Anonymous reviewer #1

This paper investigated the distribution of bubbles as a function of longitude, latitude, altitude, local time, and year (solar cycle) using the FormoSat-3/COSMIC radio occultation data acquired in 2008-2016. Their results show an agreement with the occurrence climatology of bubbles derived by other observations.

On the scientific aspect, this paper does not deliver any new findings regarding bubbles; the behaviour of bubbles (dependence on the geographic and geophysical parameters) is well established, even if this paper does not report. However, the paper demonstrates that GPS RO signal can be a good proxy for the detection of bubbles. The results are acceptable, but writing is so bad, so I recommend resubmission of the paper.

For most sentences, I could not progress to the next sentence without pointing out a problem. Below are some examples.

➔ We like to thank reviewer #1 for taking the time to read and comment on our paper. We are grateful for the valuable comments which will help us to improve our paper distinctly. Regarding the writing of the paper, we have taken your comments into consideration and made appropriate modifications.

Title

May change "Occurrence climatology of equatorial plasma bubbles derived using the FormoSat3/COSMIC GPS radio occultation data"

➔ Thank you for suggesting the title. We will replace the existing title with the suggested one, as the latter is more appropriate with the topics discussed in the paper.

Abstract

We are grateful for the constructive inputs for improving the abstract and will consider all of them in the revised manuscript.

The whole sentences should be revised.

➔ Rewrote the abstract as follows:
"The GPS Radio Occultation technique is used to detect the equatorial plasma bubbles in the F-region, which are characterized by depleted regions of electron density. The occurrence climatology of bubbles is derived using the vertical GPS radio occultation data in 2008-2016 by the FormoSat-3/COSMIC mission. The plasma bubbles are identified based on the S4 index, derived from the signal-to-noise ratio of the radio occultation profile. The analyses revealed that, the F-region irregularities associated with plasma bubbles occur mainly post sunset close to Earth's geomagnetic equator. The distribution of bubbles shows the dependence on season, longitude, and solar cycle. Through this paper, a modest attempt is made to show that GPS Radio Occultation can be used as complementary technique to investigate plasma bubbles. Additionally, the advantage in using radio occultation data is

that, we do not only get information on the occurrence of the equatorial bubble events but also on its altitude distribution."

Line 2-3: The words "emerging", "prominent" are not necessary.

→ The words "emerging", "prominent" are removed in the revised abstract as suggested and agree that it was simply unnecessary.

Line 4-5: "For investigating the plasma bubbles, a nine-year (2008-2016) long time series of signal-to-noise ratio data are used from the vertical GPS radio occultation profiles." This is bad structure. I would write "The occurrence climatology of bubbles is derived using the vertical GPS radio occultation data in 2008-2016 by the FormoSat-3/COSMIC mission."

→ Thank you very much for the ideal structure of the sentence. The existing sentence is replaced with the suggested sentence in the revised abstract.

Line 8-9: "Dependence on the solar cycle as well as distinctive seasonal variation is observed when analyzed for different years." -> The distribution of bubbles shows the dependence on season, longitude, and solar cycle.

→ According to reviewer suggestion, the changes are incorporated in the revised abstract and we agree that it improves the quality of the sentence

" The words "depreciated" and "personifies" do not sound good expressions.

→ The words "depreciated" and "personifies" are removed from the abstract and agree that inclusion of such words did not make expressions sound good.

Sections 1-3 There are many awkward expressions. Too much work to point out all of them.

→ Thank you very much for going through the section in-detail. We agree that sections 1-3 are not well written and therefore we will rephrase it to avoid awkward expressions to the best of our ability in our revised manuscript.

Conclusions

→ We are grateful to reviewer #1 for his in-detail review on the conclusion of the paper and included it in our revised manuscript in line with your suggestion.

Page 10 Line 28: " a nine-year comprehensive study of equatorial plasma bubbles …" It sounds that the authors have studied bubbles for nine years.

→ Thank you for providing the perspective to the sentence. We have rewritten and made changes to the phrase as: "In this paper, a nine-year global climatology of EPBs is presented using GPS-RO measurements obtained from the FormoSat-3/COSMIC mission."

Page 10 Line 32: There is no "striking" finding of this study. The solar cycle dependence of the bubble activity is already very well known, and this study just has identified the known phenomenon using the RO data.

➔ According to the reviewer suggestion, we agree that solar cycle dependence of the bubble activity is already well known. However, we tried to show it from the perspective of RO data and agree the unnecessity of the word 'striking'. Therefore, the word is removed from the manuscript according to authors suggestion.

Page 10 Line 33-Page 11 Line 1: The concentration of bubbles near the magnetic equator is already well known fact, and it is not an intriguing characteristic at all.

➔ Thanks a lot for this hint. Yes, the bubble climatology is already well known from other measurement techniques. In this paper we like to show the time statistical distribution of this phenomenon based on GPS RO data. We added some sentences comparing our results with those from former publications (Carter et al.,2013, Liu et al.,2016) and also with publications that are not based on GPS RO data like (Stolle et al.,2006, Xiong et al.,2010). The main finding portrays the shifting of the peak EPB occurrence from South American to African sector along geomagnetic equator as we proceed from solar minimum to solar maximum and we intend to include this in the revised manuscript.

Page 11 Line 1: "The rapid depletion of E-layer post sunset cause…" -> The rapid plasma loss in the E layer after sunset causes …

➔ We are thankful for different formulation of the sentence which is more crisp and clear. Therefore, changes are done in line with the reviewer suggestion.

Page 12 Line 1: "The study reveals the influence of solar cycle, which facilitates the contraction and expansion of plasma bubbles across the complete altitude range." Does the solar cycle contract or expand bubbles? What does this mean?

➔ Thank you for providing your perspective on this sentence. The study falls in line with the different conditions of solar activity, wherein during solar minima the scintillation activity contracts, whereas as we proceed the solar maxima, the scintillation activity expands along the altitude range. Taking your view into consideration the rephrased sentence is:" The study reveals that the periodic variation in the solar cycle has an indirect role in the vertical occurrence range of the plasma bubbles, that covers a large range during solar maximum and lower altitude range during solar minimum condition.

➔ Finally, we would like to appreciate reviewer #1 for his time in reviewing this paper comprehensively. We have included the suggestions and the changes which will significantly improve the quality of the paper.

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Anonymous reviewer #2

The present work describes characteristics of occurrence of equatorial plasma bubbles as a function of longitude, local time, altitude and solar cycle, using COSMIC radio occultation data. The year to year variations of the longitudinal distribution of S4 index (Figure 3), Longitudinal difference of the seasonal variation of occurrence of S4 (Figure 6), and solar cycle dependency of maximum altitude of S4 (Figure 7) are new results and important contribution for scientific community.

Therefore, I would recommend that the present work could be published in Angeo.

Minor comments are to be considered by authors:

➔ We would like to thank the reviewer for his valuable comments and his perspective inputs for the significant improvement of the paper and immensely grateful for the encouragement on the manuscript. We have addressed all the minor comments that are put forth by the reviewer.

Page 3 line 27, "L2 signal is close to the critical frequency of the ionosphere,,,": The authors will need to explain why they mention it. The frequency of L1 and L2 are 1.575 GHz and 1.227 GHz, respectively, are very close to each other, and these are far from the critical frequency of the ionosphere as far as I understand. If they have a special reason to not using L2, please explain it more detail.

➔ The L1 and L2 are close to each other. But L2 signal is relatively closer to the critical frequency of the ionosphere and is therefore more affected. Unfortunately, the L2 signal is much weaker and nosier to compared to L1 signal and therefore it is not always possible to distinguish between information and noise. Hence L1 signal is used for the occurrence climatology of bubbles.

Page 4, line 4, "S4max9sec denotes ,,, 9 seconds interval": Please explain why they used 9 seconds to calculate S4, instead of the original S4 value of one second.

