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Space Weather Effects Produced by the Ring Current Particles

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Abstract One of the definitions of space weather describes it as the time-varying space environment that may be hazardous to technological systems in space and/or on the ground and/or endanger human health or life. The ring current has its contributions to space weather effects, both in terms of particles, ions and electrons, which constitute it, and magnetic and electric fields produced and modified by it at the ground and in space. We address the main aspects of the space weather effects from the ring current starting with brief review of ring current discovery and physical processes and the Dst-index and predictions of the ring current and storm occurrence based on it. Special attention is paid to the effects on satellites produced by the ring current electrons. The ring current is responsible for several processes in the other inner magnetosphere populations, such as the plasmasphere and radiation belts which is also described. Finally, we discuss the ring current influence on the ionosphere and the generation of geomagnetically induced currents (GIC).

Keywords Inner Earth's magnetosphere · Ring current · Space weather

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1 Introduction

The concept of space weather includes the effects imposed by the time-varying space environment which may be hazardous to technological systems in space and/or on the ground and/or endanger human health or life. One of the important regions where these variations of space environment matter in the Sun-Earth system is the inner Earth's magnetosphere. There a lot of satellites fly and there even rather quiet times are full of dynamical processes. The ring current is one of the populations in the inner magnetosphere consisting of ions and electrons with energies of a few to hundreds of keV. The ring current energies are rather far from the ultra-relativistic energies of "killer electrons" which are especially hazardous and can penetrate even the most protected satellites in space or from the MeV and GeV energies of solar energetic particles and galactic cosmic rays which can come very close to the Earth. At the same time, the ring current has rather significant influence in terms of space weather effects.

The ring current has several distinct contributions to the space weather effects, both in terms of particles, ions and electrons, which constitute it, and magnetic and electric fields produced and modified by it at the ground and in space. Ring current is a significant contributor to the Dst-index which, in its turn, can be used as an indicator, a measure and a predictor of geomagnetic storms. Ring current keV electrons are responsible for surface charging effects on satellites. The ring current dynamics including electric and magnetic field distortions due to this dynamics is tightly related to the radiation belts and plasmasphere populations in the inner magnetosphere. The storm-time ring current has several space weather effects on the ionosphere and thermosphere via influencing on the rearranging of the ionospheric density and heating the thermosphere. The ring current contributes to the Geomagnetically Induced Currents (GIC) effects via its role in the generation of Region 2 field-aligned currents.

There have been numerous reviews on the ring current formation, dynamics and decay and reviews on space weather. While reviews of space weather effects have examined the influence of the ring current, none of them specifically focused on the ring current as a source of space weather effects. The present review addresses the space weather effects from the ring current particles compiled into a single place and avoids repetitions of the general ring current physics. The goal of this review is to stress the importance of the ring current being an inner magnetosphere population with rather moderate energies as compared to the high energy electrons and protons present in the Earth's magnetosphere. The specifics of the ring current particles can result in the space weather effects which are rather extreme without the occurrence of the extreme geomagnetic conditions. Even a presence of a moderate storm is not necessary for significant surface charging event to happen, for example.

This review is an output of "The Scientific Foundation of Space Weather" Workshop which was held during 27 June–1 July 2016 at the International Space Science Institute, Bern, Switzerland. In the following Sect. 2, we start with a very brief review of ring current discovery and physical processes. The Dst-index, the role of the ring current in producing it and predictions of the ring current and storm occurrence based on the Dst-index are presented in Sect. 3. Section 4, the heart of the review, details the space weather effects of the ring current. This begins with the effects on satellites produced by the ring current electrons (Sect. 4.1). The processes in other inner magnetosphere populations, such as the plasmasphere and radiation belts controlled by the ring current, are described in Sect. 4.2. Then, in Sect. 4.3, we discuss the ring current influence on the ionosphere and generation of geomagnetically induced currents (GIC). Finally, the ring current space weather effects are summarized in Sect. 5.

2 Ring Current in the Earth's Magnetosphere: Brief Review

The ring current is one of the oldest concepts in magnetospheric physics (see the historical review by Egeland and Burke 2012). A current flowing around the Earth was first introduced by Störmer (1907) and supported by Schmidt (1917). Chapman and Ferraro (1931, 1941) used a ring current concept for the model of a geomagnetic storm. The ring current can be described in a simplified way as a toroidal shaped electric current, flowing westward around the Earth with variable density at geocentric distances between 2 and 9 R_E. Note that we use "ring current" here with a broad definition that includes any inner magnetospheric westward or eastward current that is either symmetric or not in local time. In fact, the symmetric ring current is often dominated by the partial ring current during magnetic storms (e.g., Takahashi et al. 1990; Liemohn et al. 2001b; Mitchell et al. 2001). Ring current consists of ions and electrons with energies covering the range from about 1 to 400 keV. The main ion species are H^+, O^+, and He^+ (see the recent review by Kronberg et al. 2014, where the observations and modeling of ion circulation and effects in the ring current dynamics were presented, and references therein). The intensity of quiet time ring current is about $\sim 1\text{–}5\ \mathrm{nA/m^2}$ (Lui and Hamilton 1992), which can be as large as $50\ \mathrm{nA/m^2}$ during storm times (e.g., Vallat et al. 2005), although there is some debate about this (Liemohn et al. 2016). Although, the early measurements of the ring current particles were made onboard OGO 3 (e.g., Frank 1967), Explorer 45 (e.g., Smith and Hoffman 1974) and CRRES missions (e.g., Grande et al. 1997; Friedel and Korth 1997), the first mission, which clarified the detailed picture of the ring current energy and composition was the AMPTE mission of the late 1980s (e.g., Lui et al. 1987; Lui and Hamilton 1992; De Michelis et al. 1997). Extensive observations of the ring current were done by the most recent Van Allen Probes mission (e.g., Yu et al. 2014; Zhao et al. 2015; Gkioulidou et al. 2016; Kistler et al. 2016; Shi et al. 2016; Menz et al. 2017).

Inner magnetosphere current density can be measured in several ways. They include (1) direct measurements of ion and electron current densities, (2) particle measurements which can provide the plasma pressure and the current itself can be estimated from it, (3) multi-point magnetic field measurements and computing the current density from the curl of magnetic field, (4) remote sensing of energetic neutral atoms (ENAs) emitted from the ring current (for more detailed description of these methods, see the recent reviews by Ganushkina et al. (2015b) and Lühr et al. (2017) and references therein and the commentary by Dunlop et al. 2016).

Two main sources for the ring current particles are the terrestrial ionosphere and the solar wind. Particles from both of them populates the plasma sheet, therefore, it is an important source of the ring current (see the reviews by Ebihara and Ejiri 2003; Daglis 2001, 2006; Kronberg et al. 2014; Ebihara 2016 and references therein). Plasma sheet particles move inward when acted upon by time-varying electromagnetic fields. There are still open questions regarding this process, especially, for storm times, such as, whether substorm-associated magnetic field variations and the associated (inductive) electric fields are necessary for the buildup of the ring current energy density. While there are arguments that large-scale convection alone can account for the ring current increase, other studies have concluded that energization of ring current particles to energies over 100 keV requires smaller-scale, time-varying electric fields (see one of the earliest studies on this subject by Kim et al. 1979 and more recent reviews by Daglis and Kozyra 2002; Ebihara and Ejiri 2003; Kozyra and Liemohn 2003; Ganushkina 2005; Ebihara and Miyoshi 2011; Bourdarie et al. 2016; Ebihara 2016 and references therein).

