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Long-Term Variations of the Solar Wind Effects on South Atlantic Anomaly (SAA) using Tsyganenko Model

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Abstract: *In this paper, we are investigating the long-term variations of the solar wind effects on the South Atlantic Anomaly (SAA) using Tsyganenko model T96. The main variables of the SAA discussed here, are the latitude and the longitude (= movement) of the SAA's center, the minimum magnetic field value and the area, with respect to the altitude and the real variation of the solar wind parameters: density, three velocities components V_x, V_y and V_z, two Interplanetary Magnetic Field (IMF) components B_y and B_z, from year 1999 to 2015, including the temporal variation of the geodipole tilting angle. It is concluded that there is direct correlation between the solar wind ram pressure and Interplanetary Magnetic Field (IMF) on South Atlantic Anomaly (SAA). Since the majority of Low Earth Orbit (LEO) spacecrafts are obliged to pass through this harmful zone, where the magnetic field strength is minimum and hence, charged particles density is maximum, this new analysis is considered as essential for the design of satellite mission lifetime and effective shielding.*

Keywords: South Atlantic Anomaly; Solar wind; Magnetosphere; Earth's Magnetic Field; Spacecraft Design

1. INTRODUCTION

The trapped radiation belts, which are consisting of huge number of energetic charged particles, are harmful to spacecrafts, moving through it. The Earth's magnetic field is not a simple dipole, due to the tilt of the dipole field with respect to the Earth's rotation axis ≈ 10.5^0 and the offset from the geographic and magnetic center of the planet ≈ 500 km. As consequence, the minimum magnetic field value is found at the south of the Atlantic Ocean; hence, energetic particles are easily immersed into this zone, where it becomes an additional strong source of danger for spacecrafts. This phenomenon is called the South Atlantic Anomaly (SAA).

In this paper, we investigate the long-term variations of the solar wind effects on the South Atlantic Anomaly (SAA) using Tsyganenko model (T96), a semi-empirical model of the solar wind-magnetosphere interaction. The main variables of the SAA discussed here, as shown in Figure 2 and Figure 3 are:

- The **latitude** and the **longitude** (= **movement**) of the SAA's center,
- the **minimum magnetic field value**, and
- the **area**,

with respect to the **altitude** and the **temporal variation of the solar wind parameters**: density, three velocity components and IMF transversal components, from year 1999 to 2015, including the temporal variation of the geodipole tilting angle.

The objective of this work is to better understand the SAA behavior under severe space weather conditions, by finding correlation between the phenomenon and the solar wind parameters, with proposing the reasonable interpretation of these effects; thus, spacecraft shielding design can be improved and can save spacecrafts from early damage.

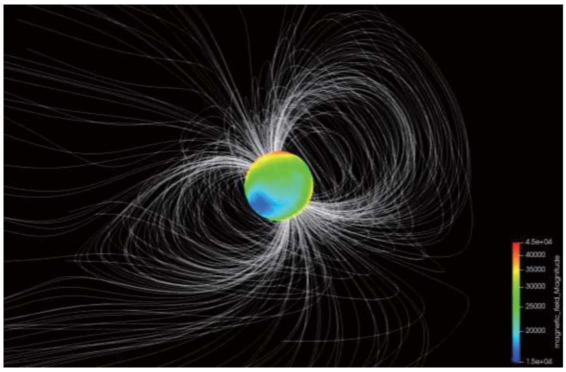

Figure 1: SAA from the outer space, including the magnetic field lines.

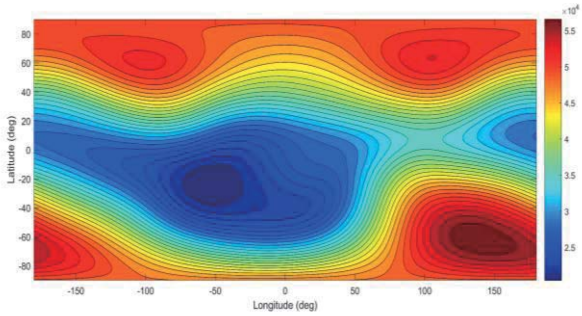

Figure 2: South Atlantic Anomaly (SAA) map @ altitude = 808 km.

