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ScienceDirect
Advances in Space Research 42 (2008) 599–609
ADVANCES IN SPACE RESEARCH (a COSPAR publication)
www.elsevier.com/locate/asr

International Reference Ionosphere 2007: Improvements and new parameters

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Received 28 June 2007; received in revised form 25 July 2007; accepted 25 July 2007

Abstract

The International Reference Ionosphere (IRI), a joint project of URSI and COSPAR, is the de facto international standard for the climatological specification of ionospheric parameters and as such it is currently undergoing registration as Technical Specification (TS) of the International Standardization Organization (ISO). IRI by charter and design is an empirical model based on a wide range of ground and space data. It describes monthly averages of ionospheric densities and temperatures in the altitude range 50–1500 km in the non-auroral ionosphere. Since its inception in 1969 the IRI model has been steadily improved with newer data and with better mathematical descriptions of global and temporal variation patterns. A large number of independent studies have validated the IRI model in comparisons with direct and indirect ionospheric measurements not used in the model development. A comparison with IRI is often one of the first science tasks by an ionospheric satellite or rocket team.

This paper describes the latest version of the IRI model, IRI-2007, explaining the most important changes that are being introduced with this version. These include: (1) two new options for the topside electron density, (2) a new model for the topside ion composition, (3) the first-time inclusion of a model for the spread F occurrence probability, (4) a NeuralNet model for auroral E-region electron densities, (5) a model for the plasmaspheric electron temperature, and (6) the latest International Geomagnetic Reference Field (IGRF) model for the computation of magnetic coordinates including their changes due to the secular variation of the magnetic field.

Keywords: Ionosphere; IRI; Global ionospheric models

1. Introduction

The International Reference Ionosphere (IRI) project was initiated by the Committee on Space Research (COSPAR) and by the International Union of Radio Science (URSI) in the late sixties with the goal of establishing an international standard for the specification of ionospheric parameters based on all worldwide available data from ground-based as well as satellite observations. COSPAR and URSI specifically asked for an empirical model to avoid the uncertainties of the evolving theoretical understanding of ionospheric processes and coupling to the regimes below and above. COSPAR's main interest was and is in a general description of the ionosphere as part of the terrestrial environment for the evaluation of environmental effects on spacecraft and experiments in space. URSI's prime interest is in the electron density part of IRI for defining the background ionosphere for radiowave propagation studies and applications. To accomplish these goals a joint COSPAR-URSI Working Group was established in 1969 and tasked with the development of the model. Over the years the membership of this Working Group has grown to now 52 experts spanning the globe (see Fig. 1). The membership roster is characterized by a good balance in terms of measurement techniques and modeling teams. Through its members the IRI project has access to almost all of the important ionospheric data

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doi:10.1016/j.asr.2007.07.048

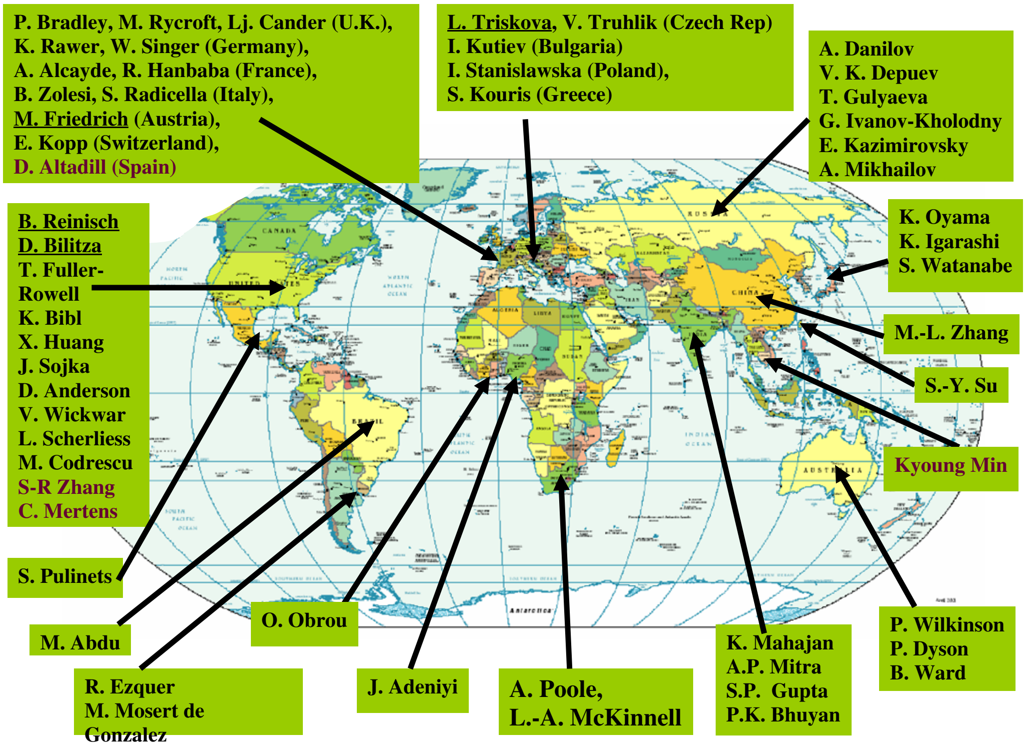

Fig. 1. Global distribution of IRI members including the newest members (red/gray) and the Steering Committee members (underlined). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this paper.)

sources, ground and space, nationally and internationally. Resolving conflicts between the results of different measurement techniques and providing guidelines regarding the reliability of the different data sources was and is an important task before the IRI team. The group has played an active role in setting guidelines for reliable D-region measurements and in assembling compilations of the most reliable rocket data for this region (Rawer, 1974; Friedrich et al., 2001; Friedrich and Torkar, 2001). The current IRI Steering Committee consists of B. Reinisch (Chair), L. Triskova (URSI Vice-Chair), M. Friedrich (COSPAR Vice-Chair), and D. Bilitza (Secretary).