The concept of the partial ring current and its closure to the ionosphere was suggested by Alfvén in 1950's. One of the earliest observational evidences were given based on OGO

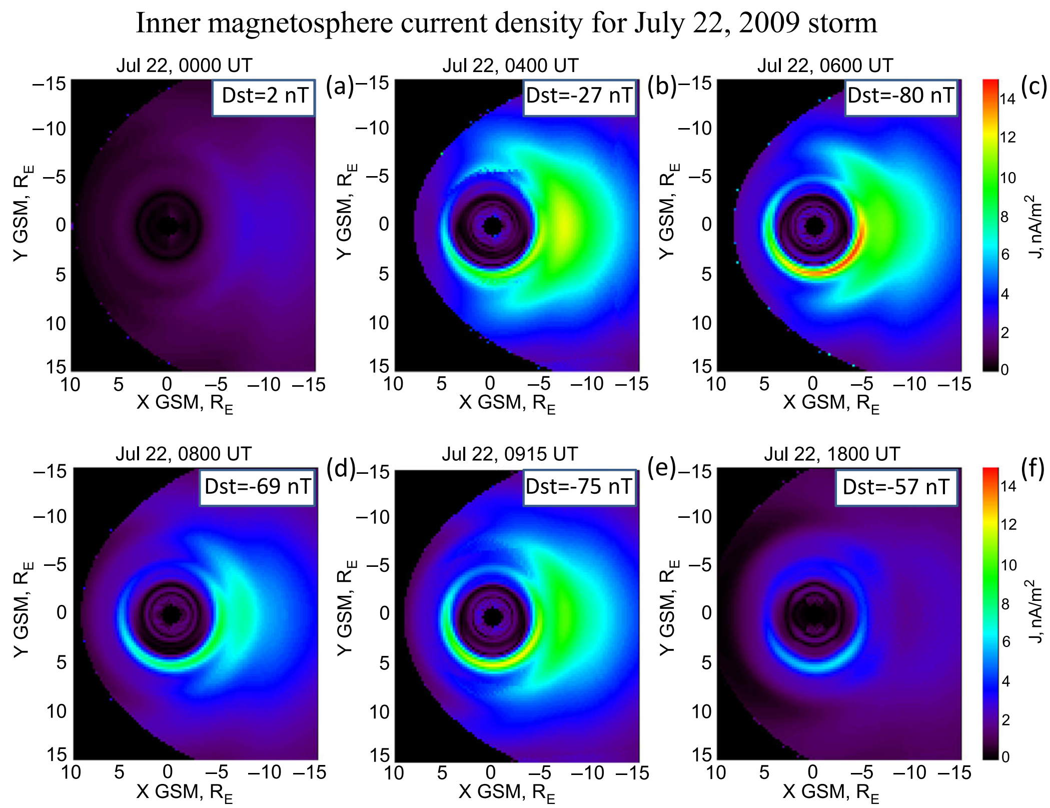

Fig. 1 Evolution of the inner magnetosphere current density in the equatorial plane computed from the curl of the magnetic field modeled with the Tsyganenko T02 global magnetospheric magnetic field model (Tsyganenko 2002a,b) during the storm event on July 22, 2009

3 measurements (Frank 1970). The magnetosphere is essentially asymmetric, compressed by the solar wind dynamic pressure on the dayside, and stretched by the tail current on the night-side. Plasma pressure distribution during disturbed times (storm times) becomes highly asymmetric due to plasma transport and injection from the night-side plasma sheet to the inner magnetosphere. The resulting plasma distribution presents a gradient in the azimuthal direction resulting in the spatial asymmetry of the ring current. The remnant of the perpendicular current must flow along a field line to complete a closure of the current (see the reviews by Ebihara and Ejiri 2003; Kozyra and Liemohn 2003; Ebihara and Miyoshi 2011; Ganushkina et al. 2015b).

Figure 1 presents an illustration on the storm time ring current dynamics. It demonstrates the distribution of the inner magnetosphere current density in the equatorial plane modeled with the Tsyganenko T02 global magnetospheric magnetic field model (Tsyganenko 2002a,b) during the storm event on July 22, 2009. The current densities of the inner magnetosphere current were computed from the curl of the model magnetic field using the Ampère's law with Maxwell's extension. Before the storm at 00 UT when Dst was 2 nT (Fig. 1a), a relatively symmetric ring current can be seen at distances inside 5 R_E and the near-Earth part of the tail current is present at distances of 10–15 R_E. The Dst becomes negative (−27 nT) at 04 UT and the ring current intensifies with the storm development (Fig. 1b) and becomes asymmetric with its peak shifted duskward at the storm maximum with Dst = −80 nT (Fig. 1c) at 06 UT. The July 22, 2009 event was a moderate storm. The increased tail current is also evident, although with lower current densities. During the storm recovery phase at 08 UT (Dst = −69 nT), the ring current density decreases (Fig. 1d), but remains asymmetric. There was a second Dst-index drop to about −75 nT at 0915 UT which can be clearly seen as a new intensification of the ring current (Fig. 1e). The July 22, 2009 storm had a long recovery phase, therefore, close to the end of the day at 18 UT when Dst was −57 nT (Fig. 1f), the ring current symmetrized but it was still not fully symmetric and its current density decreased but not to the non-disturbed level. This is rather typical storm-time evolution of the ring current.

Ring current ions are lost due to several loss mechanisms (for a recent comprehensive review, see Ebihara and Miyoshi 2011). Charge-exchange between energetic ring current ions and neutral exospheric hydrogen is thought to act as a dominant loss. Through this process, energetic ions colliding with neutral exospheric gas may acquire an electron from the cold neutral atom and become neutralized. Convection outflow occurs when a particle intersects the magnetopause, flows away along magnetosheath magnetic field lines and is lost from the ring current region. In the magnetosphere, the ring current particles experience Coulomb interaction with the thermal plasma in the plasmasphere. They transfer energy to the plasmaspheric plasma due to collisions (Coulomb drag) and some of them are also scattered into the loss cone (their pitch angle changes so that they can be lost in the atmosphere). Although classical collisional processes provide the dominant loss process for ring current ions, two classes of plasma waves are able to interact with ring current ions, namely, electromagnetic ion cyclotron (EMIC) waves and magnetosonic waves. This wave-particle interaction results in the pitch angle scattering which contributes to ion loss, especially during the main phase of a storm. For ring current electrons, charge-exchange is not a loss process. The main losses are Coulomb interactions, convection outflow and wave-particle interactions which are most important. Ring current electrons interact mainly with chorus waves observed outside the plasmasphere and hiss waves inside the plasmasphere.

This section gave a brief introduction to the ring current and the major physical processes controlling it. For additional details of ring current structure, dynamics and physics, please see the numerous reviews cited above.

3 Dst-Index as a Storm Indicator, Measure and Predictor

It has long been known that the horizontal component, H, of the geomagnetic field is depressed during periods of great magnetic disturbances and that the recovery to its average level is gradual. In 1741 Celsius observed a large magnetic disturbance in Uppsala, Sweden, and Graham observed the same in London, England, simultaneously. These large magnetic field disturbances were called "magnetic storms", and were shown to be non-local. Gauss and Weber founded a network of ground-based magnetic observatories expanded by the British and Russians. It was soon found that magnetic storms are worldwide phenomena. Much later, Akasofu and Chapman (1961), Kamide and Fukushima (1971), Kamide (1974) concluded that the near-equatorial ground disturbance of the magnetic field is a measure of the ring current. Sugiura (1964) and Iyemori (1990) used the averaged magnetic field depression observed at low latitudes to derive the Dst-index.