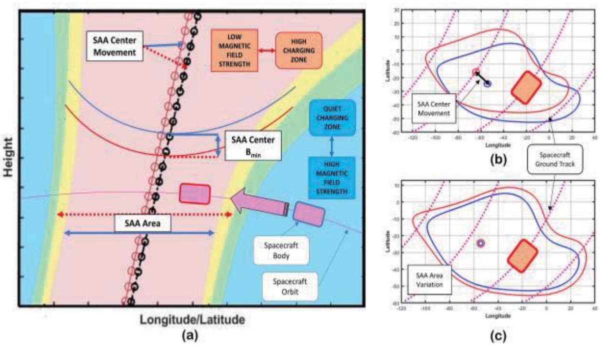

Figure 3: 2D representation of SAA, showing its main four parameters

2. METHODOLOGY

2.1. Tsyganenko Model

The Tsyganenko model is a semi-empirical representation for the magnetic field structure, based on several satellite measurements such as IMP, HEOS, ISEE, POLAR, Geotail, etc. The model consists of many external magnetospheric sources: magnetotail current system, magnetopause currents, ring current and field-aligned currents. The author of this model N.A. Tsyganenko also affords subroutines in "GEOPACK-2008" package which calculates the Earth’s internal magnetic field, using the International Geomagnetic Reference Field (IGRF) model with the addition of many coordinate transformations [1].

In T96 model, the magnetosphere's boundary is considered on the dayside as a hemi-ellipsoid, which is combined with the magnetotail by a cylindrical surface. The external magnetic field is formed by the summation of Chapman-Ferraro current, cross-tail current sheet, symmetric ring current, large-scale field-aligned currents and partial penetration of the IMF into the model magnetosphere. The model main parameters are the solar wind ram pressure, Dst-index, IMF transverse components and the geodipole tilt angle, in addition of the position and date [1] and [2].

2.2. Coordinate Transformation

The sequence of the coordinate transformation should be as follow: Geodetic (GEOD) to geographic (GEO) to geomagnetic (GSM) coordinates. Since the Earth is approximated by a spheroid, locations near the surface are described in terms of the geodetic latitude, longitude and height, and this is the definition of the "Geodetic" coordinate system.

The geodetic latitude is different from the geocentric latitude because the geodetic latitude is defined as the angle located between the equatorial plane and normal to the ellipsoid, whereas the geocentric one is defined as the angle located between the equatorial plane and the line joining the point to the ellipsoid's center.

This is the first coordinate transformation, while the second one, is achieved by calculating the dipole tilting angle, which is defined as the angle between the Earth's rotation and magnetic axis.

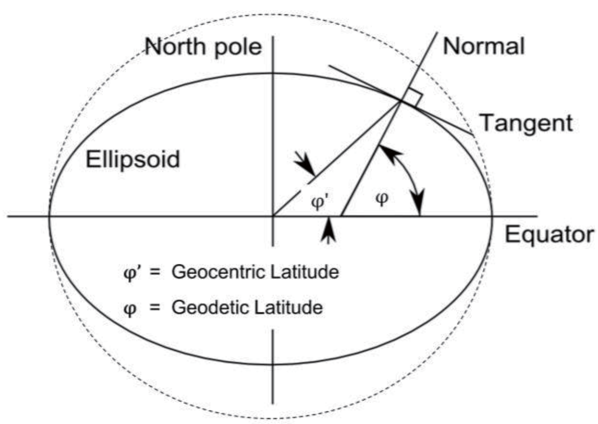

Figure 4: Geodetic and geocentric latitudes

2.3. Temporal Variation of the Dipole Tilting Angle

The x-axis is pointed from the Earth toward the Sun, which means that the “geodipole” tilt angle, which is the angle between the dipole and vertical axes, varies with respect to time, due to the angle located between the Earth’s equatorial plane and the ecliptic plane ≈ 23.5^0, added with the angle located between the rotation and dipole axes ≈ 10.5^0. The geodipole tilt angle is defined as positive when the northern hemisphere is tilted toward the Sun [3], [4] and [5].