The IRI model is continually upgraded as new data and new modelling approaches become available and this process has resulted in several major milestone editions of IRI (Rawer et al., 1978a,b, 1981; Bilitza, 1990, 2001; Bilitza and Rawer, 1996) progressing from a set of tables for typical conditions, to a global model for all phases of the solar cycle. More information about the IRI project including information about the IRI Newsletter and the IRI electronic mailer can be found on the IRI homepage at http://IRI.gsfc.nasa.gov/.

From early on the model was made available in electronic form as a FORTRAN program (ftp://nssdcftp.gsfc.nasa.gov/models/ionospheric/iri/) and more recently also as an interactive web interface accessible from the IRE homepage.

Annual IRI meetings are the prime venue for initiating and coordinating model improvements and new model developments. During years of COSPAR General Assemblies (even years, e.g., 2004, 2006) the meeting is held in the form of a special COSPAR session. In odd years (non COSPAR years) special week-long IRI Workshops are held organized by the IRI members in the workshop country. A list of meetings with links to meeting reports can be accessed from the IRI homepage. The reports give a good overview of the meeting activities and accomplishments. Progress of the IRI project is documented in a series of dedicated issues of Advances in Space Research with papers from these IRI meetings (for a list see IRI homepage). Papers from the IRI session during the 2004 COSPAR General Assembly in Paris, France were published as Volume 37, Number 5, 2006, and papers from the 2005 IRI Workshop in Ebro, Spain recently came out as Volume 38, Number 5, 2007. The workshop series continued in 2006 with an IRI-session during the COSPAR General Assembly in Beijing, China in July on the "Solar Activity Variations of Ionospheric Parameters" and a special IRI-GPS workshop in Buenos Aires, Argentina in October. The 2007 IRI workshop will be held in Prague, Czech Republic and is organized jointly with the European COST 296 project (see homepage at http://www.ufa.cas.cz/html/conferences/IRICOST2007/ which also provides access to all oral workshop presentations.

IRI describes monthly averages of the electron density, electron temperature, ion composition (O^+, H^+, N^+, He^+, O_2^+, NO^+, $Cluster^+$), ion temperature, and ion drift in the current ionospheric altitude range of 50–1500 km. An effort is underway to also include a measure of the ionospheric variability during the month in terms of a description of monthly quartiles and deciles. Being a data-based model, the accuracy of the model in a specific region and/or time period depends on the availability of reliable data for the specific region and time. One of the most important data sources for the IRI electron density is the worldwide network of ionosonde stations that has monitored the ionosphere with varying station density since the nineteen-thirties. IRI predictions are most accurate in Northern mid-latitudes because of the generally high station density in this part of the globe. At low and high latitudes ionospheric parameters show the steepest gradients, sharp peaks and deep valleys, e.g., density crests on both sides of the equator and a trough equatorward of the auroral oval, requiring a high station density to fully record and monitor the highly variable ionosphere. Unfortunately, both of these regions have rather sparse ionosonde coverage, partly because of the harsh climate conditions, and as a result the IRI predictions are less accurate at equatorial and auroral latitudes.

Besides the ionosonde network, other data sources for the model development include the incoherent scatter (IS) radars, several compilations of rocket measurements, and satellite data from in situ and topside sounder instruments. The IS radars measure all of the IRI parameters over the full altitude range, but only a few radars are in operation worldwide. Their data are essential for the description of variations with time, season, and solar activity, whereas the satellite data are a primary source for the description of the global morphology of ionospheric parameters. In the lower ionosphere the large neutral densities make radar and satellite measurements very difficult or impossible and rocket flights are the prime data source for IRI (Friedrich and Torkar, 2001; Danilov and Smirnova, 1995).

This paper introduces the newest version of the model, IRI-2007. describing the most important changes in the following chapters: (a) two new options for the topside electron density profile (Section 2), (b) a new model for the electron density in the auroral E-region (Section 3), (c) plasmaspheric electron temperatures are included for the first time (Section 4), a much improved model for the topside ion composition (Section 5), and for the first time a specification of spread F probability (Section 6).

2. Two new options for the topside electron density

For the electron density, recent IRI work has concentrated on the lowest (D and E-region) and on the uppermost (topside) part of the profile. The topside profile is of special importance because of its impact on the total electron content (TEC), which is the prime parameter needed for many ionospheric model applications. A number of studies have noted discrepancies between the IRI model and measurements, especially at high latitudes and during high solar activities. A detailed description of these shortcomings and of the ongoing efforts to improve the IRI topside model was recently published by Bilitza et al. (2006). At issue is an overestimation of electron densities in the upper topside (from about 500 km above the F-peak upward) that increases with altitude reaching about a factor of 3 at 1000 km above the peak (see Fig. 2, upper panel). The likely causes of this IRI artefact are (1) the limited data base used to develop the original IRI model, primarily Alouette 1 topside sounder data with some AE-C, and DE-2 in situ data and typical profiles from the Jicamarca incoherent scatter radar, and (2) an insufficient weighting of the low densities in the upper topside compared to the F-region densities, which are about an order of magnitude larger.