If the ring current and the Dst-index are directly related and the Dst-index serves as an indicator of a storm activity going on in the magnetosphere, the Dst-index can also serve as a predictor of a future storm occurrence. Therefore, it is useful to predict the Dst-index itself. The ability to predict storm occurrence by predicting of the Dst-index can greatly facilitate the prediction of many storm-related space weather effects. The Dst-index is computed from the observations of the ground-based magnetic field. To be able to achieve the goal of Dst-index prediction, models are necessary and these models need to be in the form of operational tools which can be further developed into forecasting tools.

There are several approaches for modeling the Dst-index. One of them is to use models which provide the magnetic field everywhere in the Earth's magnetosphere and on the ground. These models include the semi-empirical models based on the large amount of magnetic field data with specific representations of current systems in them, like the Tsyganenko models (see the review by Tsyganenko 2013 and http://geo.phys.spbu.ru/~tsyganenko/modeling.html). The most recent model version (Tsyganenko and Andreeva 2015) is intended to forecast the magnetospheric magnetic field using an optimal solar wind coupling function. A very different approach is to use the large volume of magnetic field data for reproducing the detailed structure of the magnetosphere as was done within the TS07 model (Tsyganenko and Sitnov 2007). This approach is somewhat similar to the modelling of the internal geomagnetic field with higher-order harmonics in the scalar potential expansion and it is based on extensible high-resolution expansions for the field of the equatorial current sheet. Early models of the magnetospheric magnetic field used such a method (for example, Mead and Fairfield 1975). Most recently, Andreeva and Tsyganenko (2016) and Tsyganenko and Andreeva (2016) also developed a model without a priori assumptions about the geometry of the magnetic field sources by splitting the model magnetic field into the toroidal and poloidal parts and then expanding each part into a weighted sum of radial basis functions. The Dst-index from these magnetic field models can be computed following the same procedure as for the real Dst-index using the magnetic field modeled at the locations of real Dst low-latitude stations at the Earth's surface as it is done at the World Data Center for Geomagnetism, Kyoto, Japan (http://wdc.kugi.kyoto-u.ac.jp/dstdir/dst2/onDstindex.html).

Global magnetohydrodynamic (MHD) models provide the magnetic field in the magnetosphere and on the ground and they are also used to compute the Dst-index. The detailed analysis of several MHD models' performance to calculate the Dst-index was presented in the study of Rastätter et al. (2013) which resulted from the 2008–2009 Geospace Environment Modeling (GEM) challenge defined at the 2008 GEM workshop. Two quiet and two disturbed events were selected for modeling. The three-dimensional MHD models of the magnetosphere coupled to an ionosphere electrodynamics solver evaluated were (1) the Space Weather Modeling Framework (SWMF) (Tóth et al. 2005, 2012), (2) the Open Geospace General Circulation Model (OpenGGCM) (Raeder et al. 2001), and (3) the Coupled Magnetosphere-Ionosphere-Thermosphere (CMIT) model, also referred to by the magnetospheric Lyon-Fedder-Mobarry (LFM) component (Lyon et al. 2004; Wiltberger et al. 2004). The contributions from the magnetospheric and ionospheric currents were taken into account in the Biot-Savart's integration for the approximation of the Dst-index by the North-South component of the perturbation magnetic field δB_Z (in SM coordinates) at the Earth's center location (for details, see Rastätter et al. 2013). Another challenge was focused on the reproducing the magnetic field variations at the ground-based stations (Pulkkinen et al. 2010, 2011, 2013; Rastätter et al. 2014). As a result of these challenges, the NOAA Space Weather Prediction Center (SWPC) added the SWMF to the operational forecasting tools. The real-time Dst-index together with the observed one is displayed at http://www.swpc.noaa.gov/products/geospace-global-geomagnetic-activity-plot. None of the other models are operational at present.

Another type of tools is particle, or kinetic, models (brief descriptions of the existing ring current models are give below in Sect. 4.1). From kinetic models, the Dst-index is very often obtained using the Dessler-Parker-Sckopke (DPS) relationship (Dessler and Parker 1959; Sckopke 1966). The DPS relation connects the total energy in the ring current and the change in the ground magnetic field strength. This perturbation can be considered as a rough equivalent to the Dst-index if it is assumed (Carovillano and Siscoe 1973) that it is close to the perturbation averaged around the equator of the Earth. The DPS relation was used in numerous studies for Dst-index estimates from modeling and observations and related ring current dynamics (e.g., Greenspan and Hamilton 2000; Ebihara and Ejiri 2000; Fok et al. 2001b; Jordanova et al. 2012; Ganushkina et al. 2012; Katus et al. 2015; Zhao et al. 2015). However, the Dst-index contains contributions from many other sources than the azimuthally symmetric ring current and their contributions can be significant or even largest during disturbed conditions. The suggested magnetospheric sources include (1) magnetopause currents, (2) cross-tail current, (3) partial ring current, and even (4) substorm current wedge (see the review by Maltsev 2004 and references therein) and also studies by Friedrich et al. (1999), Munsami (2000), Ohtani et al. (2001), Liemohn et al. (2001a,b), Liemohn (2003), Ganushkina et al. (2004, 2010), Kalegaev et al. (2005). The magnetic field measured on the ground contains contributions from all current systems and there is no other way to separate them but to use magnetospheric models. The 2008–2009 GEM Dst challenge (Rastätter et al. 2013), in addition to MHD models, included two kinetic ring current models, Ring Current-Atmosphere Interactions Model with Self-Consistent Magnetic Field (RAM-SCB) (Jordanova et al. 2010; Yu et al. 2011) and the Rice Convection Model (RCM) (Toffoletto et al. 2003). The Dst-index from these models was estimated by the DPS relation.

In addition to the DPS relation, the Biot-Savart's law is used to calculate the magnetic disturbance parallel to the Earth's dipole at the center of the earth induced by the azimuthal current component given by the modeled magnetospheric currents within the modeling region. Calculating the model Dst-index by the Biot-Savart's law instead of the DPS relation in nondipolar magnetic field gives larger and more realistic values, since, for example, the effect from the near-Earth tail current is included by the presence of the stretched magnetic field lines (e.g., Liemohn 2003; Ganushkina et al. 2012; Jordanova et al. 2012). None of the kinetic models with the Dst-index as an output is operational and run online in real-time. The main challenge for predicting of the Dst-index and, subsequently, storm occurrence and strength is the absence of reliable predictions of Interplanetary Magnetic Field (IMF) and solar wind parameters, days in advance. These parameters are the main drivers of global empirical and MHD magnetospheric models and kinetic magnetospheric models.

There is also a very different way to predict the Dst-index which does not include any magnetospheric modeling. Different kinds of empirical relations were obtained for the solar wind parameters and the Dst-index. One of the earliest is the relation between changes in Dst-index and the rate of ring current injection as a function of a delayed and filtered solar wind electric field and solar wind dynamic pressure derived by Burton et al. (1975). Following Burton et al. (1975), further corrections and improvements using general relation between the energy balance for the ring current given as the rate of energy input into the ring current and the decay time and DPS relation were done in later studies (e.g., Murayama 1986; Gonzalez et al. 1994; Thomsen et al. 1998; Klimas et al. 1998; Fenrich and Luhmann 1998; O'Brien and McPherron 2000; Wang et al. 2003). The model of this type which is run online in real time is the Dst forecast model by Temerin and Li (2006) at the Laboratory for Atmospheric and Space Physics (LASP, USA) (http://lasp.colorado.edu/space_weather/dsttemerin/dsttemerin.html). The Dst-index is calculated as a sum of several terms (Temerin and Li 2002, 2006). The first three terms are similar that their driver terms depend strongly on a negative IMF B_Z-component. They differ from each other by their decay terms. The next term is the pressure term which is proportional to the square root of the solar wind dynamic pressure and it is usually assumed to represent the magnetopause currents. The direct IMF B_Z term depends on the angle of the dipole with respect to the solar wind velocity. The last term in the offset term which does not depend on the IMF and solar wind parameters and can compensate for a portion of the secular and annual variation in the Dst index.