➔ We use raw 1Hz measurements from FormoSat-3/COSMIC, in which we get observations per one second. In order to compute S4 index, a running average is required and 9 second approximation proved to be favourable as seen from previous studies (Carter et al. (2013), Tsai et al. (2017)). The S4 value of one second which is mentioned by the reviewer is not obtained by raw 1Hz measurement, but they are retrieved from 50 Hz measurements recorded at 1 Hz (Syndergaard, 2006). Since we receive reduced number of 50 Hz data in the F-region (i.e. by factor of 5) when compared to raw 1 Hz measurement, we exploit and compute S4 index from the raw 1 Hz measurements.

Page 4, line 5-6, "A low pass filter is applied to the time series of these values,,,": What time series? of 9 seconds interval?

➔ Thank you for your perspective comments. The time series refers to the average of 9 seconds interval according to the calculation of S4 index published by Syndergaard, 2006.

Page 6 line 9, "S4 index is derived ,,, understanding the occurrence of plasma bubbles": The authors interpreted the observed S4 larger than 0.3 are all caused by plasma bubbles. The presence of

scintillation (or spread F), however, does not mean that it is due to Plasma Bubbles. There are possibilities of other sources such as ionospheric waves (TID, MSTID). The authors could comment on it.

➔ We completely agree with the statement made by the reviewer regarding scintillation. Spread F is a more general term for plasma bubble and other ionospheric waves. However, through literature it has been known that the ionospheric waves originate at mid latitudes and therefore also called as "midlatitude spread F" (Kelley, M. C., and Miller, C. A. (1997)). Since we use SNR based RO data, which are sensitive to strong vertical changes in the electron density, we assume that it is unlikely to see a TID signature in SNR; since TIDs have long vertical wavelength of more than 100 km, we do not expect that they are able to compress ions into compact layers. In addition, some of the previous studies based on Europe and South America (Brazil) conducted by Otsuka et al. (2013) and Figueiredo et al. (2018) respectively show that, the MSTIDs mostly occur in winter and during day time. However, very low occurrence percentage of nighttime MSTIDs reported by Figueiredo et al. (2018) near equator could be neglected, while keeping in mind the relative local time occurrence of EPBs.

Page 9, line 3 "In order to have in detail „„ analysis was performed" which is shown in Figure 6?

➔ Thank you for pointing out this. The statement made corresponds to the Figure 6. We agree that there is not much detail explanation done contributing to the figure and therefore we plan to explain it in more detail. However as of now, the sentence" In order…" will be removed in the revised manuscript and replaced with a modified phrase.

Page 11, line 5 "in the African sector during June solstice": Isn't it March Equinox? (see Figure 6).

➔ Thank you for bringing this to our notice. It is actually the March Equinox, where in the scintillation activity is dominant when compared to rest of the seasons.

Finally, we would like to appreciate the reviewer for his time in reviewing this paper extensively and have considered all his comments in order to further improve the quality of the paper.

Reference:

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Anonymous Reviewer #3

Global Climatology of Equatorial Plasma Bubbles based on GPS Radio Occultation from FormoSat-3/COSMIC by Kepkar et al looks at the seasonal, longitudinal, annual, altitude and local time variations in the occurrence of equatorial plasma bubbles as indicated by the COSMIC S4 index. The authors have failed to highlight the novelty of the work, and as such I cannot recommend it for publication. Their work is very similar to Carter et al 2013, whom they cite in reference to variation with solar activity. However, they have failed to discuss the work in the context of this paper even though Carter et al 2013 looked at the seasonal, longitudinal, annual and local time variations of equatorial plasma bubbles as indicated by the COSMIC S4 index.

➔ We like to thank the reviewer for his time in going through paper and providing constructive inputs that will improve the quality of the paper. We agree that occurrence climatology presented in this paper doesn't explain the similarities and dissimilarities in-detail with the previous studies. In order to make this study worthy of publication, we tried to address all the issues raised.

Indeed, Figure 6 of this paper is very similar to Figure 4 of Carter et al 2013. The years of data used are different. However, the differences and similarities between Figure 6 and the results from Carter et al 2013 are not discussed and it is showing how this work provides something new that is currently missing from the manuscript.

➔ We are pleased to have authors perspective concern to include differences and similarities shown in the Fig. 6 with previous publication including Carter et al. (2013). One of the main differences from the Carter's et al. (2018) paper, that this study includes seasonal occurrence surrounding the solar max year as pointed out by the reviewer and we intend to explain in more detail the difference in occurrence characteristics. In particular, only one maximum above geomagnetic equator is visible across different seasons and regions with the most EPB occurrence in the African sector during March equinox for solar maximum years (2012-2016). It is also known that different measurement techniques incur different occurrence interpretation and therefore we planned to include comprehensive comparison of EPBs based on previous publication (Burke et al. (2004a, 2004b), Gentile et. al (2006), Su et al. (2006), Stolle et al. (2006), Nishioka et. al (2008), Dao et al. (2011), Carter et al. (2013), Xiong et al. (2013), Liu et al. (2016)).

Taking each sentence from the abstract in turn below it can be seen that no new information is currently being highlighted by the authors "The analysis revealed that the F-region irregularities, associated with plasma bubbles occur mainly post sunset close to Earth's geomagnetic equator."- This has been known and written in many papers, including ones such as Sultan 1996 and others that look at the mechanism and growth rate of post sunset plasma bubbles

➔ We would agree with the reviewer's comment, that it has been known that bubbles predominantly occur at the geomagnetic equator. However, we would like to present the maxima of EPB occurrence shifting from the South American sector towards the African sector on a year wise basis, while proceeding the solar maximum year. Subsequently we plan to add this in the manuscript and make changes in the abstract too. In the local time distribution, we already know that plasma bubbles occur post sunset and therefore we

"Dependence on the solar cycle as well as distinctive seasonal variation is observed when analysed for different years." -Bourke et al 2004 looked at the climatology of plasma bubbles for both low and high solar activity, and Carter et al 2013 looked at the climatology of plasma bubbles using COSMIC S4 as a function of year.

➔ We are agreeing with the reviewer comment when it comes to the previous work done by different authors. In this paper, the seasonal variation of EPBs agrees well with the results of Burke et al. (2004) and Su et al. (2006) with peak for equinox in the African sector. However, it differs from the observation made by Carter et al. (2013), where he observes peak for equinox in the American region. This could be because of the study period (2007-2011) which covers solar minimum covered by Carter et al. (2013), while Su. et al. (2006) and this paper used datasets surrounding the solar maximum year. We plan to include this and explain in more-detail the occurrence in region wise seasonal dependence of EPBs.

"In contrast to the other ionospheric remote sensing methods, GPS Radio Occultation technique uniquely personifies the activity of the plasma bubbles based on altitude resolution on a global scale." –As mentioned throughout this review, Carter et al 2013 used COSMIC RO data to look at plasma bubbles, so more is needed to make this a new finding.

➔ It is very well known that that plasma bubbles vary with the altitude. Since not many techniques providing altitude resolution are globally spread, therefore those studies are restricted to a particular region. The GPS RO provides the advantage of having altitude resolution when it comes to studies related to the F-region scintillation (Liu et al. (2016)). So this paper intends to give information on a year wise basis, starting from solar minimum year, covering the solar maximum year followed by decreasing solar activity. It also highlights the EPBs detected from GPS-RO extending to greater altitudes and shifting its peak from lower latitudes to the higher latitudes as we proceed towards solar maximum. More information and in-detail explanation is planned to be added in the revised manuscript.

Minor comments: In section 2.1.1 Derivation of amplitude scintillation index it is unclear if the authors have used the provided s4max9sec data and are explaining how it is derived, or if they have used raw data and re-analysed it themselves. If it is the later the reasoning also needs to be made clear to the reader.

➔ The amplitude scintillation index is calculated using raw 1 Hz SNR measurements from ionPhs data. The same has been already documented in section 2.1 (Data availability). For better understanding, the used dataset will be also mentioned again in section 2.1.1 (Derivation of amplitude scintillation index) in the revised manuscript. The ionPhs data is preferred over the ScnLv1 datasets (which includes 50 Hz measurements recorded at 1 Hz (Syndergaard (2006))), because the ionPhs profiles have increased number of dataset (i.e by

factor 5) when compared to ScnLv1 datasets along the F-region altitude. Therefore, to reduce the number of interpolated occurrence number, raw SNR measurements are exploited for this study.

