 Millward, G.H., H. Rishbeth, T.J. Fuller-Rowell, A.D. Aylward, S. Quegan, and R.J. Moffett (1996a), Ionospheric F2-layer annual and semi-annual variations, *J. Geophys. Res.* 101(3).

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5.4 Model Codes and Sources

The model consists of a large and tortuous Fortran code, requires a powerful workstation or supercomputer to run, and is not particularly user-friendly. However, it is suitable for collaborative studies. Contact either Tim Fuller-Rowell (at the address given in the CTIM report) or George Millward, Space Environment Center, 325 Broadway, Boulder, CO 80303, tel. 303-497-7754 (email: gmillward@sel.noaa.gov).

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6 AFRL Global Theoretical Ionospheric Model (GTIM)

6.1 Model Content

The Air Force Research Laboratory (AFRL) Global Theoretical Ionospheric Model (GTIM) is a time-dependent, ionospheric model that calculates ion (NO^+, O_2^+, O^+, He^+, H^+) densities as a function of altitude, latitude, longitude, and local time, globally. The output from GTIM covers the height range from 90 to 1600 km on a pre-specified grid of latitudes and longitudes, depending on the scale of the phenomenon under investigation. Nominally, the output ion and electron densities are calculated every 2° dip latitude, every 5° longitude, and every 0.5 hr local time.

The model calculates O^+, He^+, and H^+ densities by solving the coupled ion momentum and continuity equations numerically using a Crank-Nicholson implicit finite differencing technique. The model includes the effects of production by solar EUV radiation and energetic particle precipitation, loss through charge exchange with the neutral atmosphere and transport by $\mathbf{E} \times \mathbf{B}$ drift, ambipolar diffusion, and collisions with neutral atmosphere. The offset between the geographic poles and geomagnetic poles is taken into account. The molecular ions NO^+ and O_2^+ are calculated under the chemical equilibrium assumption that production equals loss and no transport effects are included.

6.2 Model Uncertainties and Limitations

In calculating global ion and electron density distributions, the model uncertainties relate to how well the required inputs to GTIM can be specified. A number of studies have established that, if these can be realistically specified, then excellent agreement between calculated and observed electron density profiles is achieved. At low and high latitudes, the most important transport mechanism is $\mathbf{E} \times \mathbf{B}$ drift, whereas at mid latitudes, it is neutral winds that are critical in determining realistic ion and electron densities.

The major limitation of the model is that it is not coupled to the neutral atmosphere, the electrodynamics, or the energetics of the plasma, so that neither temperatures nor electric fields are self-consistently calculated.

6.3. Basis of the Model

GTIM solves the coupled ion (O^+, He^+, and H^+) momentum and continuity equations in a frame of reference that drifts with the $\mathbf{E} \times \mathbf{B}$ drift velocity (Eulerian frame of reference) of the ion and electrons. The r, θ, ϕ coordinate system is transformed to an α, β, γ coordinate system, where α and β are perpendicular to the geomagnetic field line direction, and γ is parallel to **B**. A number of transformations are carried out that facilitate the solving of the linear, second-order, partial differential equation. At low and mid latitudes, the solution is carried out along the entire field line from one hemisphere (90 km N) to the other (90 km S), and the boundary conditions at both ends assume $[O^+] = 0$. At high latitudes (above about ± 60° dip latitude), the upper boundary condition at 1600 km provides flux values ($N\mathbf{v}_\gamma$) parallel to **B**.

6.4 Model Input Parameters

Inputs to GTIM include a neutral atmosphere model, a solar production rate model, $\mathbf{E} \times \mathbf{B}$ drift pattern, a model for precipitating energetic electrons and protons, a horizontal neutral wind model, and a model for electron and ion temperatures. All of these inputs come from well-established references and observations and will not be detailed here.

6.5 Publication References

6.5.1 Anderson, D.N. (1973), A theoretical study of the ionospheric F-region equatorial anomaly, I; theory, *Planetary Space Sci.* 21, 409–420.

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6.6 Dates of Development and Authors

6.6.1 Dates:

1973 Development of the low-latitude portion of GTIM.

1976 Development of the mid-latitude portion of GTIM.

1994 Development of the high-latitude portion of GTIM.

1995–97 Addition of light ions (He^+ and H^+) to low- and mid-latitude portion of GTIM.

6.6.2 Authors: D.N. Anderson, D.T. Decker, M.W. Fox, R.E. Daniell, and R.W. Simon.

6.7 Model Codes and Sources

The model consists of a large number of Fortran coded subroutines that provide the GTIM output, but in no way is it well documented, user-friendly, or available to outside users. However, many collaborative studies have been carried out using GTIM.

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7 Parameterized Ionospheric Model (PIM)

7.1 Model Content

The Parameterized Ionospheric Model (PIM) is a global model of the *theoretical* climatology of the ionosphere. That is, PIM is a parameterization of the output from an amalgamation of theoretical ionospheric models, including the USU Time Dependent Ionospheric Model (TDIM) for high latitudes and the Global Theoretical Ionospheric Model (GTIM) for low and mid latitudes, augmented by the empirical plasmasphere model of Gallagher (1988). An earlier version of PIM has been described by Daniell et al. (1995).