Other techniques for Dst-index predictions include the usage of neural networks, with delayed inputs, with feed-back connections (e.g., Lundstedt and Wintoft 1994; Lundstedt et al. 2001; Watanabe et al. 2002; Pallocchia et al. 2006; Bala and Reiff 2012; Dolenko et al. 2014; Lu et al. 2016). Bala and Reiff (2012) use the solar wind-magnetosphere coupling function, the Boyle index (Boyle et al. 1997), which is an empirical approximation for the polar cap potential dependent on solar wind parameters, as basis functions to train an artificial neural network to predict the Dst-index. These predictions are shown in real time at http://mms.rice.edu/realtime/forecast.html as 1, 3, and 6 hours ahead. Another operational model is the Lund Dst model (Lundstedt et al. 2001, 2002) run at the Swedish Institute of Space Physics (IRF-Lund, Sweden) at http://www.irfl.lu.se/rwc/dst/. This model is also based on a recurrent neural network that has been optimized to be as small as possible without degrading the accuracy and it is driven by the hourly averages of the IMF B_Z-component, solar wind number density and velocity. A similar approach is used for the Dst-index predictions (Dolenko et al. 2014) available at the Skobeltsyn Institute of Nuclear Physics Moscow State University (SINP MSU, Russia) at http://swx.sinp.msu.ru/models/dst.php?gcm=1.

Yet another method includes the models based on linear moving average (MA) filters or linear auto-regressive moving average (ARMA) filters, or similar (Vassiliadis et al. 1999) and the nonlinear auto-regressive moving average model with exogenous inputs (NARMAX) applied to Dst-index (Boynton et al. 2011a; Beharrell and Honary 2016). For example, the NARMAX algorithm (Leontaritis and Billings 1985a,b) is an advanced system identification technique, similar to neural networks, which can be applied for linear and non-linear systems with physically interpretable parameters. Boaghe et al. (2001) applied the NARMAX algorithm and derived a model for the Dst-index using vBs with v as the solar wind velocity and Bs as the southward IMF component as the input. Boynton et al. (2011a) developed a model for the Dst-index using NARMAX with a different coupling function according to Boynton et al. (2011b) as an input. The advantage of this type of models is that the output of the model at a specific time can be represented by rather simple polynomial function of the previous values of inputs, outputs, and error terms (Beharrell and Honary 2016). At present, these types of models are in great demand, since they can give exact (though perhaps not always accurate) values at some time moments in a future.

Ji et al. (2012) compared the outputs from six Dst-index forecast models during intense geomagnetic storms, namely, Burton et al. (1975), Fenrich and Luhmann (1998), O'Brien and McPherron (2000), Wang et al. (2003), Temerin and Li (2006), and Boynton et al. (2011a) models. They found that the Temerin and Li (2006) model gives most reasonable results. The 2008–2009 GEM Dst challenge (Rastätter et al. 2013) also included Burton-type representations (Burton et al. 1975; Murayama 1986), NARMAX model (Boynton et al. 2011a), and Rice Dst model (Bala and Reiff 2012). All of the models showed very reasonable results, NARMAX model (Boynton et al. 2011a) was specifically mentioned.

This brief over-review of Dst prediction methods is indented to give readers an understanding of the various types of models in existence and, in particular, those running online and in real time. These models can be used as an estimate of ring current intensity and, therefore, the severity of the possible space weather effects of the ring current, which will now be discussed.

4 Space Weather Effects Related to the Ring Current

4.1 Ring Current Electrons and Effects on Satellites

Electrons with energies less than 100 keV are one of the important constituents of the ring current. Their contribution has been studied starting from the early observations of the ring current. Based on the analysis of the low-energy (<50 keV) electron and proton fluxes onboard the OGO 3 satellite, Frank (1967) showed that the electron component may provide about 25% of the ring current energy during storm times. Liu et al. (2005) analyzed Explorer 45 electron data for energies from 1 to 200 keV and found the electron contribution of about 7.5% during quiet time and about 19% during storm time. Contribution of electrons to the ring current energy content based on the recent Van Allen Probes measurements was estimated to be about 10% of the ions during storm main phase (e.g., Zhao et al. 2016).

The electron fluxes at these keV energies vary significantly with the current activity on the scale of minutes or even shorter. They can be responsible for surface charging effects which is a serious risk for satellites (e.g., Garrett 1981; Lanzerotti et al. 1998; Koons et al. 1999; Whipple 1981; Davis et al. 2008). The electrons with energies of 10's of keV do not penetrate deep into the satellite materials but stay near the surface. Secondary electrons are generated due to the interactions between the surface materials and both the incident plasma and the solar UV. The satellite's surface materials will be charged in order to have the zero net current between the surfaces and the plasma. Therefore, the surface will have nonzero voltages. Usually, the sunlit areas of the satellite's surface are positive and the shadowed areas are negative. For the conducting surfaces, the potential of the surface is uniform for reaching the equilibrium for zero net current. For insulating materials, this equilibrium can be only on several points on the surface.

Electrons have higher speeds, so they constitute the main source of initial plasma current to a satellite. The currents of photo and secondary electrons from a surface are often higher than the plasma electron current to it. If the average electron energy in the surrounding plasma is larger than 1 keV, the regions of a satellite in shadows will be charged negative to significant potentials (several kilovolts). In the dense plasma also the sunlit regions of a satellite can charge to significant levels. Secondary and photoelectron currents are different for different materials. Therefore, there is a wide range of surface potentials. The differences in potential between adjacent materials can cause the local electrical stress resulting in vacuum arcs. Surface materials can also discharge into space or to structure ground. The resulting electrostatic discharge (ESD) currents can electromagnetically couple into electronic circuits and subsystems, causing damage.

Typically, most satellite anomalies due to surface charging at geostationary orbit occur at night and early dawn (e.g., Fennell et al. 2001; Gubby and Evans 2002; O'Brien 2009). During substorms, a hot plasma is injected from the magnetotail into the nightside inner regions. They perform the gradient and curvature drifts towards dawn. These newly injected electrons can cause significant changes in the satellite charging levels.

When an anomaly occurs, the radiation environment may be more extreme than that given by the specification models used for design. However, data may not be available at the location of the satellite to fully determine the cause of the anomaly. Therefore, there is a need for physical models with the correct dynamical behavior that can be used to reconstruct the radiation environment. To determine the impact of an extreme space weather event on satellites, we need to define the space radiation environment for different orbits. This can be done by using a combination of physical models and in-situ observations.