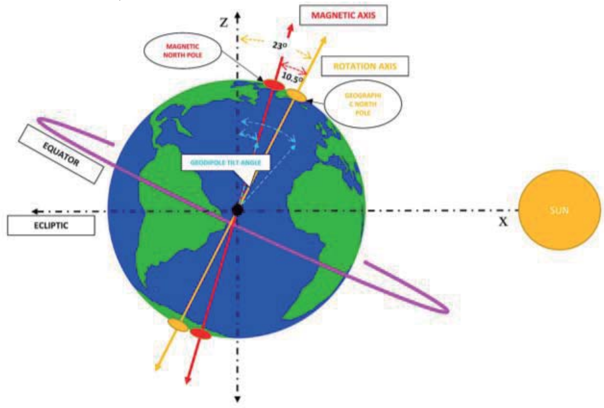

Figure 5: Geodipole tilt angle definition

2.4. ACE Spacecraft Real Data

Real data from Advanced Composition Explorer (ACE) spacecraft have been implemented into Tsyganenko model. The selected solar wind parameters are density, three velocity components and IMF transverse components, from year 1999 to 2015, 27-days average [6].

3. VALIDATION PHASE

Validation phase will be realized by comparing the results with [5].

3.1. Internal Magnetic Field (IGRF)

First, the minimum magnetic field B_{min} position of the SAA is calculated, using the International Geomagnetic Reference Field (IGRF) model. Figure 6 (top) shows the secular variation of the latitudinal variation B_{min} corresponding to an altitude of 808 km and a longitude of -52^0, and (bottom) shows the secular variation of the longitudinal B_{min} corresponding to the same altitude and a latitude of -23^0, from the years 1999 to 2009. It is clearly shown that the internal magnetic field drifts westward and northward slowly without the addition of the external magnetic field.

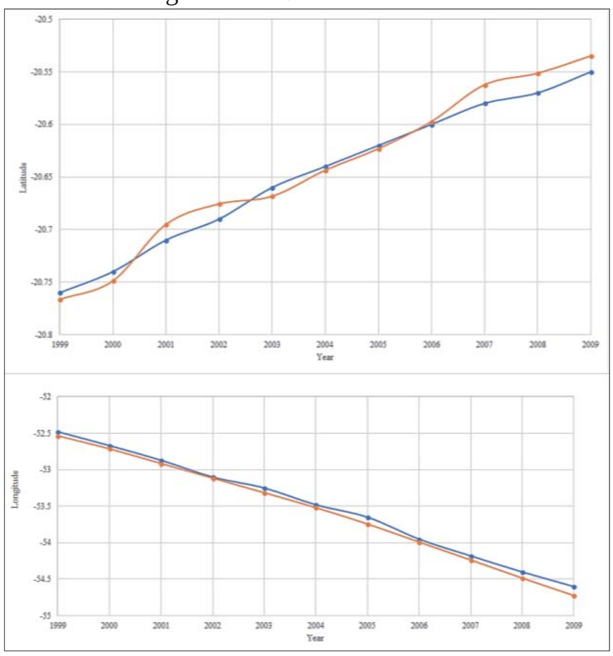

Figure 6: Secular variation of the latitudinal (top) and longitudinal (bottom) B_{min} position of the SAA using

IGRF. The blue line corresponds to the original paper results and the orange line, the calculated results.

3.2. External Magnetic Field (T96) + Internal Magnetic Field (IGRF)

Next, the external magnetic field T96, as proposed by [5], is added to the internal magnetic field, to reproduce a more realistic scenario of the Earth's magnetic field, thus, to study the movement (latitude + longitude) of the B_{min} of the SAA. Two variables are considered here: the dynamic pressure and B_{zIMF}. [5] assumed two sinusoidal profiles to simulate the temporal variation of each parameter, such as, the solar wind dynamic pressure equation is:

$$P_{dyn} = 2 + 8 \sin \frac{\pi\,(year - 1998)}{16}$$

and similarly, for B_{zIMF}.

Furthermore, each parameter is studied separately to understand its influence on the SAA's movement, in comparison with the "quiet" case, where dynamic pressure = 0.5 nPa, B_{zIMF} = 0.0 and Dst = 0.0.

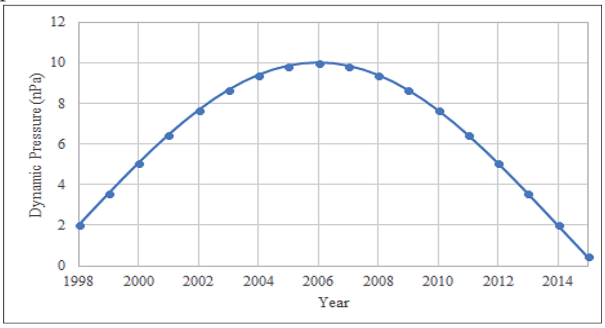

Figure 7: Solar wind dynamic pressure profile as proposed by [5]