It is unclear why the authors have chosen to use the average S4 rather than some occurrence calculation. Averages can be misleading if the distribution between cells varies, or the number of points vary etc. A justification should be added or another way to demonstrate the data should be used.

➔ We are thankful for the reviewer's hint and agree with his suggestion on having some occurrence calculation. Based on his suggestion, we modify the earlier plots showing S4 average with occurrence rate. The occurrence rate is calculated as a ratio of number of profiles having maximum S4 value greater than 0.3 to the total number of profiles in each grid.

In Figures 5 & 6 the captions state that the Figures show the EPB occurrence. In Figure 5 the numbers seem very low for this to be the case and in Figure 6 it is clearly the S4 average again, this is inconsistent, confusing and needs to be fixed.

➔ Thank you for pointing this out. As mentioned in the previous reply, we have replaced the S4 average with the occurrence rate. This will further unify the results based on the occurrence calculation in the analyses. As far as the numbers are concerned in the Figure 5, the occurrence rate is calculated as ratio of number of profiles having maximum S4 value greater than 0.3 for a particular time interval [for e.g 20 hr – 21 hr] to the total number of profiles in each grid for the same time interval [for e.g 20 hr – 21 hr]. The low numbers could be probably because of using low sampling rate data and we plan to include this reason while comparing our results with Carter et al. (2013).

In order to make this work worthy of publication the authors need to carefully discuss the results in the context of similar papers that are currently not included in the discussion of the results. Following this they need to assess and highlight what is new and different to determine if the work is novel.

➔ Finally, we would like to appreciate the reviewer for giving his comprehensive review on this paper. We will surely add and discuss the results with the previous studies in-detail. We will also incorporate the suggestion and hints provided by reviewer in the revised manuscript and improve the quality of the paper for publication.

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Changes suggested by:

1) Reviewer#1 – Magenta
2) Reviewer#2 – Cyan
3) Reviewer#3 – Blue
4) New additions – Yellow highlighted text

Occurrence climatology of equatorial plasma bubbles derived using FormoSat-3/COSMIC GPS radio occultation data

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Abstract. The ~~emerging technique of~~ GPS radio occultation technique (GPS-RO) is used to detect the equatorial plasma bubbles ~~prominent~~ in the F-region of the ionosphere, which are characterized by ~~depreciated~~ depletion regions of plasma. ~~For investigating the plasma bubbles, a nine year (2008-2016) long time series of signal-to-noise ratio data are used from the vertical GPS radio occultation profiles~~ Their occurrence climatology is derived using GPS-RO data from FormoSat-3/COSMIC between 2007 and 2017. The plasma bubbles are identified based on the S4 index derived from raw signal-to-noise ratio profiles. The analyses revealed that the F-region irregularities associated with the plasma bubbles occur mainly post-sunset close to the Earth's geomagnetic equator, and have peak shifting between America and Africa depending on different solar conditions. ~~Dependence on the solar cycle as well as distinctive seasonal variation is observed when analyzed for different years~~ Besides, the plasma bubbles show a strong dependence on the solar cycle and have a significant distribution based on regions and seasons with maximum occurrence in Africa during March equinox during high solar activity. Similarly, from the vertical resolution provided by the radio occultation technique, we see a variation in the altitudinal extent with respect to the solar cycle. Through this paper, an attempt is made to show, that the GPS-RO can be used as a primary as well as a complementary technique for investigating this ionospheric phenomenon. Finally, the major advantage of using GPS-RO compared to other techniques is, that not only information on the plasma bubble occurrence but also its detailed altitude ~~personifies~~ characteristics can be derived on a global scale.

1 Introduction

The Equatorial Plasma Bubbles (EPBs) are large regions of plasma depletion, which are prominent in the F-region of the ionosphere. These EPBs generally exist in clusters (Singh et al., 1997) and often deter the radio waves (e.g., GPS signals) penetrating through it, causing serious implication on its applications. These plasma bubbles primarily occur at low latitudes

and induce rapid fluctuation in the amplitude as well as phase of the radio signals. This distortion of the signals is often termed as scintillation (Yeh and Liu, 1982). The EPBs instigated by plasma irregularities are also known by its generic name as Equatorial Spread F (ESF), which are perceived as a spread or diffused echoes in the ionosonde readings (Booker and Wells, 1938; Whalen, 1997). Apart from scintillations in the radio signal, this irregularity manifests themselves as plume-like structures in the range time-intensity images from incoherent scatter radar (Kudeki and Bhattacharyya, 1999) and intensity bite-outs in airglow measurements (Sahai et al., 2000).

The EPBs are a night-time phenomenon and are initiated by means of the Rayleigh-Taylor Instability (RTI) mechanism in the bottomside of the F-layer (Sultan, 1996; Woodman, 2009). To trigger the RTI mechanism, various theories related to seed perturbation like atmospheric gravity waves (AGWs) as well as vertical shear of zonal plasma drift are considered amongst the likely source (Kudeki et al., 2007; Abdu et al., 2009; Huang et al., 2011; Taori et al., 2011). Other than these seed sources, off-equatorial ionospheric phenomena such as sporadic-E layers and medium scale traveling ionospheric disturbances have also been contemplated for possible seed activity along the equipotential magnetic field lines (Abdu et al., 2003; Tsunoda, 2007). However, the AGWs with wavelengths greater than 100 km are considered to have a significant impact in triggering the RTI by producing polarization electric field in the E-region, which then translates it onto the F-region along the magnetic field lines (Röttger, 1981; Tsunoda, 2010; Huang et al., 2011; Retterer and Roddy, 2014; Tsunoda, 2015). In the meanwhile, an important activity at the equator, i.e., Pre-Reversal Enhancement (PRE), plays a significant role in influencing the plasma bubble growth and vertically lifting it after the sunset. PRE is a phenomenon that causes an enhancement in the zonal eastward electric field at the sunset terminator before the electric field reverses in the westward direction during the night (Abadi et al., 2015). This enhancement in the eastward electric field creates a vertical electromagnetic (E x B) drift that influences the growth rate of RTI by lifting the plasma to heights where the ion-neutral collision rate is small (Farley et al., 1970; Fejer and Kelley, 1980; Abadi et al., 2015). The EPBs are known to occur within hours right after sunset, and the degree to which it extends in the latitude and altitude depends on the magnitude of PRE (Farley et al., 1970; Abdu et al., 2003; Abadi et al., 2015).

The depletions in the equatorial plasma were initially identified from in-situ measurements by Hanson and Sanatani (1973) and later confirmed by McClure et al. (1977). Ever since then, various techniques such as ground based observations (Woodman and La Hoz, 1976; Farley et al., 1970; Whalen, 1997; Kudeki and Bhattacharyya, 1999), airglow imagers (Sahai et al., 1994, 2000; Martinis and Mendillo, 2007), satellite-based in-situ measurements (Burke et al., 2004a; Park et al., 2005; Gentile et al., 2006; Stolle et al., 2006; Xiong et al., 2010; Dao et al., 2011) as well as Global Navigation Satellite Systems (GNSS) ground-based measurements (Basu et al., 1999; Carrano and Groves, 2007; Nishioka et al., 2008) have been used to study the EPBs. Although these techniques contributed enormously towards the understanding of the ionospheric irregularities, they lacked in providing critical information in one aspect or the other. For example, the ground-based sounders and GNSS ground receivers; although they provide crucial information related to the ionosphere and are globally distributed, they remain restricted to a landmass. On the other hand, the satellite-based in-situ instruments explore the prevailing conditions in the ionosphere along its orbital track but fail to provide crucial insight into the vertical ionospheric conditions. In recent times, the GPS-RO technique has been widely used for ionospheric investigation (Wickert et al., 2001; Arras et al., 2008; Wickert et al., 2009; Carter et al.,