Significant surface charging events can happen during rather undisturbed conditions, like small, isolated substorms (e.g., Ganushkina et al. 2013; Matéo-Vélez et al. 2016). Occurrence of a storm, even a moderate one, can be not directly related to the occurrence of the surface charging. The electron flux at the keV energies is largely determined by convective (Korth et al. 1999; Friedel et al. 2001; Thomsen et al. 2002; Elkington et al. 2004; Miyoshi et al. 2006; Kurita et al. 2011; Jordanova et al. 2016) and substorm-associated (Vakulin et al. 1988; Grafodatskiy et al. 1987; Degtyarev et al. 1990; Fok et al. 2001a; Khazanov et al. 2004; Kozelova et al. 2006; Ganushkina et al. 2013; Yu et al. 2014; Turner et al. 2015) electric fields. Since it varies on short time scales, it is not possible to average the keV electron fluxes over an orbit/day/hour as it can be done for higher energies, like MeVs. This makes the modeling of keV electron flux variations very challenging.

When modeling using physics-based models (kinetic models for the ring current), it is necessary to follow keV electrons in large-scale, time-varying magnetic and electric fields. Even though there exist several models, the correct models for these fields are extremely hard to develop. Electrons in the inner regions come from the plasma sheet where specification of a realistic boundary conditions is very nontrivial. The question of how to introduce losses for low energy electrons is still open. Here, the issue about the importance of other waves, apart from chorus and hiss, in the pitch angle scattering resulting from wave-particle interactions is still unclear. Finally, the most important factor in the electron dynamics is substorms which play a significant role in keV electron transport and energy increase. Their proper modeling has not been done yet.

Fluxes of low-energy electrons have been modeled in several studies as a part of ring current simulations. One of the widely used inner magnetosphere models is the ring current-atmosphere interactions model (RAM) (Jordanova et al. 1996) mentioned above in Sect. 3. Jordanova and Miyoshi (2005), Miyoshi et al. (2006), and, more recently, Jordanova et al. (2014) extended the RAM model to relativistic energies and electrons investigating the effect of magnetospheric convection and radial diffusion during the October 2001 geomagnetic storm and later for October 2012 storm (Jordanova et al. 2016). This model is part of the SHIELDS project of Los Alamos National Laboratory (http://www.lanl.gov/projects/shields/index.php).

Chen et al. (2006) performed magnetically self-consistent ring current simulations during the 19 October 1998 storm calculating the ion and electron transport in the equatorial plane using the kinetic proton and electron drift-loss model (Chen et al. 1994) coupled to the force-balanced representation of the magnetic field intensity (Chen et al. 2005).

Another widely used inner magnetosphere model is the Rice Convection Model (RCM), also mentioned above in Sect. 3, which describes plasma electrodynamics in the inner and middle magnetosphere and its coupling to the ionosphere (see the review by Toffoletto et al. 2003 and references therein). The Rice Convection Model Equilibrium (RCM-E) (Lemon et al. 2004) combines the drift physics computing the bounce-averaged relativistic drifts of isotropic electrons and ions with a model of equilibrium magnetic field in a force balance with the RCM-computed pressures. In addition to magnetic self-consistency, the particle transport is also self-consistent with the electric field. This model was used for the assessing of the different electron loss models for the model's ability to reproduce the observed electron fluxes of 1.2 keV to 925 keV measured by LANL 1994-084 satellite during the large 10 August 2000 magnetic storm (Chen et al. 2015).

These studies were focused on the application to specific events. The models are not run online in real time. Taking into account the space weather effects requires models run in near real time, when no changes can be made and the models are supposed to perform reasonably well for wide range of geomagnetic conditions, not just for specific storm events.

The model which is run online at the Community Coordinated Modeling Center (CCMC) (http://ccmc.gsfc.nasa.gov/index.php) in near real time is Fok Ring Current Model (FRC). This is a bounce-averaged kinetic model which calculates the temporal and spatial variation of the phase space density of ring current species, including electrons in the energy range of 1–300 keV (Fok and Moore 1997; Fok et al. 1999, 2001b). The model inputs are the solar wind driven outputs of the global MHD modeling provided in near real time by the Space Weather Modeling Framework (Tóth et al. 2005, 2012). 3D magnetic fields, as well as equatorial plasma density and temperature are obtained from the global magnetosphere SWMF GM/BATSRUS model (Powell et al. 1999; De Zeeuw et al. 2000) and 2D ionospheric height-integrated potentials are given by the ionospheric electrodynamics SWMF IE/RIM model (Ridley et al. 2001, 2004). Equatorial plasma density and temperature are used to set the boundary conditions in the plasma sheet for electrons, which move inward in the provided magnetic and computed from the ionospheric potentials electric fields. The model output given as the electron fluxes as functions of time, energy and pitch angle for different keV energy ranges in the equatorial plane is presented. At the same time, no real time comparison with the observations is shown.

A variation of the FRC model is the Comprehensive Inner-Magnetosphere Ionosphere (CIMI) model which also calculates the temporal and spatial variation of the phase space density of electrons in the energy range of 1–4000 keV (Fok et al. 2011, 2014). Instead of MHD-related inputs, this model has different inputs based on empirical models. For 3D magnetic fields, it employs Tsyganenko magnetospheric magnetic field T96 (Tsyganenko 1995) and T04 (Tsyganenko and Sitnov 2005) models. Weimer (2005) representation for ionospheric electric potentials at the model's poleward boundary at 70.3° magnetic latitude is used to set up the electric field. The initial distribution for electrons is set according to the empirical model of AE8 (Vette 1991). Boundary conditions in the plasma sheet are specified by the empirical plasma sheet models (Ebihara and Ejiri 2000; Borovsky et al. 1998; Tsyganenko and Mukai 2003). This model also provides the equatorial electron fluxes as functions of time, energy and pitch angle but it is not run in real time with no comparison with the observations.

The model which runs online in real time and which outputs are directly compared to the real time observations for low energy (<200 keV) electrons is Inner Magnetosphere Particle Transport and Acceleration model (IMPTAM) (Ganushkina et al. 2013, 2014, 2015a). IMPTAM operates online (imptam.fmi.fi) under the completed FP7 SPACECAST and SPACESTORM projects (http://fp7-spacecast.eu, http://www.spacestorm.eu/) funded by the European Union Seventh Framework Programme and under the on-going H2020 PROGRESS project (https://ssg.group.shef.ac.uk/progress2/html/) funded by the European Union's Horizon 2020 research and innovation programme. Its mirror site is also at the Center for Space Environment Modeling (CSEM) at the University of Michigan (http://csem.engin.umich.edu/tools/imptam). The driving parameters are determined by the models used in IMPTAM. The T96 model (Tsyganenko 1995) is used for the external magnetic field and the Boyle et al. (1997) polar cap potential mapped to the magnetosphere is used for the electric field. The model boundary is set at 10 R_E as a kappa electron distribution function with parameters given by the Tsyganenko and Mukai (2003) empirical model with necessary scaling for electrons. The solar wind and IMF parameters which drive the IMPTAM are solar wind density N_{SW}, dynamics pressure P_{SW}, velocity V_{SW}, IMF B_Y, B_Z, and total IMF strength. The model provides the low energy electron flux at all L-shells and at all satellite orbits, when necessary. Real time geostationary GOES 13 or GOES 15 (whenever which available) MAGED data on electron fluxes at three energies (40, 75, and 150 keV) are used for comparison and validation of IMPTAM running online (Ganushkina et al. 2015a). IMPTAM provides nowcast of keV electrons comparable to the observations.