The output from all of these models has been parameterized in terms of solar activity ($F_{10.7}$), geomagnetic activity (K_p), and season (Equinox, June Solstice, December Solstice). The format of the output of PIM is user selectable, and includes electron density profiles and/or profile parameters (TEC, N_mF_2, h_mF_2, N_mE, h_mE, etc.) on user-specified grids in latitude/longitude/altitude (geographic or geomagnetic) or azimuth/elevation/range.

7.2 Model Uncertainties and Limitations

PIM is a climatological model based on diurnally reproducible runs of physics-based models. As such, it cannot accurately reproduce specific situations, especially the storm time ionosphere. It is intended to represent typical (rather than average) ionospheric conditions.

Because the model is based on seasonal runs, it does not represent the complete annual variation of the ionosphere and is most inaccurate between equinoxes and solstices.

7.3 Basis of the Model

PIM consists of two major components: (1) a large set of coefficient files, from which the electron density profile may be derived at any specified latitude, longitude, season, and solar geophysical condition, and (2) an algorithm for reconstructing the electron density profiles from these coefficients.

PIM is based on diurnally reproducible runs of its parent physics-based models for specified solar/geophysical conditions and seasons. That is, the physics-based models are run with constant or steady state forcing functions until the steady-state response of the ionosphere is obtained. This usually occurs after a few hours of solar illumination. The output of the physics-based models consists of altitude profiles of the densities of the three dominant ions of the E- and F-regions (O^+, N_2^+, and O_2^+) on a latitude/longitude grid at regular intervals of local time or UT, depending on the model.

The ion density profiles are then represented as linear combinations of Empirical Orthonormal Functions (EOFs), which are derived from the complete set of profiles for a given set of solar/geophysical conditions. Depending on latitude region, the coefficients of the EOFs are fit by orthogonal functions in latitude, longitude, and/or UT.

The resulting coefficients are stored in files and constitute one of the two major constituents of PIM. The other component, the Fortran code itself, reconstructs the ion density profiles at the times and places specified by the user and sums the ion densities to obtain the electron density. If the user has asked for profile parameters, the height and density of the E- and F-layer peaks are found, and the profile is integrated to produce TEC.

The structures of the coefficient files differ for the various ionospheric regions. Merging between regions is accomplished by averaging between profiles in overlapping regions. Interpolation for solar/geophysical conditions between the values of the model runs is also accomplished by operating on profiles (rather than coefficients). This is because the EOFs were derived separately from each block of runs; that is, the basis functions are different for different sets of solar/geophysical conditions and different ionospheric regions.

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This will probably change in PIM version 2, which will be based on a universal set of EOFs so that all interpolation can be done in "coefficient space." It will also be based on a single, unified ionospheric model, GTIM.

7.4 Model Input Parameters

The user inputs are the date and time (UT) of the run, the solar/geophysical conditions ($F_{10.7}$ and K_p), choice of coordinates (geomagnetic or geographic), choice of output grid (latitude/longitude/altitude or azimuth/elevation/range), and the specifics of the output grid.

7.5 Publication References

7.5.1 Daniell, R.E., L.D. Brown, D.N. Anderson, M.W. Fox, P.H. Doherty, D.T. Decker, J.J. Sojka, and R.W. Schunk (1995), Parameterized ionospheric model: a global ionospheric parameterization based on first principles models, *Radio Sci.* 30, 1499–1510.

7.5.2 Gallagher, D.L., P.D. Craven, and R.H. Comfort (1988), An empirical model of the earth's plasmasphere, *Adv. Space Res.* 8, 15–24.

7.6 Dates of Development, Authors, and Sponsors

7.6.1 Dates:

1987–90 Development of the high-latitude portion of the model.

1990 Development of the low- and mid-latitude portion.

1993 Version 1 of PIM.

1997 Most recent version of the code (1.6).

7.6.2 Authors: R.E. Daniell, L.D. Brown, W.G. Whartenby, J.J. Sojka, P.H. Doherty, D.T. Decker, and D.N. Anderson.

7.6.3 Sponsor: Air Force Research Laboratory.

7.7 Model Codes and Sources

The model may be obtained by contacting Lincoln Brown at CPI, tel. 781-487-2250 (email: brown@cpiboston.com). The source code and associated coefficient files are available free of charge from either of two FTP sites on the Internet. They are also available on CD-ROM for a nominal charge. (Contact Mr. Brown for specific information.) The source code is Fortran, and each version is verified to run under MS-DOS, DEC-VMS, and Sun-UNIX operating systems. (With minor modifications, the code has been successfully run under other UNIX "flavors.") There are approximately 40–50 registered PIM users around the world.

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8 International Reference Ionosphere (IRI), 1996

8.1 Model Content

The International Reference Ionosphere is the standard ionospheric model recommended for international use by the scientific union's Committee on Space Research (COSPAR) and International Union of Radio Science (URSI). A joint working group of COSPAR and URSI is in charge of developing and improving the model. By charter, IRI, like other international standard models (e.g., CIRA, MSIS, IGRF), is an empirical model, thus avoiding the uncertainties of the evolving theoretical understanding. Annual IRI Workshops are the forum for progress/status reports of ongoing IRI projects, for comparisons with new data sources, for resolving issues of conflicting data sources, and for decisions about improvements and additions for the next release of the model. The presentations from these workshops are published in *Advances in Space Research*, Vols.(Nos.) 4(1), 5(7), 5(10), 7(6), 8(4), 10(8), 10(11), 11(10), 13(3), 14(12), 15(2), and 16(1).