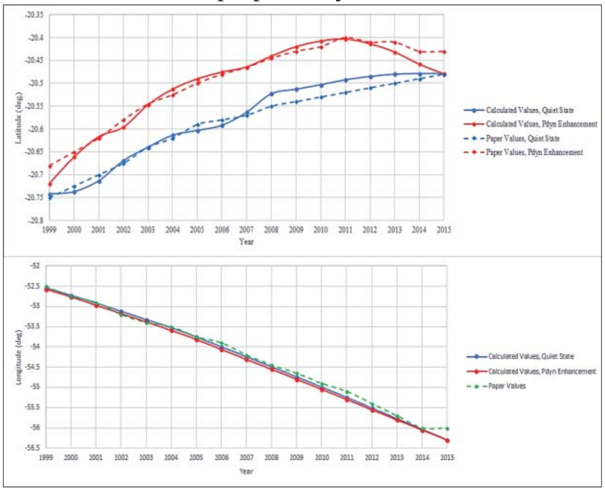

Figure 8: SAA's movement temporal variation, including external magnetic field contribution. The solid lines in both panels are the calculated values, where the blue color corresponds to the quiet case (P_{dyn} = 0.5 nPa, B_{zIMF} = 0.0 and Dst = 0.0), and the red one to dynamic pressure enhancement, whereas the dashed blue and red lines represent the results of the quiet and dynamic pressure enhancement cases, respectively, as published in [5].

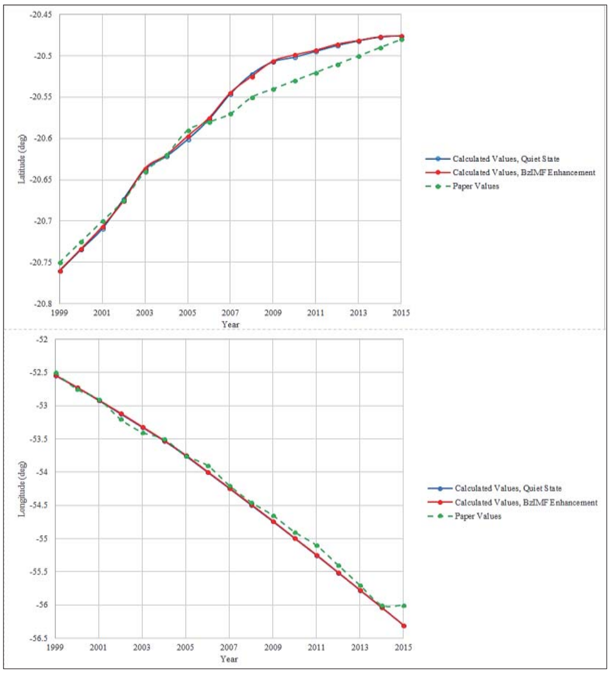

Figure 9: SAA's movement temporal variation, including external magnetic field contribution. The solid lines in both panel are the calculated values, where the blue color corresponds to the quiet case (P_{dyn} = 0.5 nPa, B_{zIMF} = 0.0 and Dst = 0.0), and the red one to B_{zIMF} enhancement, whereas the dashed green line represents the results of both the quiet and B_{zIMF} enhancement cases, respectively, as published in [5] (which are nearly superposed).

3.3. Discussion

There is a minor deviation in results, which is may be due to some missing information from [5], such as (a) the specific chosen time of the year (month, day), (b) the grid size, and (c) the geodipole tilt angle.

4. MAIN RESULTS

4.1. Global study of solar wind parameters effects on SAA

In this section, all solar wind parameters are included in the calculations, with respect to time; Dst-index is maintained as -10 nT in all calculations and the geodipole tilting angle is updated with respect to time. The target of this study is to create a global understanding of the behavior of the SAA due to the solar wind parameters variations.