To overcome this shortcoming two new options are introduced in IRI-2007. The first is a correction factor for the 2001 model based on over 150,000 topside profiles from Alouette 1, 2, and ISIS 1, 2. This term varies with altitude, modified dip latitude, and local time (Bilitza, 2004). With this correction term the IRI model represents the topside sounder data quite well as shown in the bottom panel of Fig. 2. The resulting decrease in IRI TEC will help to

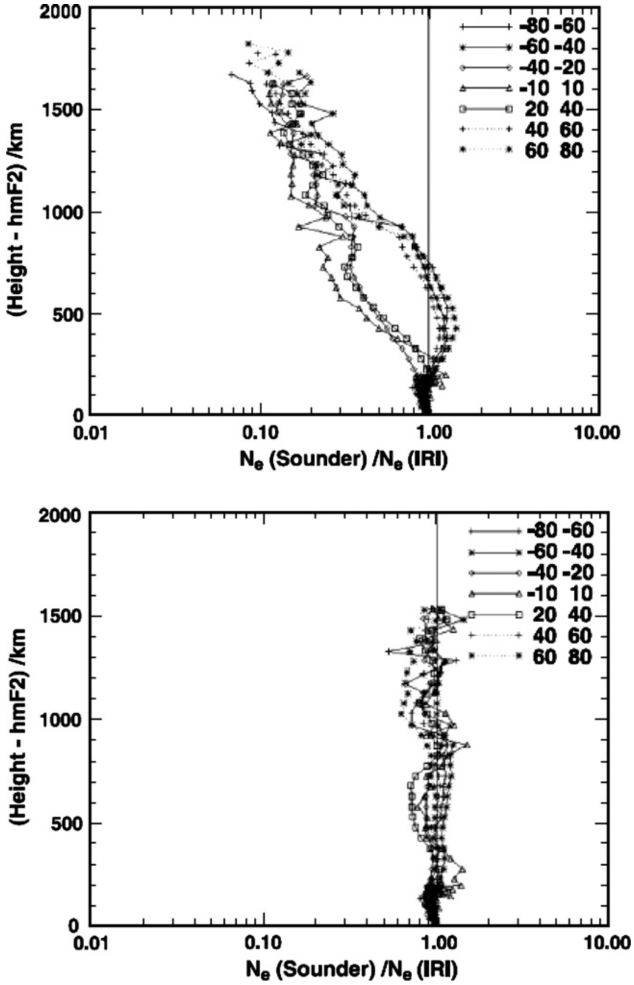

Fig. 2. Average ratio between the Alouette/ISIS sounder data and the IRI model at noon for different modified dip latitude ranges using the current IRI topside model (IRI-2001, top) and the corrected model (IRI-2007a, bottom). The model and data are normalized to the respective F-peak densities and heights (Bilitza, 2004).

overcome differences recently noted by Jee et al. (2005) in comparisons of IRI-2001 with TOPEX measurements. This option is called IRI-2007a in the rest of the paper.

The second option (IRI-2007b) is the NeQuick topside model that was developed by S. Radicella and his collaborators over the last decade (Radicella and Leitinger, 2001; Coisson et al., 2006) and is the most mature of the different proposals for the IRI topside that were described by Bilitza et al. (2006). The NeQuick topside model uses an Epstein-layer function with a height-dependent thickness (i.e., scale height) parameter and in this way produces a smooth transition from an atomic oxygen ionosphere near the F-peak to a light ion ionosphere higher up. The model parameters were determined based on fitting this function to ISIS 1, 2 and Intercosmos 19 topside sounder profiles. Comparisons with TOPEX TEC data have shown that NeQuick provides an improvement over the present IRI TEC predictions (Coisson et al., 2004). IRI uses the latest version of the NeQuick model as presented by Coisson et al. (2006).

In Fig. 3 the different topside options are compared with topside sounder measurements from ISIS-2. The observed topside electron density values are plotted versus the model values using IRI-2001 as well as the two new options. The panel for IRI-2001 shows the misrepresentation at high altitudes (i.e., low densities), and the other two panels illustrate that this is no longer a problem for IRI-2007. In Table 1 the standard deviations are listed for the different models for different topside sounder data sets including data from Alouette 1, 2, and ISIS 1, 2. In addition to IRI-2001 and the two new IRI-2007 options Table 1 also includes the model proposed by Triskova et al. (2006) based on Atmosphere Explorer and Intercosmos data and primarily intended for computing absolute ion densities in conjunction with their ion composition model (Triskova et al., 2003). But this model does not allow updating with the measured F-peak parameters and thus shows much larger discrepancies to the data than the new 2007 options.

The table and plots document the significant improvement in the topside electron density introduced with the new IRI-2007 topside models. Of the two new options the NeQuick option provides the better results for all four data sets.

Both new options will also provide for a smoother transition to plasmaspheric models, which in the past had problems connecting to the IRI (Gallagher et al., 2000), because IRI values at the ionosphere-plasmasphere boundary were much larger than the values from plasmaspheric models. A very promising new effort is the vary-Chap approach of Reinisch et al. (2007) that uses instead of the standard Chapman function with constant scale height, a slightly more complex Chapman-type function that is derived when assuming a height-varying scale height. The flexibility of the vary-Chap approach simplifies the merging of the IRI topside profile with a plasmaspheric model, as illustrated in Fig. 4. This is accomplished by adjusting the parameters that determine the height-varying scale height function including the transition height h_T that marks the transition