The GPS-RO is a space-based technique, which involves two satellites, i.e., GPS and Low Earth Orbiting (LEO), operating on a high-low satellite satellite tracking (HL-SST) mode (Wickert et al., 2001, 2009). Its operational principle is mainly based
5   on LEO satellites tracking the radio signals from the GPS satellites, as they penetrate through the Earth's ionosphere and atmosphere, causing the signal to bend while crossing it. The fundamental observable, i.e., bending angle, obtained from bending of the signal at the point of closest approach to the Earth is measured as an additional Doppler shift for accurate frequency and orbit geometry measurements (Kursinski et al., 1997, 1999). In the ionosphere, the electron density profiles are obtained using the onion peeling algorithm (Lei et al., 2007). While, in the stratosphere and troposphere, temperature
10   and pressure profiles are obtained through refractivity profiles (Wickert et al., 2002; Jakowski et al., 2004). In addition to providing such a wealth of information, this technique mitigates various technical shortcomings by operating under all weather conditions and providing long term stability without requiring calibration from time-to-time (Rocken et al., 1997). Due to GPS-LEO geometry, the GPS-RO technique provides measurements with a high vertical resolution that are globally distributed. In the past, various LEO missions contributed enormously towards radio occultation operations that led to the rise of one
15   mission to another, starting from GPS/MET (GPS/METeorology), CHAMP (CHAllenging Minisatellite Payload), GRACE (GRAvity recovery and Climate Experiment), FormoSat-3/COSMIC (Formosa Satellite -3/Constellation Observing System for Meteorology, Ionosphere, and Climate) (Anthes et al., 2008; Wickert et al., 2009; Arras et al., 2010) to FormoSat-7/COSMIC 2 mission.

2   Data analysis

20   In this study, we use the measurements provided by FormoSat-3/COSMIC that perform global limb soundings using GPS-RO technique. The FormoSat-3/COSMIC mission is a constellation of six microsatellites, which provide $\sim 2,000$ continuous real-time neutral atmospheric and ionospheric profiles daily (Anthes et al., 2008). However, after orbiting for more than 13 years and exceeding its planned lifespan of five years, the number of RO profiles has significantly reduced to approximately 20% since the middle of 2016. This is because currently only one out of six satellites is operational under degraded mode (Chu et al.,
25   2018). Nevertheless, this study comprises of measurements taken during the years 2007-2017 that includes nearly 5.5 million ionospheric profiles.

For our investigations, we use *ionPhs* (*ion*ospheric excess *Ph*ases) data which belong to *level 1b* dataset. These FormoSat-3/COSMIC observation files are freely available on the web portal of COSMIC Data Analysis and Archival Center (CDAAC) database, which are managed by University Corporation for Atmospheric Research (UCAR), Colorado, United States of Amer-
30   ica. In addition, CDAAC also provides *'ScnLv1'* scintillation datasets, which contains off-line constructed S4 data calculated from $50\,\mathrm{Hz}$ that are recorded at $1\,\mathrm{Hz}$. But from the several thousand *ScnLv1* profiles that are retrieved daily, only less than one-fourth profiles can be reconstructed for the F-region altitude of the ionosphere (Tsai et al., 2017). Thus exploiting *ionPhs* dataset is justifiable, which are almost five times more than the *ScnLv1*. The derivation of *ionPhs* profiles is based on the as-

sumption of spherical symmetry; however, it is not valid for EPBs (Jakowski et al., 2004; Arras, 2010). These *ionPhs* datasets are retrieved at 1 Hz sampling rate with ∼ 2 km of altitude resolution along the vertical range of ∼ 60 km above Earth's surface up to the orbital height of the LEO (∼ 800 km).

In particular, we make use of the raw Signal-to-Noise ratio (SNR) of the GPS L1 (1,575 MHz) *ionPhs* measurements. ~~Since~~
~~the frequency of the L2 signal is close to the critical frequency of the ionosphere, the L2 signal becomes more susceptible to~~
~~ionospheric irregularities. On the other hand, L1 signal is easily available and shows strong strong signal characteristics when~~
~~compared to L2~~ This is because the L1 measurements show strong signal characteristics, and are received with a relatively higher intensity when compared to the GPS L2 (1,227 MHz) signals which are weaker and noisier. On the other aspect, SNR measurements are preferred over electron density profiles since they are straightway available and no further treatment is required. Additionally, from literature we know, that amplitude variation in the SNR profile has a direct influence on the vertical gradient of the electron density which provides critical information on the underlying space weather conditions (Wickert et al., 2004; Arras et al., 2008). From Fig. 1 it is visible that the EPB's signature characterized by sharp depletion in the electron density corresponds to strong oscillations in the SNR profiles. Subsequently, a high amplitude scintillation index is derived from these fluctuations.

The scintillations caused by plasma bubbles are identified by deriving amplitude scintillation index, i.e., S4 index, from the SNR of the GPS L1 signals. This is because the variations in the SNR can be associated with the vertical changes in the electron density that mainly occur in line with the irregularities, for example, the EPBs (Hajj et al., 2002; Arras and Wickert, 2018). For subsequent analyses of the plasma bubble, attributes such as SNR of GPS L1 signal, Universal time, altitude, latitude, and longitude are extracted from the *ionPhs* datasets. Following that, the S4 index is computed from the raw SNR measurements as described by Syndergaard (2006) in Eq. 1.

$$S4max9sec = \frac{\sqrt{\left\langle \left(I - \left\langle \bar{I} \right\rangle \right)^2 \right\rangle}}{\left\langle \bar{I} \right\rangle} \tag{1}$$
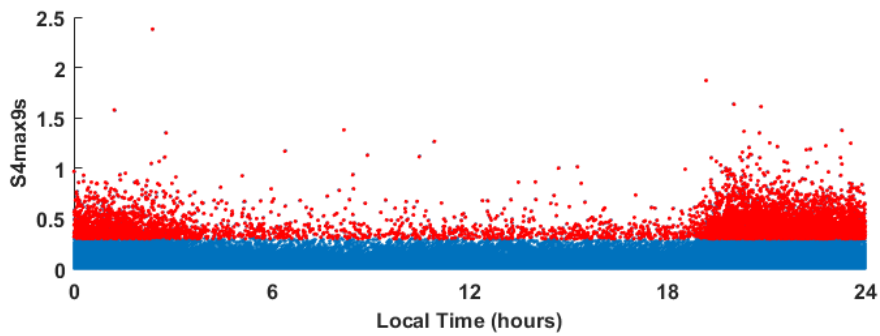
where $S4max9sec$ denotes the scintillation index calculated over nine seconds interval, *I* is the square of the Signal-to-Noise (SNR) ratio of L1 GPS signal, and the bracket $\langle \rangle$ stands for average taken over nine seconds. In addition, a low pass filter is applied to the ~~this~~ time series of nine seconds interval to obtain a new average of the intensity $\langle \bar{I} \rangle$ for constructing a long-term detrended $S4max9sec$ index (Syndergaard, 2006).

A simple representation of $S4max9sec$ versus local time during the year 2014 is depicted in Fig. 2, which shows scattered scintillation values caused due to varying electron density gradient. Additionally, it also highlights low $S4max9sec$ values during the day and high values during the night. The high values, usually observed during the night, are due to the plasma instabilities in the F-region after sunset. Altogether about 0.5 million profiles were retrieved in 2014, out of which only 6,130 (i.e., ∼ 1.2 %) global profiles were classified as strong scintillation events originating from possible plasma instabilities.