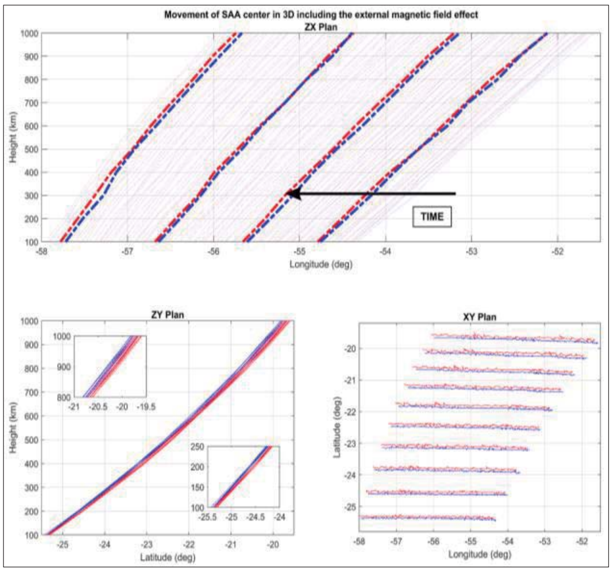

Figure 10: Three views of SAA, showing the effect of the external magnetic field on the movement of SAA's center

(red lines), with respect to altitude. The thick lines in the top panel (ZX plan) represent the SAA's center each ≈ 4 years.

Discussion: From Figure 11**,** we can extract some useful information:

- From the top panel (ZX plan), SAA's center is accelerating toward the West, and the external magnetic field effect enhances this acceleration.
- From the lower left panel (ZY plan), SAA's center is mostly affected by the external magnetic field at higher altitudes.
- From the lower right panel (XY plan), SAA's center is accelerating toward the North, precisely, at the higher altitudes, and, the external magnetic field effect enhances this acceleration, too.

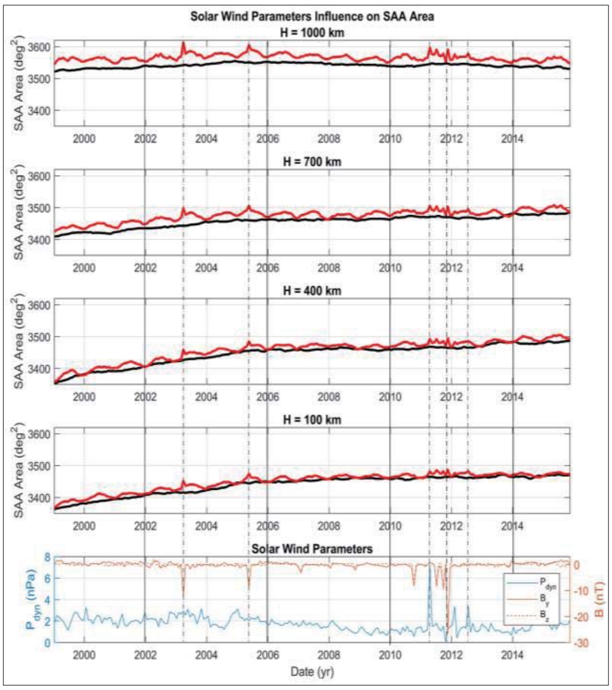

Figure 12: The effect of adding external magnetic field on the SAA's area from year 1999 to 2015 (red lines) and internal magnetic field only (blue lines), with respect to altitude.

Discussion: From Figure 13**,** it is observed clearly that:

- the ram pressure and IMF are affecting the SAA's area; the rapid increase in SAA's area is corresponding to the external magnetic field enhancements, shown here as dashed lines.
- Moreover, at the higher altitudes, the increase in SAA's area is greater.

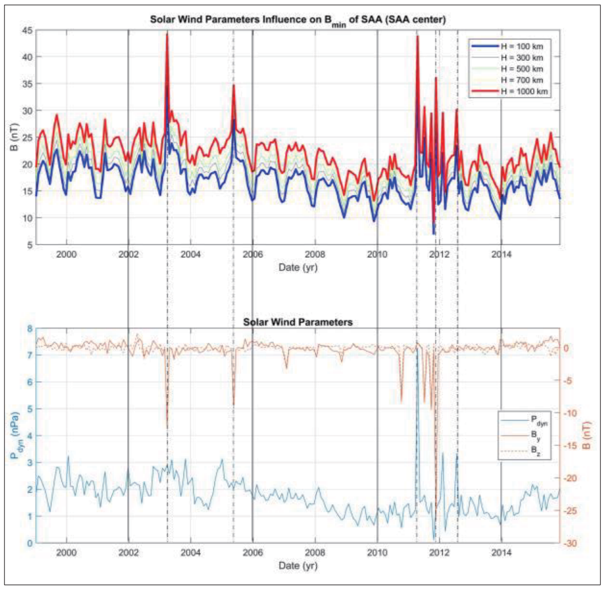

Figure 14: The effect of external magnetic field on the absolute difference of B_{min} (calculated based on the internal magnetic field only and with the external magnetic field) of the SAA's center from year 1999 to 2015, with respect to altitude.