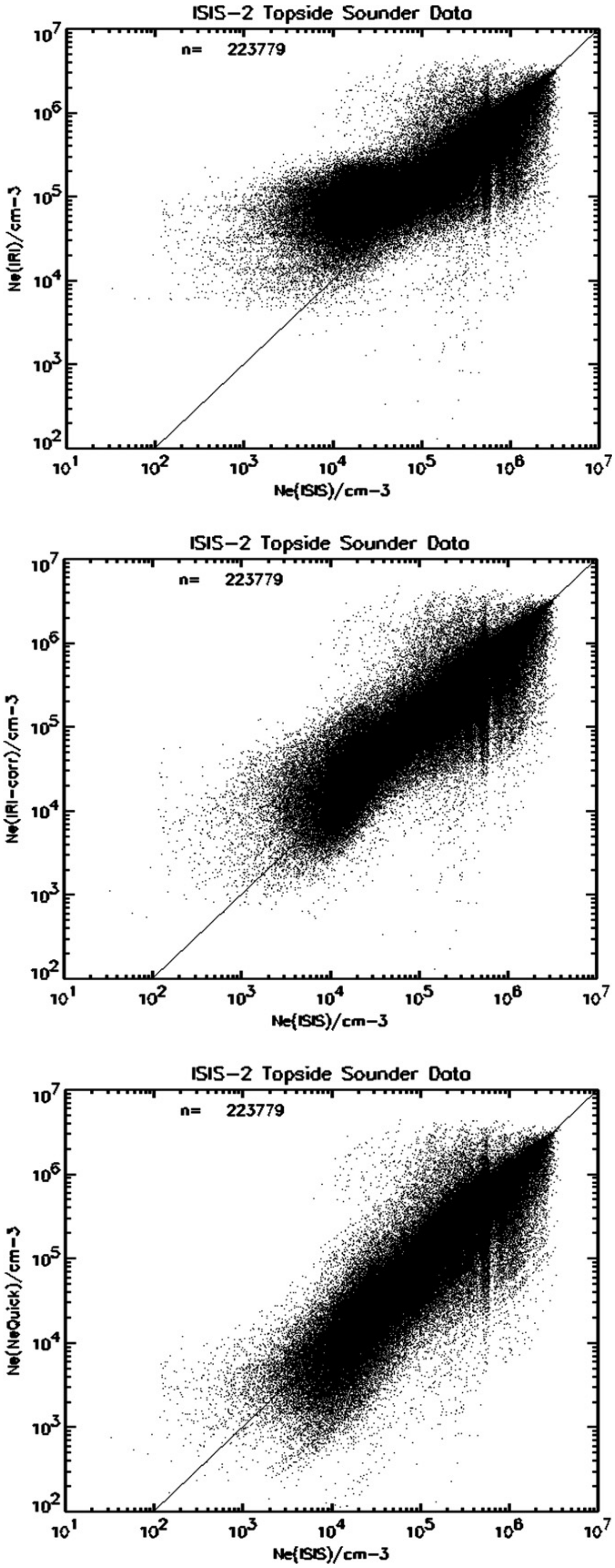

Fig. 3. A comparison of ISIS-2 topside sounder electron density data versus the model predictions by IRI-2001 (top panel), by IRI-2007a (middle), and by IRI-2007b (bottom). The number of data points is 223,779. Note the over-estimation by IRI-2001 at low densities (high altitudes).

Table 1
Mean and standard deviation (std) of the data-model differences [(data-model)/data] for the different Alouette and ISIS data sets (n = number of profiles)

	ISIS-2		ISIS-1		Alouette-2		Alouette-1u		Alouette-1p	
	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean
IRI	10.39	−2.12	7.44	−1.79	9.90	−2.23	4.50	−0.50	2.73	−1.01
cor	2.97	−0.61	2.72	−0.43	2.04	−0.38	2.44	−0.22	1.55	−0.41
NeQ	1.92	−0.31	1.74	−0.21	0.98	−0.04	1.96	−0.11	1.48	−0.36
TTS	8.32	−2.34	3.23	−0.76	4.58	−1.66	4.30	−0.99	3.69	−0.76
n	25,214		20,105		5166		19,434		12,900	

IRI, IRI-2001; cor, IRI-2007a; NeQ, IRI-2007b; TTS, Triskova et al. (2006) model.

from an oxygen-dominated ionosphere to light ion dominance and the scale height H_T at this transition point.

3. Electron density changes in the lower ionosphere

The IRI generally describes the E-region electron density well, but it does not yet include the ionization enhancement at auroral latitudes caused by precipitating particles. One of the new features in IRI-2007 is a Neural Network (NN) model for this auroral region that was trained with a large volume of EISCAT incoherent scatter data (~700,000 data points) and also with 115 profiles obtained from rocket borne wave propagation experiments (McKinnell et al., 2004; McKinnel and Friedrich, 2006). The model describes the density variations in terms of local magnetic time, riometer absorption, local magnetic index K, solar zenith angle, and atmospheric pressure, the later accounts for variations with height and season. The riometer absorption and K index track storm-related changes in the E-region. This modeling approach uses ground-based radio wave absorption measurements as the proxy to represent storm-time changes in the E-region. (Fig. 5). Absorption measurements are accessible online from a number of stations, e.g., data from the Finnish IRIS station are available at http://www.sgo.fi/Data/Riometer/.

For the non-auroral D-region IRI offers three different options: (1) the standard model based on a small selection of representative rocket profiles (Mechtley and Bilitza, 1974; Bilitza, 1981), (2) the FIRI model (Friedrich and Torkar, 2001; Friedrich et al., 2001) based on a compilation of rocket data with simultaneous radio propagation and in situ measurements, and (3) the Danilov et al. (1995) model based on a compilation of Russian rocket data not included in the FIRI set. A special feature of the Danilov model is the inclusion of representative profiles for conditions of Winter Absorption Anomaly and Stratospheric Warming. IRI offers three options for the D-region electron density to illustrate the large uncertainties that still exists in this altitude domain. Data are limited to the few locations where rockets can be launched or where incoherent scatter radars operate in the special mode required to measure D-region densities. Much more data from many