A purely empirical model for ion flux and electron flux in the energy range ∼1 eV to ∼40 keV at geosynchronous orbit (GEO) was developed by Denton et al. (2015, 2016, 2017) based on a total of 82 satellite-years of observations from the Magnetospheric Plasma Analyzer instruments on Los Alamos National Laboratory satellites (http://gemelli.spacescience.org/mdenton/). The model provides the electron flux values at any energy and local time for given values of the 3-hour Kp-index or solar wind electric field ($-vB_z$). The Kp version of the model also provides flux values for given values of the daily F10.7 index. The limited number of driving parameters makes this model not suitable for fast variations of keV electrons. Even though the model is called empirical, no equations are provided which can be easily used to relate electron flux at a specific energy with the driving parameters.

A very different approach is used in the SNB3GEO models (Balikhin et al. 2011; Boynton et al. 2015, 2016) based on Multi-Input Single-Output (MISO) Nonlinear AutoRegressive Moving Average with eXogenous inputs (NARMAX) methodologies (Leontaritis and Billings 1985a,b). In the applied system identification approach, models are automatically deduced from input-output data by the system identification algorithms. NARMAX is capable of modeling nonlinear dynamics within the system and can provide a simple polynomial function with intuitive understanding of how the inputs change the output. The model is run online in real time at the University of Sheffield Space Weather Website (http://www.ssg.group.shef.ac.uk/USSW/UOSSW.html) and under the H2020 PROGRESS project (https://ssg.group.shef.ac.uk/progress2/html/index.phtml) funded by the European Union's Horizon 2020 research and innovation programme. The model inputs are the solar wind velocity, density and pressure, the fraction of time that the IMF was southward, the IMF contribution of a solar wind-magnetosphere coupling function following Boynton et al. (2011b) and the Dst-index. The model output is the fluxes for 30–50 keV, 50–100 keV, 100–200 keV, 200–350 keV and 350–600 keV directly compared to the GOES MAGED observations at geostationary orbit. This model also contains a forecast. For low energy electrons, it is not possible to forecast one day ahead because the same day variations in the solar wind affect the current low energy electron flux. Boynton et al. (2016) calculated the past 24 hour averages for each hour and, therefore, the input time lags in the algorithm were shifted hourly, not daily. It is stated that the model provides accurate forecasts with prediction efficiencies ranging between 66.9% and 82.3%. At the same time, smaller-scale variations are not forecasted but they constitute the most important factor when trying to estimate the surface charging effects from keV electron variations.

None of the models has explicit representation for substorms which are a crucial factor in the transport and acceleration of keV electrons. There have been several studies aimed at the modeling of electron injections as they are well-known signatures of a substorm in the near-Earth space (Li et al. 1998; Zaharia et al. 2000; Sarris et al. 2002; Gabrielse et al. 2012, 2014, 2016; Ganushkina et al. 2013, 2014). These models give relatively good agreement with the observed dispersionless electron injections at geostationary orbit during specific events (Ingraham et al. 2001; Fok et al. 2001a; Li et al. 2003; Mithaiwala and Horton 2005; Liu et al. 2009). The substorm-associated electromagnetic fields are very complex and their proper representation is still missing from the modeling efforts for keV electrons in the inner magnetosphere. No technique is implemented yet to include substorm influence on modeled fluxes in real time.

Ring current electrons in the keV energy range represent a real threat to equatorially orbiting spacecraft. In the midnight-to-dawn sector, fresh injections can intensify the low-energy electron fluxes and cause surface charging, sometimes with detrimental effects. Several models exist which nowcast or forecast these electrons, providing at least some level of awareness about this population. The critical influence of substorms on the near-Earth keV electrons, however, has not yet been fully implemented into a real time and online prediction tool.

4.2 Ring Current and Inner Magnetosphere Populations

4.2.1 Ring Current and Radiation Belts

The ring current is often thought of as a lower-energy part of the outer radiation belt that surrounds Earth in a toroidal shape. However, these are really two distinct populations with very different dynamics and responses to solar wind forcing (e.g. Schulz and Lanzerotti 1974; Liemohn 2006; Reeves et al. 2016). Naturally, there does exist a coupling between the two energy regimes, as they overlap in spatial extent most of the time. In fact, a very significant influence of the ring current on radiation belt losses during the main and recovery phases of geomagnetic storms (e.g. Ukhorskiy et al. 2015).

The first effect is related to the diamagnetic consequences of a partial ring current that develops during storms. Inflation of the near-Earth magnetic field due to ring current changes (e.g. Parker and Stewart 1967; Tsyganenko et al. 2003; Ganushkina et al. 2010) alters the drift paths of the relativistic electrons in the radiation belts, causing the adiabatic "Dst effect" (e.g. Kim and Chan 1997), which can become a real loss of particles at the magnetopause (e.g. West et al. 1972; Hudson et al. 1998; Ukhorskiy et al. 2006). This process has been identified as contributing rapid loss for up to 90% of the pre-existing population of both radiation belt electrons (100's keV to multi-MeV) energies and energetic ring current protons (100's keV to >1 MeV) (Turner et al. 2014).

The second effect is due to pitch angle scattering of relativistic electrons via wave-particle interactions. The notable mode here is electromagnetic ion-cyclotron (EMIC) waves, since these waves are able to very efficiently interact with high-energy radiation belt electrons (Summers et al. 1998; Meredith et al. 2003), and are driven by unstable ring current proton distributions (Anderson and Hamilton 1993). The anisotropy required for EMIC wave growth is fueled by ring current proton injections, which are convected inward to the inner magnetosphere during intervals of enhanced storm and substorm activity (e.g. Young et al. 1981; Jordanova et al. 2001). Recent simulations combined with the data from the Van Allen Probes (Mauk et al. 2013), the mission specifically designed for radiation belts, have demonstrated the dramatic effect on >1 MeV electron pitch angle distributions that EMIC waves can have (see, for example, Usanova et al. 2014). While this study did not find a clear way for EMIC waves to produce a full dropout of the core electron population, the flux levels were reduced substantially at lower pitch angles, indicating significant precipitation. Electron precipitation can have impacts on human society at the ground level, as well as terrestrial weather and climate systems (e.g. Rodger et al. 2010). Cutting edge models need to incorporate radiation belt losses from both of these effects: loss to the outer boundary of the magnetosphere via magnetopause shadowing and loss from atmospheric precipitation due to EMIC wave scattering.

Radiation belt enhancement and acceleration events are likewise tied to ring current dynamics. Local acceleration can provide significant acceleration of electron populations in the heart of the outer belt. The process is generated by VLF whistler-mode chorus waves, which grow as a result of a temperature anisotropy in few-10s keV electrons (Helliwell 1967) likely caused by substorm injections (Tsurutani and Smith 1974; Meredith et al. 2001). This anisotropic population of ring current energy electrons is often called the "seed" population, wherein the source of the free energy for chorus wave growth is available. Chorus waves interact with "seed" electrons at energies of 10's to 100's of keV through cyclotron resonance and can accelerate electrons to very high energies (Kennel and Petschek 1966; Kennel and Thorne 1967; Li et al. 2008, 2012; Thorne 2010). Whistler-mode chorus plays a critical role in accelerating ring current electrons to relativistic energies in the outer belt (Horne et al. 2005; Green 2006; Chen et al. 2007), including to "killer" electron energies that can have disastrous space weather consequences to sensitive systems (Baker 2001; Fennell et al. 2001).

4.2.2 Ring Current and Plasmasphere

The ring current overlaps the cold, dense plasmasphere surrounding Earth, with the center peak of the ring current typically co-located with the plasmapause boundary (Kozyra et al. 1997; Burch et al. 2001). The ring current can effect the shape of the plasmasphere (e.g. Goldstein et al. 2003; Liemohn et al. 2004; Gallagher et al. 2005), and the location of the plasmapause boundary, thereby sculpting the energy-dependent radiation belts and influencing electron precipitation to the atmosphere and locations of enhanced spacecraft charging.