IRI provides monthly averages of the electron density, the ion composition (O^+, H^+, He^+, NO^+, O_2^+, N_2^+, and cluster ions), the electron temperature, and the ion temperature for magnetically quiet conditions. Efforts are underway to include models for ionospheric storm effects and models for the ion drift and spread-F.

The IRI model, its background, database, and mathematical formulas are explained in detail in special reports published by URSI (Rawer et al., 1978), by the WDC-A-STP (Rawer et al., 1981), and by the NSSDC (Bilitza, 1990).

8.2 Model Uncertainties and Limitations

Like any empirical model, IRI is as good and representative as the data that are available for developing/improving the model. Since most of the ionospheric data have been accumulated at European and North American latitudes, these regions are also the ones that are best represented in IRI. The Northern hemisphere and the continents in general are better represented than the Southern hemisphere and the oceans, again because of obvious differences in data volume. The IRI model should be primarily used for subauroral latitudes. At auroral and polar latitudes, the model has to rely on data from just a few stations and satellites, clearly not enough to fully describe this highly variable region. At these high latitudes, IRI should be considered as a first estimate for describing the background ionosphere.

The uncertainties are typically as follows in Table 2:

Table 2 — IRI Model uncertainties for D, E, and F region parameters

Region	**Peak height**	**Peak density**	**Temperatures**	**Ion composition**
F region	±15%	±30%	±20%	±50%
E region	±5%	±10%	±10%	±50%
D region	±10%	±70%	(undetermined)	(undetermined)

Improvements in the accuracy of the electron density values can be obtained by introducing measured values for the F peak height and density; IRI supports this option. In addition, IRI provides an option to use measured electron densities to obtain more accurate electron temperatures by employing the well-known anti-correlation between electron temperature and density.

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8.3 Basis of the Model

The IRI electron density model uses the CCIR world maps for the F and E peak parameters. A special formula was developed by the IRI team to convert the CCIR-given M3000 propagation factor to the F peak height. For the F peak density an additional choice is given with the URSI-88 maps. These were developed by a special URSI Working Group (C. Rush, Chair) and have shown better results than CCIR in the ocean areas. In addition, a user can enter measured peak parameters into IRI, if available. The CCIR formulas for the F1 ledge and the E peak densities were modified for IRI to better agree with more recent measurements. The IRI topside is based on an analytical representation of Bent's compilation of Alouette and ISIS topside sounder data. Incoherent scatter data from Jicamarca and Arecibo and AEROS and AE-C *in situ* measurements have been used to improve the formula at low latitudes. The representation of the region between E and F peaks is based on ionosonde real-height profiles and on incoherent scatter data (valley). The D-region model assumes an inflection point at 80 to 88 km; this height is correlated to the transition from molecular to cluster ions. The global and temporal variation of the density at that point was modeled with the help of all available (reliable) rocket data.

The electron and ion temperature models are based largely on AEROS RPA and AE-C, ISIS-1, ISIS-2 Langmuir probe data. These data provide a global mapping of temperatures at several altitudes. The whole profile was then established with the help of incoherent scatter data from Jicamarca, Arecibo, and Millstone Hill. At 120 km, the plasma temperatures coincide with the value given by the COSPAR International Reference Atmosphere (CIRA); this was one of the COSPAR requirements. Through all altitudes the temperatures are such that $T_n < T_i < T_e$.

The IRI ion composition model assumes charge neutrality. IRI primarily models the global and temporal variation of atomic and molecular oxygen ions (O^+, O_2^+) and then fills up to 100% with light ions (H^+, He^+) above the F peak and with NO^+ ions below. The model is based on a compilation of rocket and satellite RPA and IMS data. The rather limited database makes the ion composition model the weakest part of the IRI. Problems with instrument calibrations have made it difficult to use IMS data from several of the early satellites. Discrepancies were also found between satellite and incoherent scatter measurements. Efforts are now focusing on using the transition heights (light ions to O^+, O^+ to molecular ions, molecular to cluster, cluster to negative ions) as the characteristic parameters of the composition profiles.

8.4 Database

Electron density: ionosonde (E-, F-peak, bottomside), incoherent scatter radar (h_mF_2, E-valley, topside), absorption (D-region), rockets (D-, E-region), Alouette, ISIS topside sounder (topside), AEROS, AE-C, DE-2 *in situ* (topside); ion composition: RPA and IMS measurements from satellites (AE-C, AEROS-B, S3-1, OGO-6, Electron 2, 4, Cosmos 274, Sputnik 3) and rockets; temperatures: Langmuir probe and RPA measurements from AEROS-A,B, ISIS-1,-2, AE-C, -E, DE-2, incoherent scatter data from Jicamarca, Arecibo, Millstone Hill, St. Santin, Malvern.