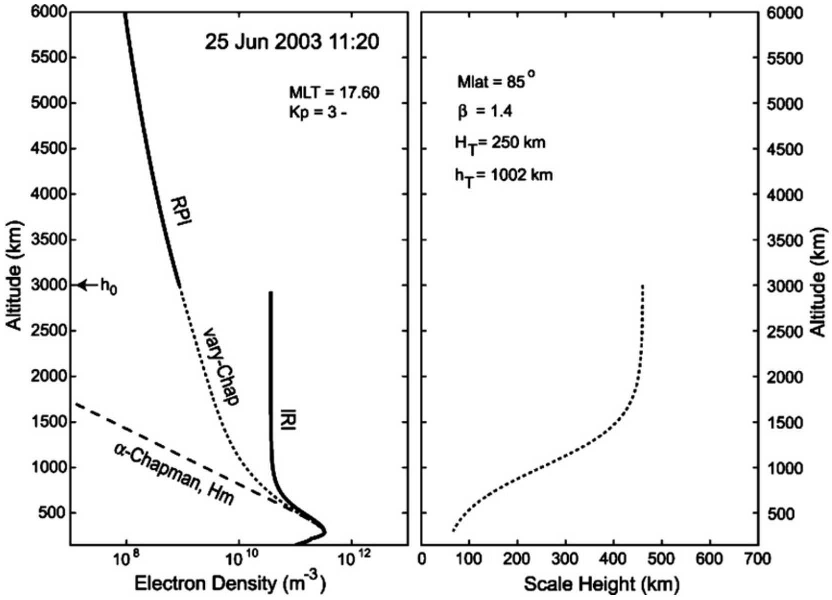

Fig. 4. Vary-Chap interpolation (dotted line) between the RPI plasmasphere model (Huang et al., 2004) and the IRI peak at a magnetic latitude (Mlat) of 85°N on Jun 25, 2003. Also shown is the α-Chapman profile with constant scale height that provides a good fit near the peak but is much too small higher up. The right panel shows the derived scale height function with the transition height $h_T = 1002$ km, a scale height $H_T = 250$ km at h_T, and a shape factor $\beta = 1.4$. (Reinisch et al., 2007).

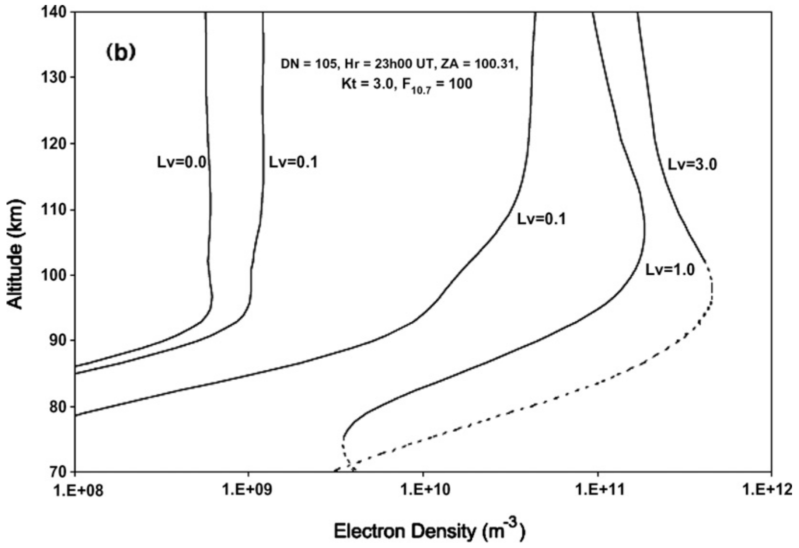

Fig. 5. IMAZ model profiles for auroral E-region density for different levels of riometer absorption L_v (McKinnel and Friedrich, 2006).

global positions are required to build a reliable global D-region model for all levels of solar activity for use in IRI. First E and D region profiles were recently obtained with the Jicamarca incoherent scatter radar and were compared with the three IRI options (Chau and Woodman, 2006). Good agreement was found with the FIRI and Danilov models. It was noted that densities in the E-region bottomside are smaller than predicted by the standard IRI model and that the FIRI model provides a better representation also of this region. The FIRI model formalism, however, is such that it cannot be normalized to an E-peak and thus it is difficult to continuously merge the FIRI model with the rest of the IRI profile. Beginning with IRI-2007 FIRI will therefore be provided as a standalone electron density model for the lower ionosphere (D- and E- region).

4. Plasma temperatures

Several new mission-specific plasma temperature models have been put forward at IRI meetings. These include the Hinotori T_e model at 600 km altitude and high solar activity of Oyama et al. (2004), the SROSS-C2 T_e model at 500 km and low solar activity of Bhuyan and Chamua (2006), the ROCSAT-1 T_i model at 600 km and high solar activity of Su and Yeh (2006) (all three are low-inclination satellites covering the low-latitude ionosphere), the Akebono T_e plasmaspheric model of Kutiev et al. (2002), and the Millstone Hill T_e, T_i radar models of Holt et al. (2002). The plasmaspheric model is now scheduled for inclusion in IRI-2007 as the first step towards extending IRI to plasmaspheric altitudes. The Akebono model was selected, because it is based on more than 13 years of measurements by the Thermal Electron energy Distribution (TED) instrument, far exceeding the database of other plasmaspheric models and because a general good agreement has been reported in comparisons with other data sources. Theoretical models also have relied heavily on the Akebono data to better understand plasmaspheric processes (see Kutiev et al. (2002) for references).