Discussion: From Figure 15**,** it is shown that:

- the ram pressure and IMF are affecting B_{min} of the SAA's center; the rapid increase in B_{min} of the SAA's center is corresponding to the external magnetic field enhancements, shown here as dashed lines.
- Likewise, at the higher altitudes, the increase in B_{min} of the SAA's center is larger.

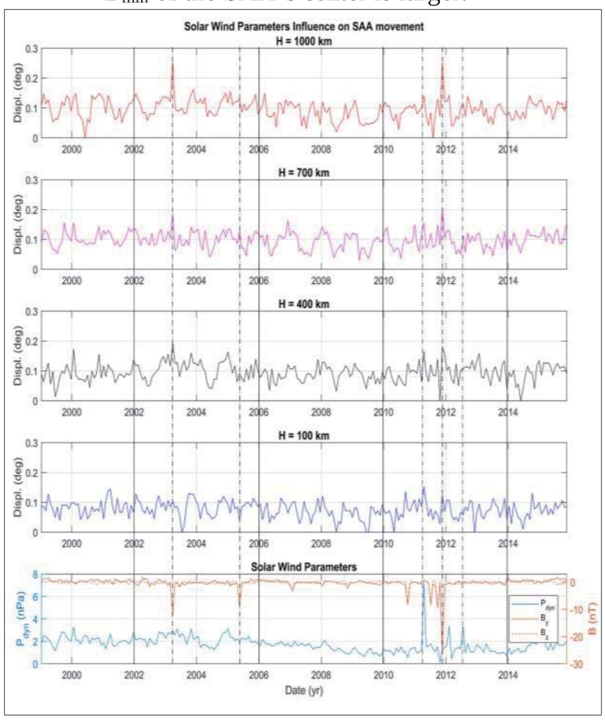

Figure 16: The effect of external magnetic field on the movement of SAA's center from year 1999 to 2015, with respect to altitude.

Discussion: From Figure 17**,** it is remarked that:

- the ram pressure and IMF are affecting the movement of SAA's center; the rapid variation in the movement of the SAA's center is corresponding to the external magnetic field enhancements, shown here as dashed lines.

- Similarly, at the higher altitudes, the variation in the movement of the SAA's center is greater.

4.2. Parametric Study of the Influence of the Solar Wind Parameters on SAA

In this section, each solar wind parameter is included in the Tsyganenko model individually, with respect to time, and the other parameters are set as constant values. The objective of this study is to determine the solar wind parameters which have the stronger influence on the phenomenon.

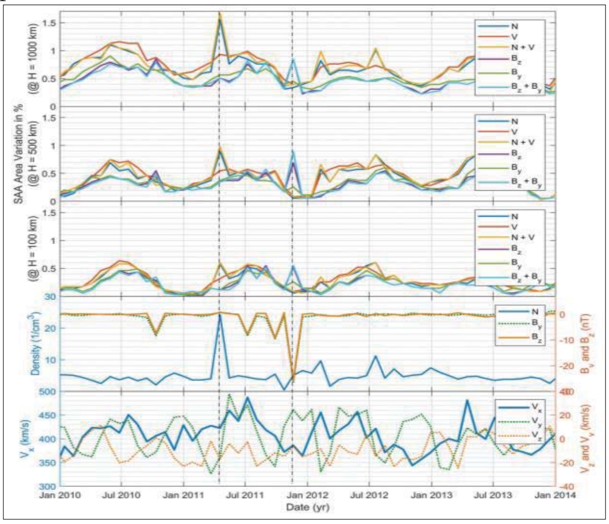

Figure 18: The effect of each solar wind parameter on SAA's area from year 2010 to 2014, with respect to altitude.

Discussion: From Figure 19**,** the ram pressure (density case (N) and density with velocity case (N+V)) has a greater influence on the SAA's area, than the IMF.