8.5 Publication References

8.5.1 Bilitza, D. (1990), International reference ionosphere 1990, NSSDC/WDC-A-R&S 90-22, Greenbelt, MD.

8.5.2 Bilitza, D., K., and E.G. Rawer, eds. (1994), Ionospheric models, *Adv. Space Res.* 14(12).

8.5.3 Rawer, K., S. Ramakrishnan, and D. Bilitza (1978), International reference ionosphere 1978, URSI Special Rept., Brussels, Belgium.

8.5.4 Rawer, K., D. Bilitza, and S. Ramakrishnan (1978), Goals and status of the international reference ionosphere, *Rev. Geophys.* 16, 177–181.

8.5.5 Rawer, K., J.V. Lincoln, and R.O. Conkright (1981), International reference ionosphere IRI-79, WDC-A-STP Rept. UAG-82, Boulder, CO.

8.5.6 Rawer, K., and W.R. Piggott (1990), Development of IRI-90, *Adv. Space Res.* 10(11).

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8.5.7 Rawer, K., and W.R. Piggott (1991), Enlarged space and ground data base for ionospheric modeling, *Adv. Space Res.* 11(10).

8.5.8 Rawer, K., W.R. Piggott, and A.K. Paul (1993), Advances in global/regional descriptions of ionospheric parameters, *Adv. Space Res.* 13(3).

8.5.9 Rawer, K., W.R. Piggott, and A.K. Paul, eds. (1995), Off median phenomena and IRI, *Adv. Space Res.* 15(2).

8.5.10 Rawer, K., D. Bilitza, and W. Singer, eds. (1995), The high latitudes in the IRI, *Adv. Space Res.* 16(1).

8.5.11 Rawer, K., D. Bilitza, K. Mahajan, and A. Mitra, eds. (1996), Low and equatorial latitudes in the IRI, *Adv. Space Res.* 18(6).

8.6 Dates of Development and Authors

8.6.1 Dates:

1968 Working Group established.

1972 First set of preliminary tables.

1978 IRI-78, URSI Special Report.

1981 IRI-80, WDC-A-STP Report UAG-82.

1986 IRI-86 (also on diskette for use on PCs).

1990 IRI-90, NSSDC Report 90-22.

1995 IRI-95, anonymous FTP and WWW.

8.6.2 Authors: COSPAR/URSI Working Group (K. Rawer, L. Bossy, and D. Bilitza, Chairs).

8.7 Model Codes and Sources

The model codes can be retrieved from the anonymous FTP site at nssdca.gsfc.nasa.gov in directory pub/models/IRI; an ASCII version of the model coefficients can be found in directorypub/models/IRI90ASCII. The software package also can be obtained on diskette from NSSDC's request coordination office (CRUSO), National Space Science Data Center, NASA/GSFC, Code 633.4, Greenbelt, MD 20771, tel. 301-286-6695, FAX 301-286-1771 (email: request@nssdca.gsfc.nasa.gov). The model can also be accessed and run interactively online at http://nssdc.gsfc.nasa.gov/space/model. There are also web pages describing the model and listing the Working Group composition and the IRI Workshops that have been held so far.

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9 Empirical Model of the Ionosphere (EMI)

9.1 Model Content

The empirical model of the ionosphere provides number densities (cm^{-3}) of

Atomic ions:	H^+, He^+, N^+, O^+
Molecular ions:	N_2^+, NO^+, O_2^+
Electrons:	N_e

as a function of

Altitude:	50–4000 km
Latitude:	dipole latitude, N_2, O_2, O, NO
Time:	day count d (annual variation)
	magnetic local time τ
Solar activity:	solar flux $f_{10.7}$
	for quiet geophysical conditions ($K_p \leq 3$)

The number densities **n** of the ion species and the electrons are obtained from the appropriate figures (Köhnlein, 1989a and 1989b). At $F_{10.7} = 84 \times 10^{-22}\ Wm^{-2}\ Hz^{-1}$ and $K_p \leq 3$:

Average density (time independent):
see Köhnlein (1989a and 1989b, Figs. 3–6),

$\log_{10}n$ vs. altitude;

Time-independent density (latitudinal):
see Köhnlein (1989a and 1989b, Figs. 7–18),

$\log_{10}n$ vs. altitude at $\phi = 90°, 45°, 0°, -90°$;

$\log_{10}n$ vs. dipole latitude at discrete heights;

Annual variation:
see Köhnlein (1989a and 1989b, Figs. 19–30),

$\log_{10}n$ vs. altitude at equinox and solstice conditions (d = 80, 173, 266, 356);
comparison with data: $\log_{10}n$ vs. day count at discrete heights;

$\Delta \log_{10}n$(relative):
dipole latitude vs. day count at discrete heights;

Diurnal variation:
see Köhnlein (1989a, Figs. 31–46), and Köhnlein (1989b, Figs. 31–48),

$\log_{10}n$ vs. altitude at $\phi = 0°, 45°$, and $\tau = 0h, 6h, 12h, 18h$;

comparison with data:

$\log_{10}n$ vs. magnetic local time at discrete heights and $\phi = 0°, 45°$;
$\Delta \log_{10}n$(relative):
dipole latitude vs. magnetic local time at discrete heights;

And superpositions thereof, i.e.,
diurnal variation + relative annual variation
$\Rightarrow$ diurnal variation at a selected day of the year;
annual variation + relative diurnal variation
$\Rightarrow$ diurnal variation at a selected magnetic local time.