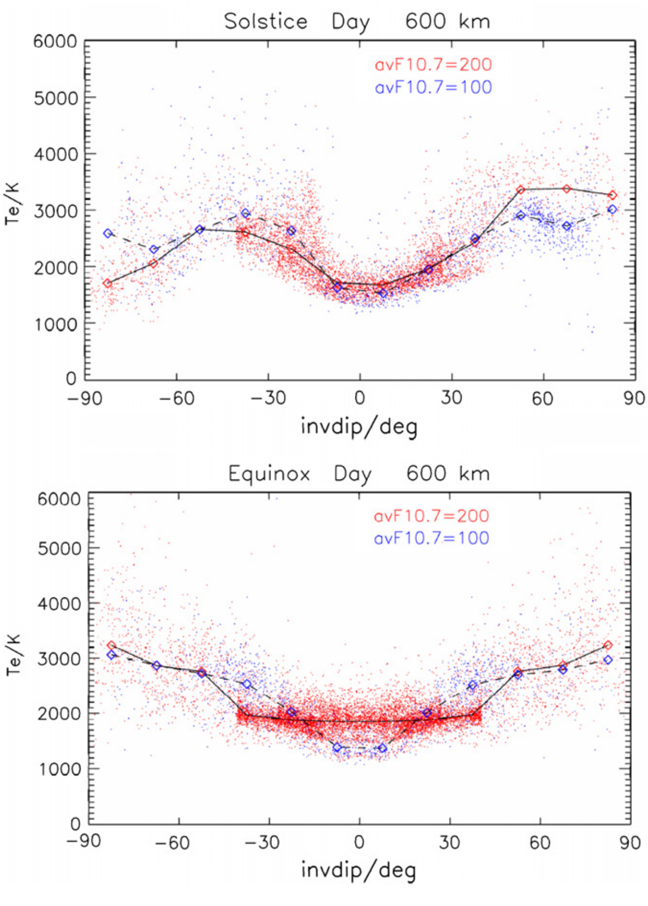

Fig. 6. Electron temperature from satellite database versus dip latitude for high (red) and low (blue) solar activity and for summer solstice (upper panel) and equinox (lower panel); the special invdip latitude is used here which is close to the dip latitude at middle and low latitudes and close to invariant latitude at higher latitudes; the solar index is the solar radio flux at 10.7 cm wavelength. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this paper.)

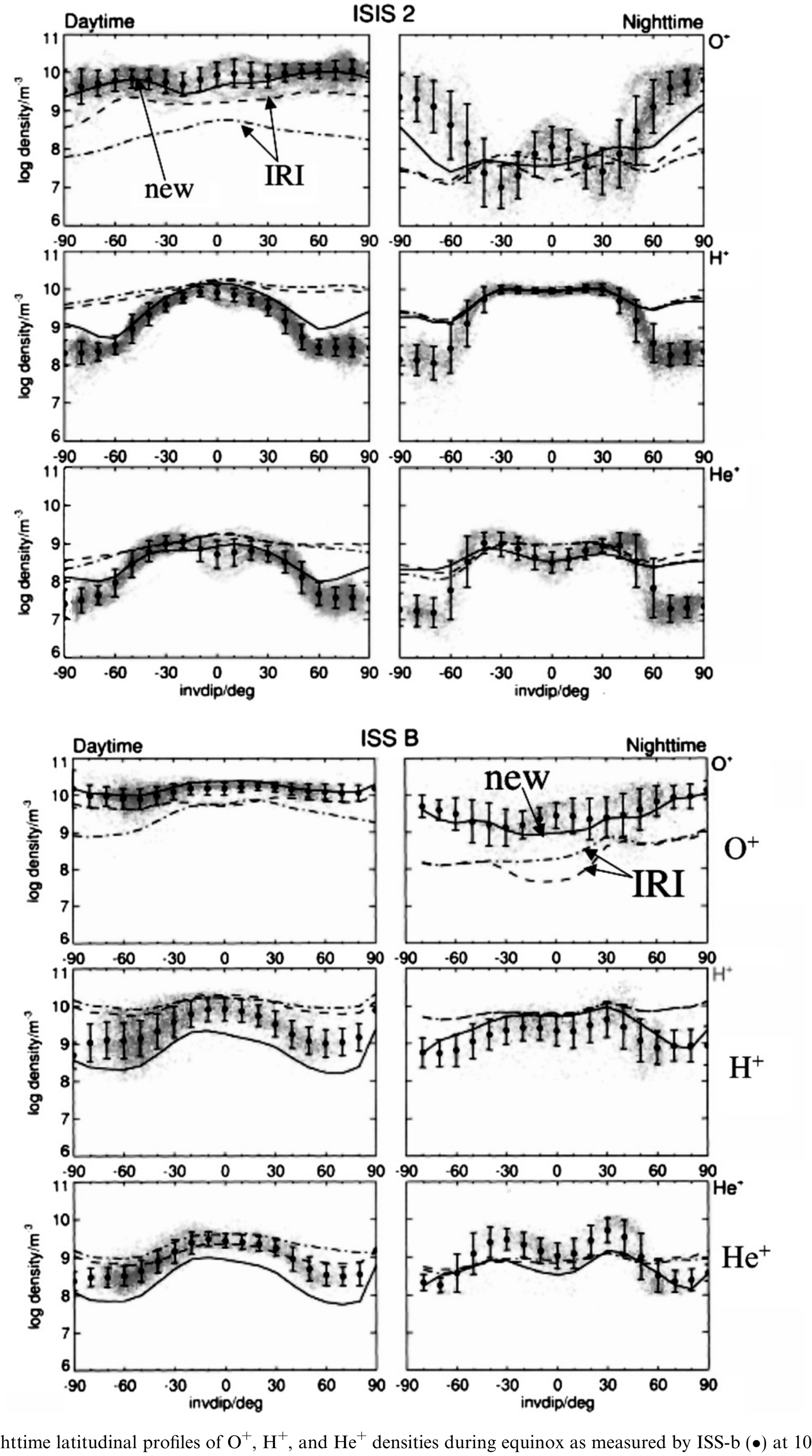

Fig. 7. Daytime and nighttime latitudinal profiles of O^+, H^+, and He^+ densities during equinox as measured by ISS-b (•) at 1000 km (top panel) and as predicted by the new IRI model (solid line) and by the earlier IRI standard (dashed line) and Danilov-Yaichnikov option (dash-dot line). The bottom panel shows a similar comparison for ISIS-2 at 1400 km also at equinox.