For this study, we classified scintillation events based on different $S4max9sec$ index. Hereafter $S4max9sec$ index will be referred to as the S4 index and the same is presented in Table 1 along with different scintillation categories. Within this
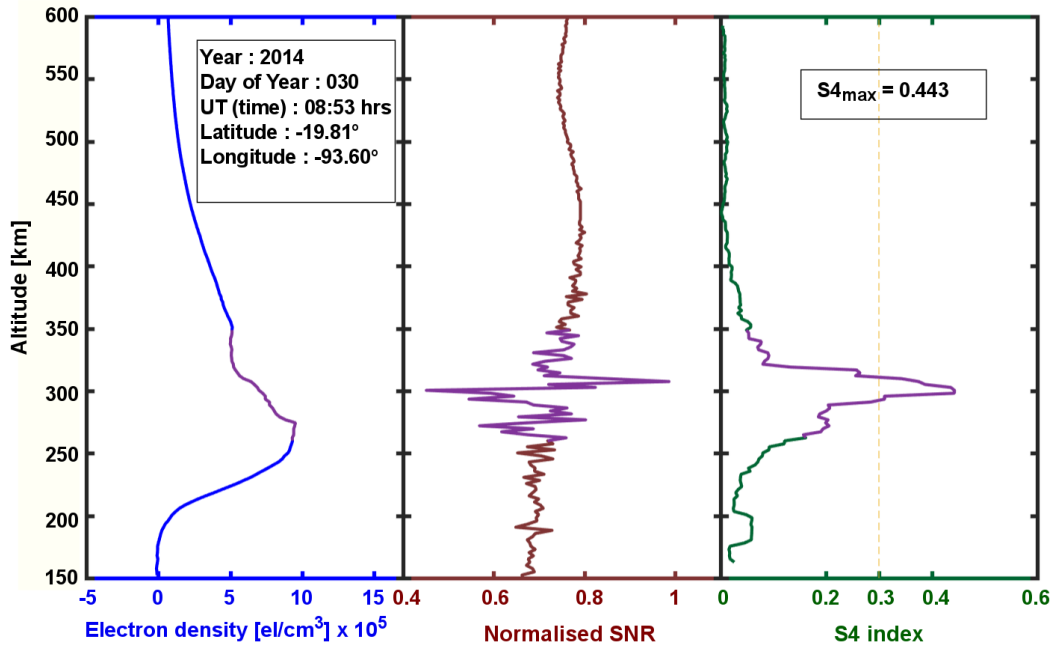
Figure 1. Electron density profile (ionPrf product) in conjunction with normalized SNR and derived S4 index (ionPhs product). The purple color line in the plot shows depletion in electron density and corresponding fluctuations of normalized SNR profile and high index values in the S4 plot.

Figure 2. Plot of $S4max9sec$ as a function of local time (LT) during 2014. The blue dots represent the scintillation index less than 0.3, whereas strong scintillations are represented by the red dots having S4 index larger than 0.3.

study, we consider the S4 index greater than 0.3 to quantify strong scintillation events influenced by possible plasma bubbles (Brahmanandam et al., 2012; Carter et al., 2013).

S4 values	scintillation category	occurrence (2014)
$S4 \geq 1.0$	high	0.02%
$0.3 < S4 < 1$	moderate	1.19 %
$S4 \leq 0.3$	low	98.79%

Table 1. Categorization of S4 index intensity.

3 Results

The FormoSat-3/COSMIC measurements between mid-2007 and 2017 are exploited to understand the occurrence of EPBs. In this study, we used COSMIC measurements starting from June 2007. This time-interval was selected to avoid the influence of orbit maneuvers in the data which were present until May 2007. Since the FormoSat-3/COSMIC satellites fly in non-sun-synchronous orbit, they effectively perform global soundings. However, in order to centralize this study in the equatorial region, we only consider the measurements within the latitudinal extent of $50°$ N/S. By determining this limit, we exclude the polar scintillation events and lay focus on the equatorial ones. Also, we set the altitude range between 150 km and 600 km to avoid the influence from the E-region and the noisier information from the GPS-RO profiles above 600 km.

3.1 Global distribution of EPBs

The EPBs are field align irregularities, which occur along the geomagnetic equator and peaks during the time of year when the magnetic field lines are closely aligned with the sunset terminator (Tsunoda, 1980, 1985). A global occurrence climatology of the EPBs for almost 11 years is presented in Fig. 3. It shows that the EPBs follow the course of the magnetic equator along with longitude dependence for different years, comparable to the morphology of F-region scintillations presented by Tsai et al. (2017). The EPB occurrence rate is calculated as a ratio of a number of profiles having S4 index greater than 0.3 to a number of all RO profiles within the specified grid integrated over the complete local time range. Furthermore, the 11-year climatology corresponds to the solar cycle outlining the descending-ascending-descending phase. As we proceed towards the solar minimum year 2009, i.e., descending phase, we see the EPB occurrence rate declining with the peak appearing in the South American sector. Whereas, as we advance towards the solar maximum year 2014, i.e., ascending phase, the EPB occurrence rate increases gradually with the peak stretching along the Atlantic-African region with each passing year. However, as we approach towards the next descending phase, it is again noticeable, that the EPB occurrence rate decreases with the peak migrating towards the South American region. Throughout this climatology, we see that a finite proportion, if not the peak occurrence, of EPBs are present in the South American region. One of the reasons conferred by Huang et al. (2001) suggests the existence of a weaker magnetic field in that region, which accounts for RTI irregularities caused due to vertical plasma drift

because of the zonal electric field during the sunset. On the contrary, Burke et al. (2004a) argued on the weak occurrence rates of EPB during high solar activity citing reason towards increased E-region conductivity because of particle precipitation in the South Atlantic anomaly. Besides, McClure et al. (1998) proposed possible seeding from the gravity waves emerging from the troposphere in the Andes, which has been investigated by Su et al. (2014). The author confirmed a very good correlation only in the South American region due to gravity waves originating in the intertropical convergence zone. However, in the Atlantic-African region, there was a positive but still weak correlation. For such correlations, the author implied, that in addition to gravity waves, there could be other seed perturbations causing plasma instabilities. From the year-wise EPB occurrence, we observe that towards low solar activity almost negligible EPB occurrence is observed in the Atlantic-African, Asian, and Pacific region. This signifies possible association of PRE to seed the EPBs in this region since we know that the magnitude of PRE is largely affected by solar activity (Stolle et al., 2008; Abadi et al., 2015). Thus we recognize the substantial occurrence of EPBs during high solar activity when the PRE has its peak magnitude, while a very weak occurrence rate of EPBs exists during low solar activity when the PRE amplitude is also at its minimum.
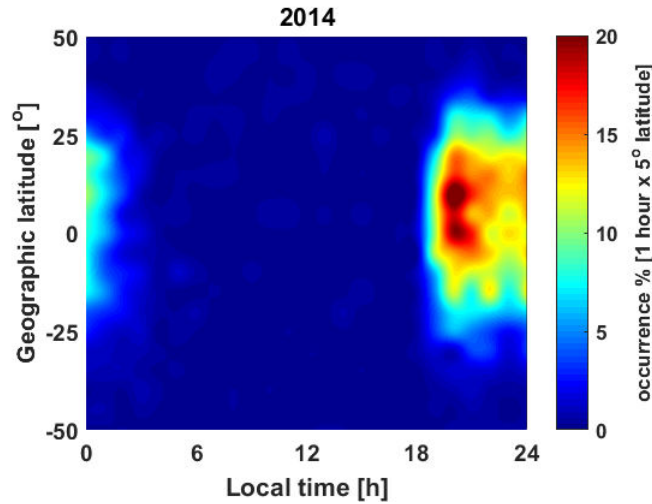
3.2   Local time dependency