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9.2 Model Uncertainties and Limitations

The discrepancies between the model and the observations (used) are shown for the annual and diurnal variations in Köhnlein (1989a and 1989b, Figs. 20, 23, 26, 29, 32, 33, 36, 37, 40, 41, 44, 45), and in Köhnlein (1989b, Figs. 46 and 47). In general, the model agrees well with the observations.

The uncertainties of the model are mainly due to the uneven data coverage and the simplicity of the analytical approach (e.g., linearity, no longitudinal terms, no disturbed conditions).

Data from epochs not used in the database may show greater deviations from the model. This is especially true for disturbed geophysical conditions that are not considered in the model (also see Köhnlein, 1993).

9.3 Basis of the Model

The vertical and horizontal structures of the model are treated on an equal footing.

The plasma parameters are expanded into spherical harmonics (Köhnlein, 1989a, Eqs. 2.1–2.10), wherein the model coefficients depend on altitude, solar flux $F_{10.7}$, and the geomagnetic index K_p.

Restricting the model to quiet geophysical conditions ($K_p \leq 3$), the above coefficients depend linearly on $F_{10.7}$, whereas their height variations are expressed by cubic spline functions.

9.4 Database

The database of the model consists of observations by satellites, incoherent scatter stations, and rocket profiles covering the time interval 1964–1979 (Köhnlein, 1989a, Table1 therein; and Köhnlein, 1989b, Table1 and Figs.1 and 2 therein).

9.5 Publication References

9.5.1 Köhnlein, W. (1989a), A model of the terrestrial ionosphere in the altitude interval 50–4000 km: I. atomic ions (H^+, He^+, N^+, O^+), *Earth Moon Planets.* 45, 53–100.

9.5.2 Köhnlein, W. (1989b), A model of the terrestrial ionosphere in the altitude interval 50–4000 km: II. molecular ions (N_2^+, NO^+, O_2^+) and electron density, *Earth Moon Planets.* 47, 109–163.

9.5.3 Köhnlein, W. (1993), Comparison of the ion composition data with empirical models (comment), *Adv. Space Res.* 13(3), 85–86, 125–132.

9.6 Dates of Development, Authors, and Sponsors

9.6.1 **Date:** 1983.

9.6.2 **Author:** W. Köhnlein.

9.6.3 **Sponsors:** Deutsche Forschungsgemeinschaft and University of Bonn.

9.7 Model Codes and Sources

The model was developed in Fortran code specifically adapted to a CDC computer.

Because of the detailed graphical representation, Köhnlein (1989a and 1989b) can be used as a quick reference for ion and electron densities at low solar fluxes ($F_{10.7} \approx 84$) and quiet geophysical conditions ($K_p \leq 3$) in the altitude interval 50–4000 km.

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10 The Sheffield University Plasmasphere-Ionosphere Model (SUPIM)

10.1 Model Content

The Sheffield University Plasmasphere-Ionosphere Model (SUPIM) is a mathematical model that describes the distribution of ionization within the Earth's mid- and equatorial latitude ionosphere. In the model, time-dependent equations of continuity, momentum, and energy balance for the O^+, H^+, He^+, N_2^+, O_2^+, and NO^+ ions, and the electrons are solved along magnetic field lines for the ion and electron concentrations, field-aligned velocities, and temperatures. The magnetic field is an eccentric-dipole representation of the Earth's magnetic field, the offset between the magnetic and geographic poles being determined from the first eight non-zero terms of the usual spherical harmonic expansion of the geomagnetic scalar potential used in the International Geomagnetic Reference Field (IGRF). Particular cases of the eccentric dipole are the tilted-centered dipole and the axial-centered dipole. These cases are obtained by truncating the spherical harmonic expansion after the first three non-zero terms and the first term, respectively.

Included in the model are numerous physical and chemical processes. The principal processes include ion production due to solar EUV radiation, ion production and loss due to chemical reactions between the constituent ions and with the neutral gases, ambipolar and thermal diffusion, ion–ion and ion-neutral collisions, thermospheric meridional and zonal winds, electrodynamic drift, thermal conduction, photo-electron heating, frictional heating, and a host of local heating and cooling mechanisms.

Enhancements/modifications have been made to the "standard" model for specific studies. For example, inclusion of sub-auroral ion drifts (SAIDs), a self-consistent, low-latitude atmospheric dynamo model, anisotropic ion temperatures, vibrational excitation of N_2, the separation of O^+ into its ^4S, ^2D, and ^2P states, and vertical neutral winds.

Depending upon the inputs, the model can describe different solar cycle, seasonal, daily, and magnetic activity variations. It can also provide descriptions of the diurnal, altitude, latitude, and longitudinal variations.

10.2. Model Uncertainties and Limitations

10.2.1 To a large extent, the reliability of the calculated ionospheric parameters depends upon the accuracy to which the model inputs can be specified.