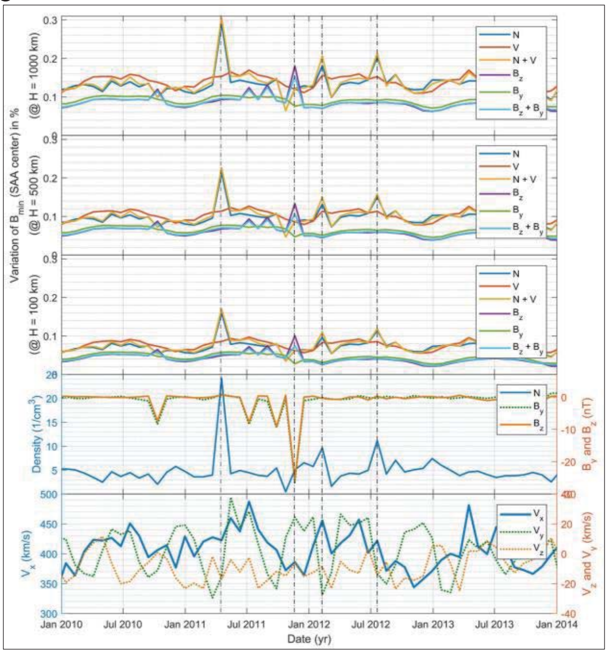

Figure 20: The effect of each solar wind parameter on B_{min} of SAA's center from year 2010 to 2014, with respect to altitude.

Discussion: From Figure 21**,** the ram pressure (density case (N) and density with velocity case (N+V)) has also a greater influence on the B_{min} of the SAA's center, than the IMF.

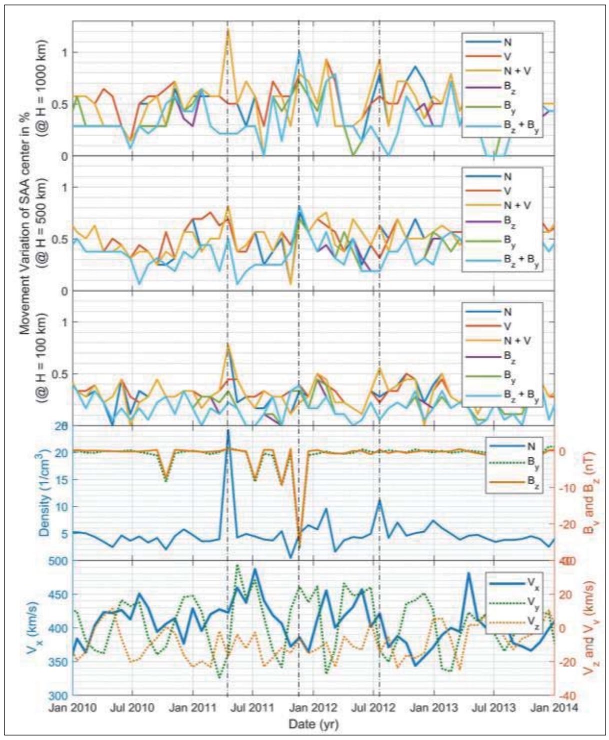

Figure 22: The effect of each solar wind parameter on the movement of SAA's center from year 2010 to 2014, with respect to altitude.

Discussion: From Figure 23**,** the ram pressure (density case (N) and density with velocity case (N+V)) has, as well, a greater influence on the movement of the SAA's center, than the IMF.

5. CONCLUSION AND DISCUSSION

To analyze the long-term variation of the South Atlantic Anomaly (SAA), from the point of view of the magnetic field, we have adopted IGRF and T96 model to study the SAA's behavior, by implementing real solar wind data, from ACE spacecraft from the years 1999 to 2015. Our main conclusions can be summarized as follows:

- The anomaly is strongly correlated with the external magnetic field, even if the region of interest is lying below 1.15 Re (≈ 1000 km). This is due to the variation of the magnetic field lines corresponding to the input solar wind conditions.
- SAA is also correlated to the variation of the geodipole tilting angle, since the magnetosphere structure and shape, are directly depending on it.
- All the SAA parameters, area, B_{min} and area, are more affected by the external magnetic field at the higher altitudes, because, as long as we move toward the Earth's center, the internal magnetic field is more dominant and therefore, SAA becomes less dependent on the outer solar wind conditions.
- It was deduced from Figure 16 that ram pressure is more affecting the SAA than IMF, whereas from Figure 16, at the lower altitudes, SAA is mostly affected by density and velocity, and, in the higher altitudes, the IMF components are dominant, hence, the global study of the solar wind parameters is more realistic than the parametric one, to study the SAA variations, as it might be a significant coupling between the solar wind dynamic pressure and IMF components.

Consequently, further analyses are strongly recommended to better understand the SAA behavior under severe space weather conditions; such as adopting T01 and T05 models and studying the short-range variations of the solar wind parameters effects on the SAA.

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