From the previous studies based on various probing techniques, it is evident that the EPBs are a night-time phenomenon, that includes small scale irregularities inside the bubble that lead to turbulent structures causing scintillations (Woodman and La Hoz, 1976; Whalen, 1997; Sahai et al., 2000; Gentile et al., 2006; Yokoyama, 2017). A general local time occurrence of EPBs during 2014 is presented in Fig. 4. This local time representation of EPBs is based on the global soundings retrieved from the FormoSat-3/COSMIC satellites which fly in non-sun-synchronous orbit. The EPB occurrence rate is based on calculation similar to the global distribution occurrence, but for a different grid composition. It is clear from the Local Time (LT) representation, that the EPBs develop around 19:00 LT shortly after the sunset when the polarization electric field shorts E-region conductivity causing a ~~rapid depletion of plasma~~ rapid loss of plasma, which is similar to the results affirmed by Stolle et al. (2006) using CHAMP in-situ measurements. In general, we know that a substantial occurrence rate is observed during the high solar activity year, while fewer EPBs are generated during low solar activity year (Basu et al., 2002). In Fig. 5, we present a closer look at the occurrence of EPBs based on solar maximum (2014) and solar minimum (2009) year. The occurrence rate is calculated as a ratio of the S4 values greater than 0.3 to the total number of S4 profiles for a particular hour bin starting from 19:00 LT. From the analysis we can witness, that during solar maximum the EPBs culminate approximately one hour earlier, i.e., 21:00 LT, than what is observed during solar minimum year, i.e., 22:00 LT; which is in agreement with the EPBs detected using CHAMP and GRACE in-situ measurements by Xiong et al. (2010). However, our local time occurrence slightly differs from the local time distribution presented by Carter et al. (2013); wherein in his analysis, a high solar activity year peaks about an hour later than the solar minimum year for all season-longitude. The local time occurrence characteristics presented in this paper agree well with the argument conferred by Burke et al. (2009) who suggests, that the slow process of gravity-driven currents over weak PRE magnitude influences the EPB occurrence to peak at a relatively later local time for the solar minimum year.
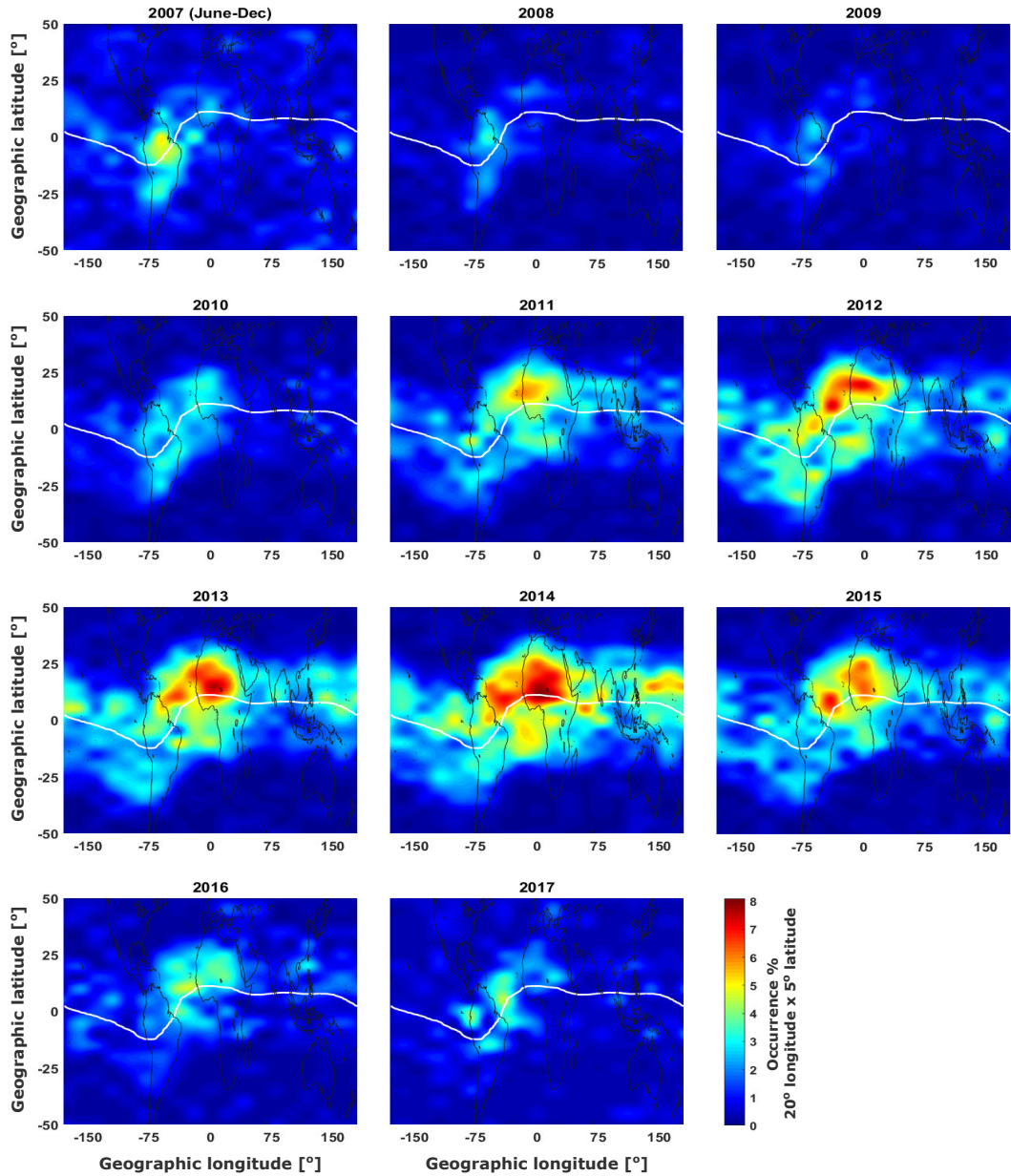
Figure 3. Plot of geographical latitude [°] v/s geographical longitude [°] of EPBs from mid-of 2007 to 2017. The white solid line depicts the geomagnetic equator.

3.2.1 Region-wise seasonal dependence of EPBs

Based on the argument put forth by Tsunoda (1985), we know that the region-wise seasonal occurrence of plasma bubbles depends on the close alignment of the magnetic field line with the sunset terminator. In order to ~~to have in-detail cateogorical~~

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Figure 4. Local time dependence of equatorial plasma bubble occurrence during 2014.
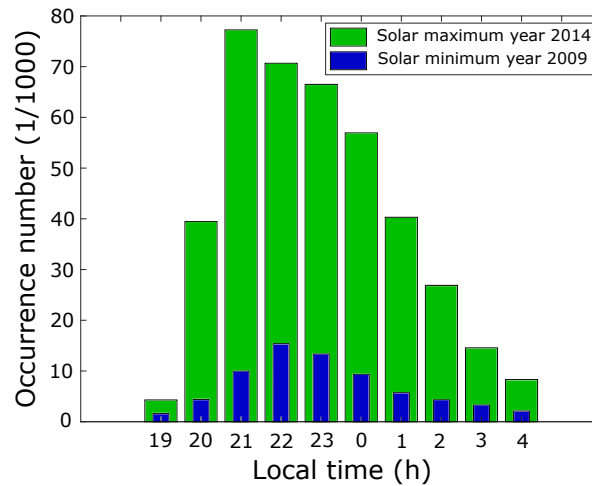
Figure 5. Occurrence of plasma bubbles based on local time during the solar minimum year (2009) and solar maximum year (2014) respectively.

~~study, region-wise analysis was performed.~~ analyze the region-wise seasonal occurrence characteristics of EPB, the longitude extent is discretized in four different sectors of 90° each, which includes America (110°W-20°W), Africa (20°W-70°E), Asia (70°E-160°E) and Pacific (160°E-110°W). These longitude sectors are further compared with different seasons based on three-month interval around each solstice and equinox. The region-wise seasonal occurrence is based on geomagnetic latitude with
5   respect to local time and envisaged in Fig. 6 which is similar to the seasonal-longitude occurrence presented for solar minimum conditions (2007-2011) by Carter et al. (2013). In comparison, in this study around 2.2 million profiles are analyzed to present
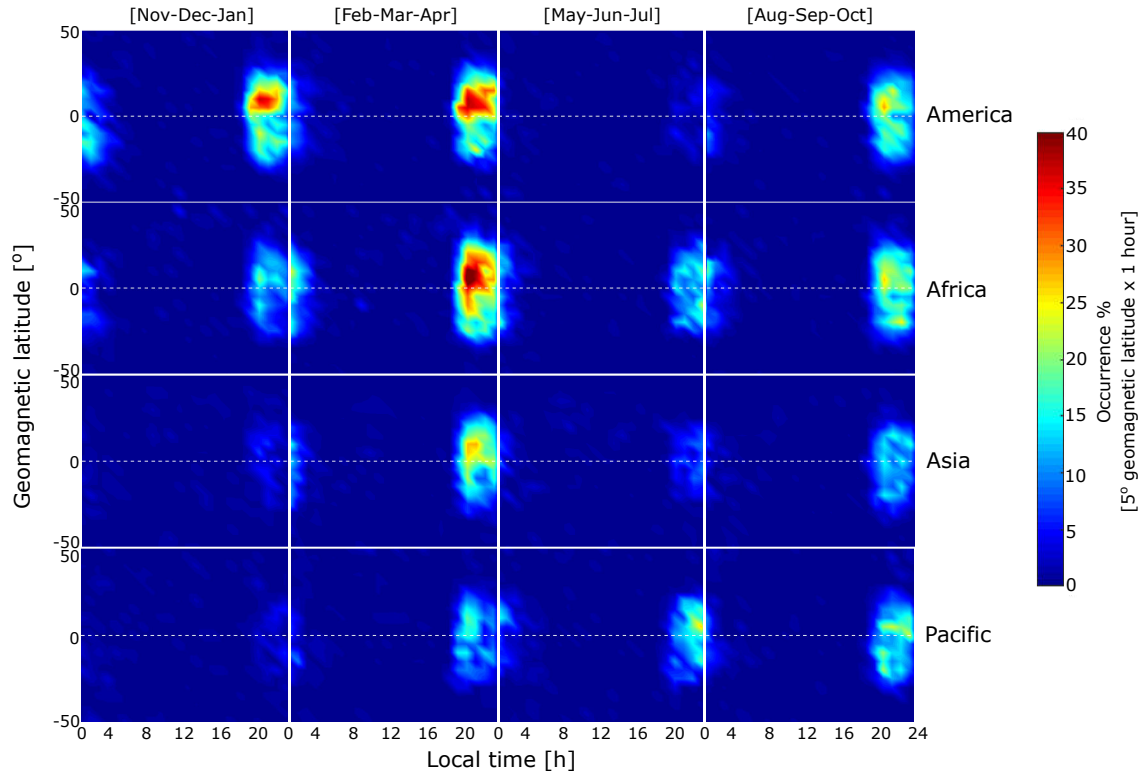
Figure 6. EPBs occurrence during the years 2012-2016 for different longitude sectors (regions) based on three-month intervals (season). White dashed lines represent geomagnetic dip equator.