10.2.2 Except for a few locations, the model inputs of thermospheric wind and the vertical $\mathbf{E} \times \mathbf{B}$ drift are poorly known. Some adjustments to these parameters may be needed.

10.3 Basis of the Model

10.3.1 The model is a mathematical formulation of the known physical and chemical processes of the Earth's ionosphere and plasmasphere. The motion of the plasma is considered to be due to ambipolar diffusion parallel to the magnetic field with an additional $\mathbf{E} \times \mathbf{B}$ drift perpendicular to the magnetic field.

10.3.2 The model equations are solved at a discrete set of points along an eccentric dipole magnetic field line from a base altitude of around 120 km in the northern hemisphere to a base altitude of around 120 km in the southern hemisphere. There are switches in the model code to make the magnetic field a tilted-centered or axial-centered dipole.

10.3.3 At mid-latitudes, the vertical $\mathbf{E} \times \mathbf{B}$ drift velocity has little effect on the model results and is usually taken to be zero. For many applications, only one field line needs to be considered.

10.3.4 At equatorial latitudes, inclusion of the vertical $\mathbf{E} \times \mathbf{B}$ drift is essential as this drift gives rise to the equatorial anomaly. Under the influence of a vertical $\mathbf{E} \times \mathbf{B}$ drift the plasma associated with a particular

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magnetic field line is associated with a different magnetic field line at later times. Thus, in order to provide reasonable 24 hr coverage of the modeled parameters within a specified altitude and latitude region, the model equations have to be solved for many magnetic field lines.

10.3.5 The continuity, momentum, and energy balance equations for each constituent ion and the electrons form a set of highly nonlinear, second-order partial parabolic equations. The equations are first linearized in them, and then finite differences are used for the spatial and temporal derivatives. The resulting coupled tri-diagonal systems of linear algebraic equations are solved by a standard technique.

10.3.6 At the lower boundary of each hemisphere (z = 120 km), the ions and electrons are taken to be in chemical equilibrium, and the densities are obtained by equating the local sources and sinks. Likewise, the ion and electron temperatures are obtained by equating local heating and cooling rates.

10.3.7 The time step is usually taken to be 15 min. The spatial step along the magnetic field line varies along the field line, and the number of points increases with increasing apex altitude. A mathematical formulation is used to give the point distribution. The points are arranged to give a spatial step of about 5 km at F-region altitudes.

10.4 Model Input Parameters

10.4.1 Latitude and longitude of ground station, day, and year.

10.4.2 An IGRF (presently IGRF85) for the determination of the magnetic field.

10.4.3 A solar EUV flux spectrum (presently from EUV94).

10.4.4 A thermosphere model (presently MSIS-86) for the determination of the neutral densities and temperatures.

10.4.5 A thermospheric wind model (presently HWM-90) for the determination of the meridional and zonal winds.

10.4.6 A vertical $\mathbf{E} \times \mathbf{B}$ drift model.

The model inputs described in section 4.1 are read into the model from an input file. The model inputs described in sections 4.2 and 4.3 are incorporated into the model code as sets of subroutines. The subroutines permit easy modification as improved values become available and for the modifications/changes made in applications of the model to particular studies.

10.5 Publication References

10.5.1 Bailey, G.J., and R. Sellek (1990), A mathematical model of the earth's plasmasphere and its application in a study of He^+ at L=3.0, *Ann. Geophys*. 8, 171–190.

10.5.2 Bailey, G.J., R. Sellek, and Y. Rippeth (1993), A modeling study of the equatorial topside ionosphere, *Ann. Geophys*. 11, 263–272.

10.6 Dates of Development, Authors, and Sponsors

10.6.1 Dates

1975 One-hemisphere model-ions O^+ and H^+

1978 Extended to two hemispheres.

1979 He^+ added to one-hemisphere model.

1980 Major revision—two-hemisphere model, axial-centered dipole magnetic field, energy balance equations, new numerical procedures for solving model equations, ions O^+ and H^+.

1983 $\mathbf{E} \times \mathbf{B}$ drift added.

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1990 Major revision—the ions He^+, N_2^+, O_2^+, and NO^+ added.

1993 Major revision—magnetic field represented by an eccentric dipole.

1994 Two-stream approximation method used to determine photoelectron-heating rates.

1995 Changes made to numerical procedures to improve numerical stability.

10.6.2 Author (principal): Graham J. Bailey, School of Mathematics and Statistics, Applied Mathematics Section, The University of Sheffield, Sheffield S3 7RH, UK.

10.6.3 Sponsors: Plasma Physics and Astronomy Research Council (PPARC), UK.

10.7 Model Codes and Sources

The model is not user-friendly, and collaboration, in the first instance, is required between the user and the author (Graham Bailey). The author would be happy to discuss collaborations with interested groups. The author would consider enhancing/modifying the model and model codes to meet specific requests. The model codes are written in Fortran and have been developed for use on a high-performance PC. It is straightforward to modify the codes for use on workstations and mainframes.