Enhanced convection during geomagnetically active times leads to erosion of the plasmasphere such that the boundary contracts throughout local times (e.g. Nishida 1966), although a high-density plume can form on the duskside of Earth (e.g. Brice 1967; Carpenter 1970; Spasojević et al. 2003). Drainage plumes may also form, allowing direct transport of plasmaspheric particles to the outer magnetosphere (Grebowsky 1970; Chen and Wolf 1972; Rasmussen et al. 1993; Goldstein et al. 2004). Additionally, sub-auroral polarization streams (SAPS) can contribute to the erosion of the plasmasphere on very fast timescales (Gonzales et al. 1978; Burke et al. 1998; Foster and Vo 2002; Califf et al. 2016). During storm time, ring current injections influence the near-Earth electric field (Jaggi and Wolf 1973; Fok et al. 2001a) to the extent that the ionospheric convection pattern is affected which has space weather effects on human technologies such as GPS signal processing (Yeh et al. 1991; Foster et al. 2002).

The variation of plasmaspheric dynamics contribute to distinct consequences that effect the ring current population. First is the myriad roles of wave-particle interactions. When the plasmasphere begins to refill after a period of erosion to low radial distances, the outward expansion of the sharp density boundary once it overlaps the inner edge of the ring current can trigger lower hybrid wave growth (Roth and Hudson 1992). These waves can then accelerate low-energy ring current ions. Another effect is the growth of whistler-mode chorus waves much closer to Earth during an eroded plasmasphere, which will both scatter and accelerate a range of ring current electrons and ions. One more effect is the growth of EMIC waves in plasmaspheric plumes (Posch et al. 2010), which are triggered by ring current proton anisotropies. The existence of a high-density plume can encourage EMIC wave growth, which can contribute to losses of the "killer electrons" at ultra-relativistic energies (Horne and Thorne 1998). Finally, VLF hiss waves, which exist inside the dense plasmasphere, can produce a slow and steady loss of ring current electrons and protons (Thorne et al. 1973; Kozyra et al. 1994).

The position of many of these wave-particle interactions depends on the dynamics of the plasmasphere and plasmapause boundary. The location of the plasmasphere therefore effects where in space, and on the ground, many space weather consequences of the ring current are localized. Modeling of the plasmasphere, ring current, and associated plasma waves are essential for comprehensively defining the space weather environment.

4.3 Ring Current and Ionosphere and Below

The ring current not only influences the near-Earth magnetosphere with space weather consequences, but also alters the ionosphere and thermosphere. This is done through closure of the partial ring current and the generation of strong ionospheric flows. Inner magnetospheric plasma populations are often highly asymmetric in local time during active times, which creates localized pressure peaks and corresponding field aligned currents (FACs) at the two ends of the pressure crescent (Wolf 1970; Fok et al. 2001b; Liemohn et al. 2001a). These region 2 FACs become current source and sink regions in the ionosphere, where horizontal currents flow to close the circuit. The resulting horizontal electric fields in the ionosphere can be drastically different than the "standard" closure of the region 1 FACs, especially near the equatorward edge of the auroral zone and at subauroral latitudes. They are often poleward electric fields associated with a strong westward (sunward) flow in the midlatitude ionosphere. These flows have dramatic consequences for ionospheric density and thermospheric density, temperature, and composition.

4.3.1 Ring Current and Ionosphere and Thermosphere

The closure of the ring current FACs through the ionosphere create subauroral polarization streams (SAPS). The term SAPS was first coined by Foster and Burke (2002) to classify the evening-sector increase in electric field equatorward of the electron precipitation boundary. Because the plasma sheet ions drift closer to the Earth in this sector, region 2 FACs enter the ionosphere at a latitude without much ionization from the precipitation of keV-energy electrons. Foster and Vo (2002) and Erickson et al. (2011) presented statistical analyses of these electric fields and ionospheric flows, showing a clear dependence of SAPS intensity and spatial extent with geomagnetic activity. Ridley and Liemohn (2002) showed that they were directly linked to the partial ring current localized pressure peak, and other observations and numerical modeling has confirmed and further quantified this relationship (e.g. Garner et al. 2004; Mishin and Burke 2005; Liemohn et al. 2005; Yu et al. 2015; Yuan et al. 2016; Califf et al. 2016). SAPS are relatively stable during storms, being a persistent feature across the evening sector that can last for many hours (e.g. Huang and Foster 2007) as the hot ions in the inner magnetosphere slowly drift through near-Earth space. However, SAPS also occur during less active times, including isolated substorms (e.g. Karlsson et al. 1998; Wang et al. 2008).

These strong flows greatly perturb the storm-time ionospheric density configuration at midlatitudes. Pintér et al. (2006) showed that SAPS cause significant density depletion in the fast-flow channel. However, just equatorward of the peak of the flow channel, the higher densities from lower latitudes can become entrained in the westward flows, creating storm enhanced density (SED) plumes, which are anomalously high ionospheric electron densities on the dayside at mid-to-high latitudes during storms (e.g. Kelley et al. 2004; Heelis and Coley 2007). Yin et al. (2004) showed that SAPS created a SED over the USA during the 15 July 2000 storm, influencing Global Positioning System (GPS) communications. In fact, total electron content (TEC) maps created from GPS signal processing has been extensively used to quantify the timing and intensity of SEDs (e.g. Bust et al. 2007; Wen et al. 2007; Yizengaw et al. 2007; Basu et al. 2008; Coster and Skone 2009). SEDs have been shown to extend right through the dayside auroral zone into the polar cap, becoming tongues of ionization and, if breaking off, polar cap patches (e.g. Horvath and Lovell 2009, 2015). Interestingly, Sojka et al. (2004) and David et al. (2011) showed that SEDs might actually be a locally produced phenomenon, with the horizontal SAPS flows driving ExB drift in slant paths, suppressing recombination and allowing a new, higher equilibrium density at these locations. Schunk et al. (2012) assessed their online ionospheric prediction model, the Global Assimilation of Ionospheric Measurements (GAIM) model, especially for the low and midlatitude regions. They concluded that a significant part of the error of the results was due to uncertain magnetospheric inputs to the code. It is clear that the ionosphere is greatly perturbed by the electric fields related to the closure of the partial ring current with effects at all local times and across a range of latitudes.

The neutral upper atmosphere is also affected by these strong subauroral electric fields. Wang et al. (2011) conducted a statistical study of the influence of SAPS on the thermosphere, finding a 10% increase in density within the flow channel, presumably from heating. This was further explained with numerical modeling by Wang et al. (2012), who found that SAPS cause increases in global thermospheric temperature, but this effect takes days to fully develop. They also found that SAPS drive large thermospheric zonal winds due to ion-neutral drag. The heating also caused compositional changes to the thermosphere, with upwelling of molecular-rich atmosphere and downwelling of atomic-oxygen-rich gas elsewhere. Mishin et al. (2012) found that SAPS can create atmospheric gravity waves near 300 km altitude, presumably related to this localized thermospheric density and temperature enhancement.

A final example is Codrescu et al. (2012), who examined real time simulations of the Coupled Thermosphere-Ionosphere Plasmasphere-Electrodynamics model, CTIPe, who compared upper atmospheric neutral mass density results against CHAMP observations. They found that the total amplitude of the perturbations was well captured but the timing was not, indicating that nonlinear feedback in the system, such as that from the ring current, could be crucial in accurately predicting thermospheric space weather effects.