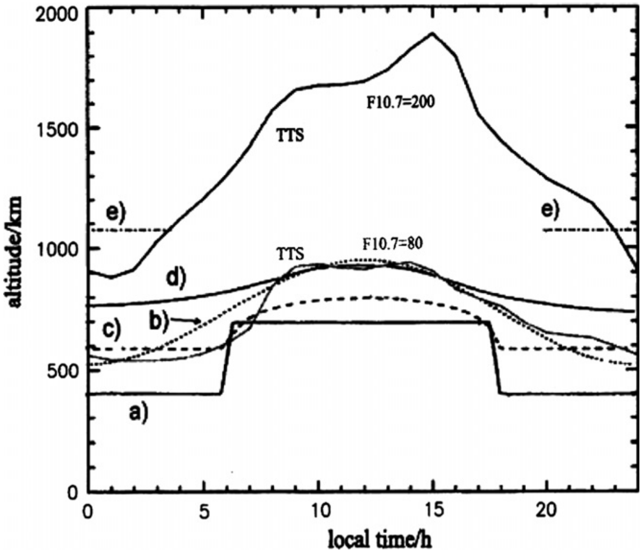

Fig. 8. Diurnal variation of the Upper Ion Transition Height as given by several models illustrating the large uncertainties in modelling this important parameter: (a) IRI standard model (see pp. 71–76 in Bilitza, 1990), (b) Danilov and Yaichnikov (1985), (c) Miyazaki (1979) model based on Taiyo in-situ measurements, (d) Kutiev et al. (1984) based on in-situ measurements from OGO-6, IC-2, Alouette-1, and ISS-b, (e) Intercosmos 13 model (Kutiev et al., 1994), and (f) the most recent model of Truhlik et al. (2004) (TTS) that includes variations with solar activity.

The IRI plasma temperature models currently do not explicitly include variations with solar activity. There is an implicit dependence because of the constraint $T_n \leqslant T_i \leqslant T_e$ where T_n is the CIRA (1988) neutral temperature which varies with solar activity. The ionospheric electron temperature indeed does show variation with solar activity but these variations are generally small compared to the significant increase observed for the electron density. This is easy to understand since both the heat gain and heat loss of the electron gas depend on electron density and thus both increase with increasing solar activity compensating each other and producing only a small net change in electron temperature. Incoherent scatter studies have shown that this change can be positive or negative depending on the season, altitude, and time of day. A systematic and global description of these dependencies for IRI requires a large data base and has to rely on satellite data since the ground-based T_e instrument, the incoherent scatter radar, exists only at a few locations worldwide. Such a database of satellite in situ measurements was recently assembled and first results were presented at the 2005 IRI workshop by Bilitza et al. (2007). In Fig. 6, T_e values from this database are plotted versus magnetic latitude for different levels of solar activity. At mid-latitudes T_e increases with solar activity in summer and decreases in winter and equinox. This is a result of the relative change of the heating and cooling terms over the solar cycle and is well reproduced by theoretical models. At low and equatorial latitudes the data show a small increase for solstice and a much larger increase for equinox. The causes of these seasonal differences near the equator are not clear yet and need to be investigated with theoretical models.

5. Ion composition

The ion composition model has traditionally been the weakest part of the IRI model because of the scarcity of well-calibrated global ion density measurements. The present IRI model is largely based on a compilation of Russian high-altitude rocket measurements of Danilov and Yaichnikov (1985) and Danilov and Smirnova (1995), and on a limited amount of incoherent scatter radar data. Working with the satellite in situ measurements from AE-C, -E, and Intercosmos 24, Triskova et al. (2003) have developed a new model for the ion composition in the topside ionosphere. Comparisons with other satellite data (e.g., ISS-b and ISIS-2 in Fig. 7) show that this new model performs much better than the old IRI model and it was therefore introduced as the new IRI ion composition model.

It is important to note that the IRI describes the ion composition and not the absolute ion densities. The ion composition is the percentage of the density of a specific ion versus the total ion density; charge neutrality means the total ion density is equal to the electron density. To get absolute ion densities one has to multiply the ion composition percentages with the electron density. This approach has the advantage that charge neutrality is easy to enforce and the disadvantage that the accuracy of the absolute IRI ion densities depends not only on the accuracy of the ion composition model but also on the electron density model (see Section 2).

The IRI team is also investigating modeling approaches that make use of the upper and lower transition heights since these are the most characteristic parameters of the ion composition profile (Bilitza and Kutiev, 1990). The lower height marks the point of 50% O^+ and 50% molecular ions, whereas the upper height is determined by 50% O^+ and 50% light ions (H^+, He^+). A number of recent modeling studies (e.g., Marinov et al., 2004; Webb et al., 2006) have used newly available Alouette and ISIS topside sounder data (Huang et al., 2002; Bilitza et al., 2003, 2004) to deduce the global and diurnal variations patterns of the upper transition height and to develop models for this important parameter. However, large discrepancies remain between the different models as shown in Fig. 8 largely due to the different databases used.