EPB's distribution between 2012-2016 covering the crest of the solar cycle 24, i.e., 2014. In general, we observe that the EPBs are distributed on either side of the dip equator with only one maximum on the positive side of the dip equator across all longitudes and seasons. On the contrary, two maxima on either side of the dip equator were observed by Carter et al. (2013) during solar minimum condition using FormoSat-3/COSMIC data, whereas only one peak at the dip equator was observed by
5   Burke et al. (2004a) with Republic of China SATellite (ROCSAT)-1 observations in the period 2000-2002. In the American region, we see the substantial occurrence of EPBs across all the seasons, except the June solstice (May-June-July). Whereas in the African region, we see the comparable occurrence of EPBs across all the season but the least number of EPBs in the December solstice. Across all longitude sectors, the least occurrence of EPBs was recorded in Asia for most of the seasons. In principle, maximum occurrence during both equinoxes are observed in Africa and agrees well with the results presented
10   by Burke et al. (2004b) and Su et al. (2008); but it defers from the maximum equinoctial occurrence in America presented by Carter et al. (2013). This discrepancy for the maximum equinoctial occurrence could arise due to measurements involving different solar conditions; wherein during solar minimum conditions peak occurrence was observed in the American region (Carter et al., 2013), whereas during high solar activity we see peak occurrence in the African region.

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Furthermore, we see asymmetries in the equinox and solstice seasons. For example, we observe negligible EPBs during June solstice in the American sector compared to the rest of the seasons. This is because of the larger sunset time lag in the former that abstains from the formation of EPBs according to the hypothesis presented by Tsunoda (1985). Whereas more EPBs are seen during the June solstice than the December solstice in Africa, Asia, and Pacific region. But for this scenario, the sunset time lag approach could not justify the occurrence; however it was rationalized by Nishioka et al. (2008) citing the reason towards the integrated flux tube conductivities in the F-region and its seasonal occurrence which proved to be favorable for the solstice asymmetry in Africa, Asia, and Pacific sectors. On the aspect of equinox asymmetry, we see significant occurrence in March equinox (February-March-April) than September equinox (August-September-October) in America, Africa, and Asia, except the Pacific region and agrees well with Burke et al. (2004b). In general, few EPBs are recorded in the region where the strength of the equatorial magnetic field is strong in the Eastern hemisphere, e.g., Asian and parts of Pacific sectors. Whereas comparably more EPBs are observed in the region of a relatively weak equatorial magnetic field, i.e., American and African longitudes (Burke et al., 2004a, b).

3.3 Altitude variations and solar cycle dependency

The FormoSat-3/COSMIC measurements provide height dependent information, which is valuable as compared to the measurements from the other contemporary techniques for investigating plasma bubbles on a global scale. From the generalized notion, we know that the EPBs are generated in the bottomside of the F-region as a consequence of RTI and move upwards by means of the electrodynamic process (Whalen, 1997; Kelley, 2009; Woodman, 2009). For manifestation, we present the altitude distribution of EPBs in Fig. 7 on a year-wise basis. It is noticeable that the year-wise altitudinal distribution occurs in accordance with the different conditions of solar activity. The study also reveals that the periodic variation in the solar cycle plays an indirect role in influencing the vertical occurrence range of the plasma bubbles; wherein a large range is covered during high solar activity, i.e., 2014 and lesser altitude range during low solar activity, i.e., 2009. Besides, we observe peak occurrence at an altitude of $\sim 420\,$km during 2014, and $\sim 240\,$km during 2009. The extent to which the EPBs are uplifted in the altitude is motivated by the magnitude of the PRE which depends on the solar activity (Fejer et al., 1999; Stolle et al., 2008; Abadi et al., 2015; Liu et al., 2016). In addition, the EPBs which are primarily generated at the geomagnetic equator elongates in latitude due to the dominance of PRE (Abdu et al., 2003; Liu et al., 2016). This is obvious in the altitude distribution of the plasma bubbles; wherein during low solar activity the EPBs are almost contained at the geomagnetic equator, while during high solar activity the EPBs are spread out on either side of dip equator Liu et al. (2016). The seed perturbation along with the altitudinal variation of the EPBs is largely attributed to the PRE phenomenon which is an outcome of degenerated conductivity in the E-region along with enhanced zonal electric field at the sunset (Farley et al., 1970; Stolle et al., 2008; Su et al., 2014). Ideally, the PRE lifts the plasma in the F-layer by means of $E\times B$ drift to an altitude where the neutral-ion collision frequency is low which is inversely proportional to the growth rate of plasma bubble (Fejer et al., 1999; Abadi et al., 2015). In the process, the EPBs continue to proceed higher in altitude until the eastward electric field on the top of the bubble becomes zero and eventually they decay (Krall et al., 2010).
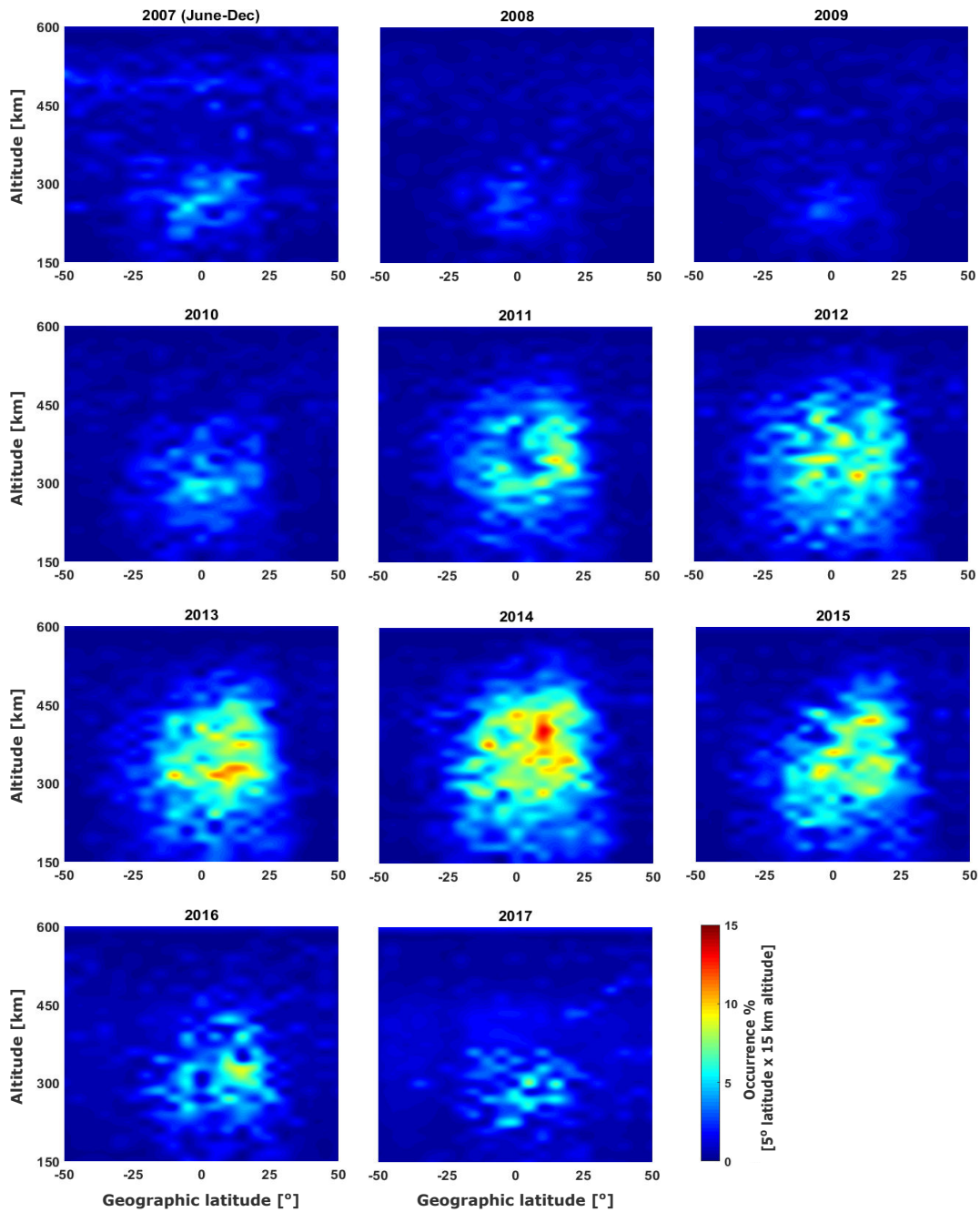
Figure 7. Plot of geographical latitude v/s altitude of equatorial plasma bubbles for showing vertical distribution during the years between mid-of 2007 and 2017.