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11 The Field Line Interhemispheric Plasma Model

11.1 Model Content

The Field Line Interhemispheric Plasma (FLIP) Model 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. In addition, continuity and momentum equations are solved to provide the densities of minor neutral species [$N(^2D)$, $N(^4S)$, NO] and the first six vibrational levels of N_2 in both hemispheres. A large number of other minor ion and neutral densities are calculated from chemical equilibrium between 80 and 600 km in the northern and southern hemispheres. Other outputs from the model include particle and heat fluxes, electron heating and cooling rates, photoelectron fluxes, chemical production and loss rates, and, most significantly, airglow emission rates. Major neutral densities are supplied by the MSIS model. A three-dimensional version of the model is obtained by simulating several hundred corotating flux tubes.

11.2 Model Uncertainties and Limitations

11.2.1 In several recent studies, the FLIP model typically produces F2 peak electron densities within 30% of the measured densities during the daytime, despite the potential for large errors in several key inputs. At night, discrepancies between measured and modeled densities can often be as much as a factor of 2.

11.2.2 During quiet times, the error in the inputs for the solar EUV flux, MSIS neutral densities, reaction rates, and cross-sections are typically about 20%. During magnetic storms, uncertainties in the MSIS neutral densities may be much larger, resulting in similar errors in calculated electron densities.

11.2.3 The largest uncertainty for ionospheric modeling at mid latitudes is the neutral wind magnitude. However, when measurements of h_mF_2 are available, the uncertainty is reduced to about 20% by using the algorithm that we have developed.

11.2.4 The current FLIP model is basically a mid-latitude model because it neglects convection electric fields, which are important at equatorial and auroral latitudes.

11.2.5 The uncertainty of the plasma content of plasmaspheric flux tubes is not important during the daytime but can produce about a 50% error in calculated N_mF_2 at night.

11.2.6 The FLIP model is a low-speed model that is not applicable in the plasmasphere for ion densities below about 100 cm^{-3}.

11.3 Basis of the Model

11.3.1 The FLIP model calculates the plasma densities and temperatures along complete magnetic flux tubes, from 80 km in the northern hemisphere, through the plasmasphere, to 80 km in the southern hemisphere, as a function of time. A tilted dipole approximation is used for the Earth's magnetic field.

11.3.2 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 scheme is stable and time steps are generally 0.5 hr except near twilight, where 10 min or less are used.

11.3.3 A variable spatial grid is set up along the magnetic field line. There are approximately 200 grid points distributed in such a way as to give a grid spacing of less than 10 km in the ionosphere and less than one scale height of H^+ in the plasmasphere.

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11.3.4 The boundary conditions imposed at the feet of the flux tube near 100 km are chemical equilibrium for ions and thermal equilibrium for temperatures. The initial plasmaspheric H^+ density must also be specified.

11.3.5 A unique feature of the FLIP model is the option to employ measurements of h_mF_2, N_mF_2, and topside T_e as additional constraints for different types of studies.

11.4 Model Input Parameters

11.4.1 The standard model can be run by simply specifying the date and the geographic location, but there are a large number of other options.

11.4.2 Activity indices K_p, daily $F_{10.7}$, and average $F_{10.7}$ for the MSIS neutral density, HWM-93 wind, and solar EUV flux models are read from a file but can also be specified.

11.4.3 Measured h_mF_2, N_mF_2, and topside T_e can be input from a file. The h_mF_2 is automatically turned into a neutral wind so that the model h_mF_2 follows the observed values.

11.4.4 There are a large number of adjustable parameters, such as time step and length of the run, which control the action of the model.

11.5 Publication References

11.5.1 Torr, M.R., D.G. Torr, P.G. Richards, and S.P. Yung (1990), Mid- and low-latitude model of thermospheric emissions, 1, $O^+(^2P)$ 7320 and N_2 (^2P) 3371, *J. Geophys. Res.* 95(21), 147.

11.5.2 Richards, P.G. (1991), An improved algorithm for determining neutral winds from the height of the F2 peak electron density, *J. Geophys. Res.* 96(17), 839.

11.5.3 Richards, P.G., D.G. Torr, B.W. Reinisch, R.R. Gamache, and P.J. Wilkinson (1994), F2 peak electron density at Millstone Hill and Hobart: comparison of theory and measurement at solar maximum, *J. Geophys. Res.* 99(15), 5.

11.5.4 Richards, P.G., D.G. Torr, M.J. Buonsanto, and D.P. Sipler (1994), Ionospheric effects of the March 1990 magnetic storm: comparison of theory and measurement, *J. Geophys. Res.* 99(23), 359.

11.5.5 Richards, P.G., J.A. Fennelly, and D.G. Torr (1994), EUVAC: A solar EUV flux model for aeronomic calculations, *J. Geophys. Res.* 99, 8981.

11.5.6 Richards, P.G., D.G. Torr, M.E. Hagan, and M.J. Buonsanto (1995), A new algorithm for improved ionospheric electron density modeling, *Geophys. Res. Letters* 22, 1385.

11.5.7 Richards, P.G. (1996), The field line interhemispheric plasma model, *Solar-Terrestrial Energy Program: Handbook of Ionospheric Models*, edited by R.W. Schunk, p. 207.