6. Other changes (Spread F and IGRF 10)

The IRI-2007 version will for the first time include a model for the occurrence probability of spread F. This will be a regional model for the Brazilian longitude sector based on the work of Abdu et al. (2003) using ionosonde observations in Brazil. The model describes the variations of the probability with latitude, local time, day of year, and solar activity. Fig. 9 shows that the spread F model repro-

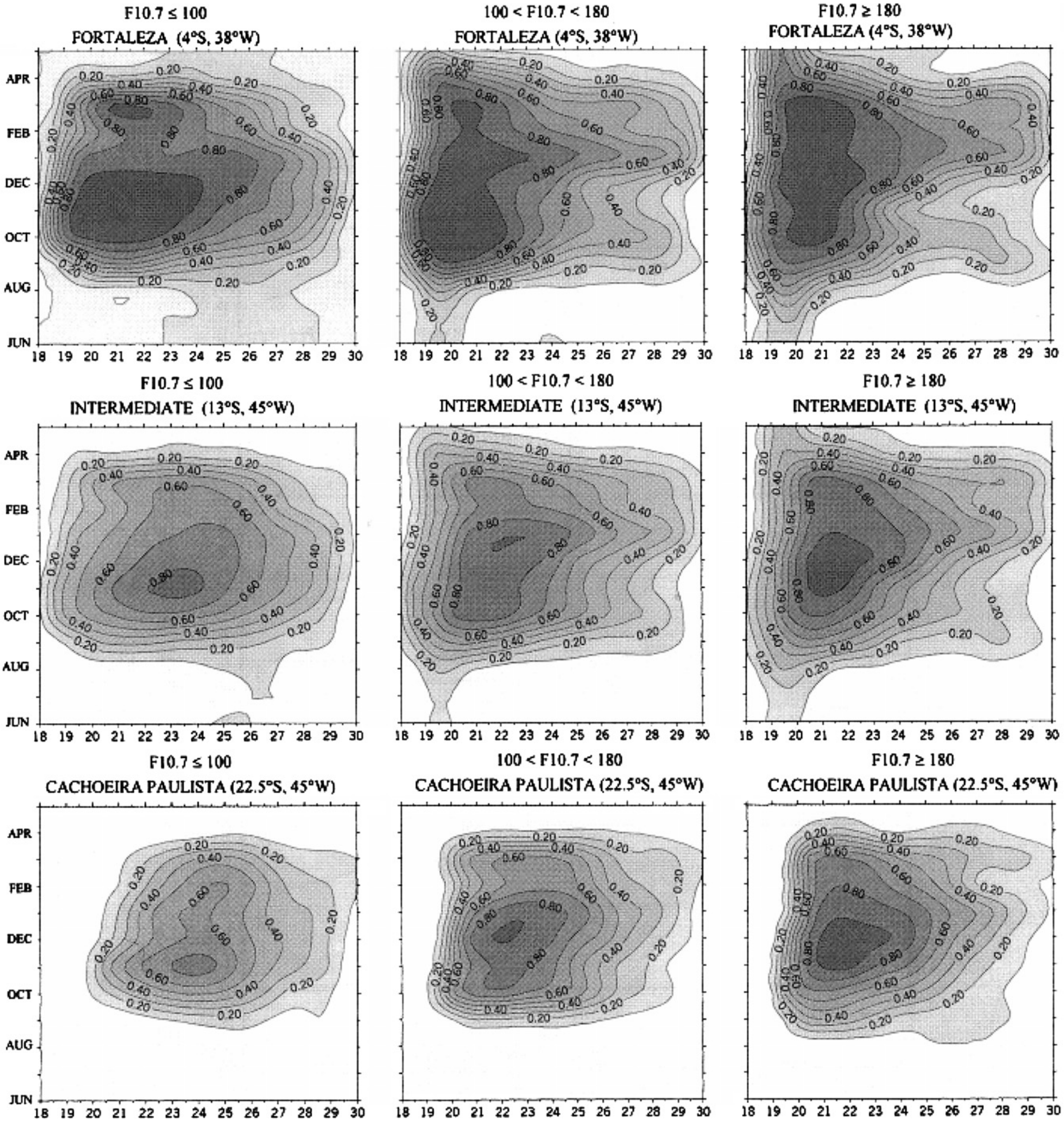

Fig. 9. Probability of spread F as a function of Local Time (x-axis: LT = 25 is same as LT = 1 AM) and month at the Brazilian ionosonde stations Fortaleza (upper row) and Cachoeira Paulista (lower row) and an intermediate latitude (middle row) for different levels of solar activity (below F10.7 = 100 – left column, above F10.7 = 180 – right column, and in-between – middle column (Abdu et al., 2003). Illustrating the fact that spread F is primarily a winter night phenomenon and probabilities increase with solar activity.

duces the well-known fact that this phenomenon is primarily observed near the magnetic equator at nighttime during September through April. Efforts are underway to model the global occurrence statistics with the help of topside sounder data and by combining existing models for the Brazilian and Indian longitude sectors.

The magnetic field model in IRI was updated to the latest generation (10) of the International Geomagnetic Reference Field (IGRF) (see homepage at http://www.ngdc.noaa.gov/IAGA/vmod/). The IGRF model is used to compute the magnetic field coordinates needed by the IRI model including dipole coordinates as well as magnetic latitude, dip latitude, modified dip latitude, and invariant latitude. For all coordinates the long-term (secular) change of the magnetic field is taken into account.

7. Summary

This paper presents the latest version of the widely used International Reference Ionosphere (IRI) model, describing the various improvements and additions that led to this latest version. Several ongoing IRI activities are briefly described. All are directed towards future improvements of the IRI model, most importantly a new approach to modelling the topside and plasmaspheric electron density and work towards the inclusion of solar activity variations for plasmas temperatures. The IRI is a truly international project with contributions from scientists from all parts of the globe. This wide range of activities has made the IRI the international standard for ionospheric parameters and a registration process with the International Standardization Organization (ISO) is currently underway (ISO website).

The IRI Fortran software can be obtained from the solar-terrestrial models archive of NASA's Space Physics Data Facility and National Space Science Data Center at http://nssdcftp/models/ionospheric/iri/iri2007/. A web interface for computing and plotting IRI values is accessible from the IRI homepage at http://IRI.gsfc.nasa.gov.

Acknowledgements

The data and services of NASA's Space Physics Data Facility (SPDF) and National Space Science Data Center (NSSDC) have contributed greatly to the success of the IRI effort. The work reported here was support by NSF Grant 0417666 and NASA Grant 05-LWS05-161.

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