Note that SAPS have been related to the faster, narrower channels of flow known as polarization jets (Galperin et al. 1974) or sub-auroral ion drifts (SAIDs) (Anderson et al. 1993). SAPS, however, are broader in latitude and lower in intensity than these sharp spikes in electric field and ionospheric flow. One hypothesis for the relationship between these phenomena is the localized intensification of the SAPS field as increased temperature enhances the ionospheric recombination rate and lowers the conductivity in the SAPS channel (Wolf et al. 2007).

4.3.2 Ring Current and GICs

Geomagnetically induced currents (GIC) (Pirjola 2000; Boteler 2001) can disrupt normal transmission system operations triggering voltage collapse or damage transformers (e.g. Kappenman et al. 1997; Molinski 2002; Wik et al. 2009). The magnitude of GIC flowing in the high-voltage power transmission networks is determined by the horizontal geoelectric field (e.g. Pirjola 2002, 2013). The induced geoelectric field on the ground is mainly controlled by currents in the magnetosphere and ionosphere, and by the conductivity of the Earth (e.g. Pirjola 2000, 2002; Ngwira et al. 2013).

The large-scale electric currents in the ionosphere are coupled to the magnetosphere through field-aligned currents (FACs). The Region 1 currents that reside on open field lines are driven by the solar wind, which acts as a generator (Siscoe et al. 1991) by dayside reconnection. On closed field lines, their formation can be due to processes taking place in either the boundary layer (Lotko et al. 1987) or in the plasma sheet (e.g. Antonova and Ganushkina 1997; Toffoletto et al. 2001).

The Region 2 currents flow at lower latitudes and can be mapped to the ring current region. They are produced by the pressure gradient dynamics in the inner magnetosphere (Vasyliunas 1970; Birmingham 1992; Heinemann 1990; Heinemann and Pontius 1991). Thus, the ring current dynamics contributes to the GIC effects via its role in the generation of Region 2 FACs. Numerous other studies have examined the connection between conductance and the ring current (e.g. Fok et al. 2001b; Jordanova 2003; Sazykin et al. 2002; Khazanov et al. 2003; Ebihara et al. 2004; Liemohn et al. 2005), showing that the partial ring current closure can strongly perturb the inner magnetospheric electric fields.

GICs with large amplitudes are of primary concern for high-latitudes but, at the same time, the GICs were recently observed at the magnetically mid- and low-latitudes during storm times (e.g. Kappenman 2003; Trivedi et al. 2007; Marshall et al. 2012; Zhang et al. 2015; Barbosa et al. 2015; Watari 2015). The presence of the enhanced ring current during storms may be directly related to the GIC generation at these latitudes. The exact connection between the storm-time ring current and these subauroral GICs, however, has yet to be fully understood.

The geoelectric field can be computed in different ways but it is necessary to have the ground-based geomagnetic field obtained either from observations (Viljanen et al. 2006; Pulkkinen et al. 2012; Ngwira et al. 2013) or from the first-principles-based MHD modeling of the magnetosphere-ionosphere system as surface variations of magnetic field at the ground-based stations (Pulkkinen et al. 2013; Glocer et al. 2016) and a representative ground conductivity structure (Pirjola 2002). The ring current physics needs to be properly modeled for the geoelectric field calculations, especially during extreme space weather events.

5 Summary

The space weather effects from the ring current particles with keV energy range cannot be considered as highly obvious as those from the "killer" electrons or from the solar energetic protons with energies of tens of MeVs but they are nevertheless quite significant. Figure 2 summarized the space weather effects that can be produced by the ring current. One of the definitions of space weather includes the time-varying conditions in the space environment that may be hazardous to technological systems on the ground. Ring current has a direct influence on the Dst-index which is computed from the ground-based magnetic field observations and which is an indicator of a storm activity. Electrons with energies less than

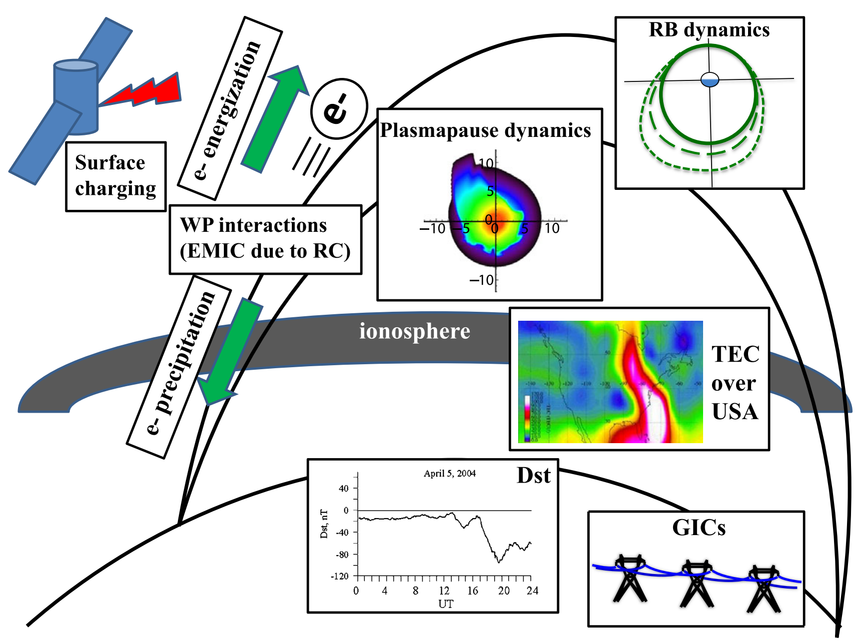

Fig. 2 Space weather effects due to ring current

100 keV are one of the important constituents of the ring current. The electron fluxes at these keV energies vary significantly with the current activity on the scale of minutes or even shorter. The keV electrons do not penetrate deep into the satellite materials but stay near the surface. They can be responsible for surface charging effects which is a serious risk for satellites.

Ring current dynamics are tied to both radiation belt losses and enhancements by affecting the efficiency of magnetopause shadowing and driving various wave-particle interactions. These consequences can be dramatic and impulsive, thereby altering the higher-energy space weather environment suddenly. With the addition of the overlapping plasmasphere, the picture is complicated further. Effective space weather models need to account for the myriad interacting density regimes and particle populations that are related to ring current changes.

The storm-time ring current has several detrimental space weather effects on the ionosphere and thermosphere. The partial ring current closes through the ionosphere, which leads to the SAPS phenomenon of strong westward flows at mid-latitudes. This rearranges the ionospheric density, creating SED plumes across the dayside middle and high latitude regions, extending even over the polar caps. These density enhancements adversely affect GPS signals, resulting in location errors of 50–100 meters during large events. Furthermore, the thermosphere is heated by the SAPS flows, leading to chemistry changes, and thermospheric winds ramp up to match the ionospheric flows during prolonged SAPS intervals.

The ring current contributes to the Geomagnetically Induced Currents effects via its role in the generation of Region 2 FACs. The magnitude of GIC is determined by the horizontal geoelectric field which is mainly controlled by currents in the magnetosphere and ionosphere, and by the conductivity of the Earth. The large-scale electric currents in the ionosphere are coupled to the magnetosphere through field-aligned currents (FACs). The Region 2 currents which can be mapped to the ring current region are generated by the pressure gradient dynamics in the inner magnetosphere.

The dynamics of the ring current is a preeminent factor in space weather forecasting, thereby of critical importance to the health and safety of our spacecraft systems. The ring current does not interact independently and alone, it is tied to the greater system.

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