11.6 Dates of Development, Authors, and Sponsors

11.6.1 Dates

1979 Development of interhemispheric solutions for $[O^+]$, $[H^+]$, T_e, and T_i.

1980 Interhemispheric solutions for photoelectron flux and solutions for minor ion and neutral densities added.

1981 Diffusion equations for vibrationally excited N_2 effects included.

1982 Improvements to the photoelectron flux model to reproduce observed flux.

1986 Developed original algorithm for obtaining winds from h_mF_2.

1991 Improved algorithm for getting winds from h_mF_2.

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1992 Added energetic electron precipitation for auroral studies.

1993 Developed algorithm to cause model to reproduce both h_mF_2 and N_mF_2.

1994 Developed EUVAC solar EUV flux model.

1995 Developed algorithm to reproduce observed topside ionosphere.

11.6.2 Author (principal): Phil Richards, Computer Science Department, The University of Alabama in Huntsville, Huntsville, AL 35899, USA.

11.6.3 Sponsors: National Aeronautics and Space Agency, National Science Foundation.

11.7 Model Codes and Sources

A VAX version of the model is available to be installed at the user's institution. A UNIX version is also under development. The model runs from DEC command files that are well documented. There is also an interface that helps the user understand the model and aids in the setting up of the DEC command files. Some previous users with a good knowledge of the ionosphere have been able to run the model with little additional help. The author also runs the model for collaborative studies. Contact person: Phil Richards, Computer Science Department, The University of Alabama in Huntsville, Huntsville, AL 35899, USA (email: pgrichds@gmail.com).

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12 Global Assimilation of Ionospheric Measurements–Full Physics (GAIM-FP)

12.1 Model Content

The GAIM-FP model was developed at Utah State University (Schunk et al., 2004; Scherliess et al., 2004, 2009, 2010). The model uses a physics-based model of the ionosphere-plasmasphere system and a Kalman filter as a basis for assimilating a diverse set of real-time (or near real-time) measurements. The physics-based model is the Ionosphere Plasmasphere Model (IPM), which is global and covers the E-region, F-region, topside ionosphere, and plasmasphere from 90 to 30,000 km. It takes account of six ion species (NO^+, O_2^+, N_2^+, O^+, H^+, He^+). The primary output of the GAIM-FP model is a time-dependent, three-dimensional plasma density distribution at user-specified times. However, the model also provides quantitative estimates of the accuracy of the reconstructed plasma densities, as well as the self-consistent drivers of the ionosphere-plasmasphere system (e.g., neutral winds and electric fields). In addition, auxiliary parameters are provided, including N_mE, h_mE, N_mF_2, h_mF_2, slant, and vertical TEC. The GAIM-FP model assimilates bottomside N_e profiles from a variable number of ionosondes, slant TEC from a variable number of ground-based GPS/TEC stations, *in situ* N_e from the DMSP satellites, occultation data, and line-of-sight UV emissions measured by satellites. The model can be run in a global, regional, or local mode. Forecasting is accomplished by running the IPM forward in time from a given GAIM-FP specification using predictions for the IPM inputs.

12.2 Model Uncertainties and Limitations

12.2.1 The accuracy of the reconstructed ionosphere depends on the amount of data assimilated, the diversity of the data types, and the quality of the data.

12.2.2 When very little data are assimilated, the output of GAIM-FP is primarily from the physics-based model (IPM).

12.2.3 Plasma instabilities and bubbles are not taken into account in the physics-based model (IPM).

12.2.4 GAIM-FP only assimilates data between ±60° geomagnetic latitudes. The plasma density distribution at high latitudes is provided by the physics-based model, which is currently only driven by the geophysical conditions.

12.3 Basis of the Model

The GAIM-FP model rigorously evolves the ionosphere and plasmasphere electron density field and its associated errors using the full physical model. Advantages of this rigorous approach are expected to be most significant in data-sparse regions and during times of severe weather. Necessary approximations to make the model computationally tractable capitalize on the newest developments in oceanographic data assimilation. The model is based on a new physics-based model that is composed of an Ionosphere-Plasmasphere Model (IPM) that covers low and mid-latitudes. The new physics-based model includes six ion species (NO^+, O_2^+, N_2^+, O^+, He^+, H^+), ion and electron temperatures, and plasma drifts parallel and perpendicular to the geomagnetic field. These models use the International Geomagnetic Reference Field, which accurately describes the relative positions of the geographic and geomagnetic equators and the declination of the magnetic field lines. The physics-based model covers the altitude range from 90 to 30,000 km, which includes the E-region, F-region, topside ionosphere, and plasmasphere. Different data sources are assimilated via an ensemble Kalman filter technique and quality control algorithms are provided as an integral part of the model. The outputs of the GAIM-FP model are provided on user-specified altitude, latitude, and longitude grids; local horizontal grids as small as 25 × 25 km are also possible.

In practice, the resolution adopted depends on the data distribution, and runs are frequently conducted with a 7.5° longitudinal resolution and a 1–2° latitudinal resolution in the global mode. In the regional mode, spatial resolution can be 3.75° in longitude and 1° in latitude if there are sufficient data to warrant such a resolution. In altitude, the spatial resolution of the output is currently 4 km in the E-region and 10

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