From the occurrence climatology presented in this paper, it is apparent that the EPBs materialize in accordance with the solar activity by the influence of the seed perturbation such as PRE. Thus more EPBs are detected during maximum solar activity
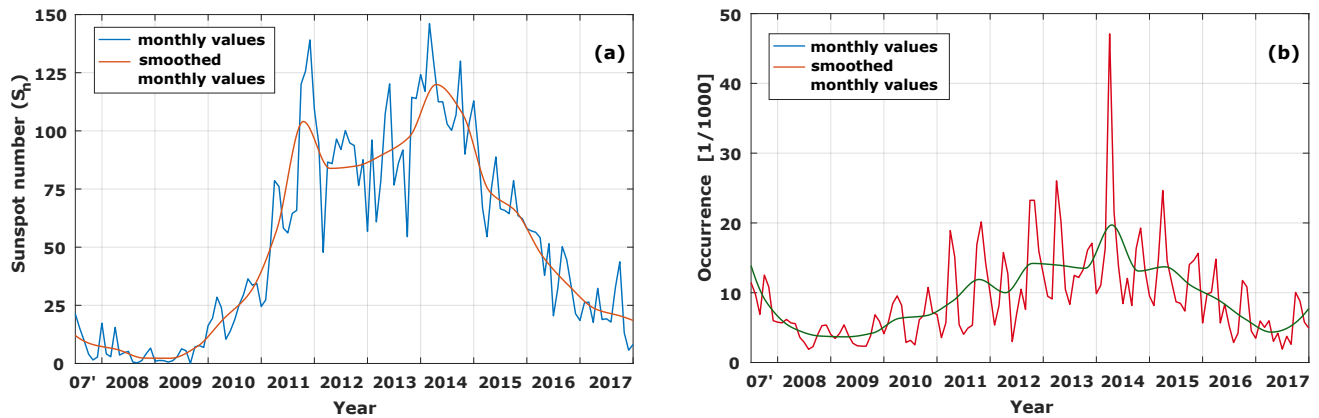
Figure 8. Comparison plot of (a) Sunspot cycle (b) Occurrence trend of equatorial plasma bubbles from mid-of 2007 to 2017, having monthly values and smoothed monthly values using low pass filter.

==than the minimum (Basu et al., 2002).== A brief analogy is presented in Fig. 8 in support with the argument, which shows the sunspot cycle and relative occurrence numbers of EPBs with semi-annual structures across different years. Further, Fig. 8a depicts the current sunspot cycle represented by the monthly number of sunspots (blue solid line) and a smoothed curve (orange solid line), whereas Fig. 8b shows an annual occurrence trend of plasma bubbles characterized by monthly (red solid line) and smoothed monthly values (green solid line) from mid-of 2007 to 2017. ==On the global spectrum, the EPBs occur in line with the solar activity; however, it is not a conventional scenario on a regional basis. Nishioka et al. (2008) showed that the influence of solar conditions is bounded to a particular region and season. For example, the EPBs in the African and Asian sectors appear in congruence with the solar cycle; however the same is not observed in the American sector as revealed in Fig. 3. This could most likely be due to the presence of gravity wave perturbations, which seed EPBs despite weak PRE magnitudes during solar minimum conditions in the South American region (Burke et al., 2004a; Stolle et al., 2008; Su et al., 2014).==

4   Conclusions

~~In this paper, a nine-year comprehensive study of equatorial plasma bubbles is presented using GPS-RO measurements obtained from the FormoSat-3/COMSIC mission~~ This paper provides a brief occurrence climatology of EPBs covering around 10.5 years of GPS-RO measurements derived from FormoSat-3/COSMIC. ==The scintillations induced in the radio waves caused by the EPBs are detected using amplitude scintillation index known as the S4 index. By classifying the S4 data, subsequent analyses are carried out by exploiting the strong scintillation events.== In this study, we see ~~intriguing charachteristics~~ that the EPBs occurring along the geomagnetic equator have peak occurrence oscillating between America and Africa during solar minimum and solar maximum years respectively. Furthermore, the year-wise global distribution of EPBs shows ~~striking~~ good congruency with solar activity, especially in Africa. ==Thus implying on the influence of vertical drift from PRE which also==

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depends on the solar activity. However, there is no clear dependency of the solar cycle in the American sector. On hindsight, it is also known, that gravity-driven current has a strong correlation on the occurrence of a plasma bubble only in the American sector. Therefore, it is presupposed that the EPBs are triggered with different seed perturbations for different regions. Apart from the global distribution of EPBs, we know that the EPBs develop post-sunset around 19:00 LT, right after the enhancement in the zonal eastward electric field at the sunset. From the local time of the EPB occurrence for different solar conditions, it is observed that the EPBs generated during solar maximum year peaks earlier than the EPBs during the solar minimum year. This implicates the dependency on PRE which has a stronger magnitude of vertical plasma drift during high solar activity than during low solar activity. On the other hand, when we analyzed region-wise seasonal occurrence, we observed maximum EPBs in Africa during ~~June~~ March equinox. Almost in all longitude sectors, more EPBs were detected in the March equinox than the September equinox. Whereas for solstice months it justifies the argument from Tsunoda (1985), wherein more EPBs are encountered at longitudes with positive (negative) declination during June (December) solstice and have good agreement with Burke et al. (2004b), Su et al. (2008), and Carter et al. (2013). Recently it was articulated by Xiong et al. (2010) through his comparative study of EPBs using CHAMP and GRACE in-situ measurements, that more EPBs are encountered at an altitude below 300 km than above. However, since the in-situ measurements detect the EPBs at its orbital altitude which is usually above ~ 400 km, some signatures of EPBs are merely detected. Thus, the GPS-RO becomes convenient for investigating the EPBs for their vertical soundings at the same time providing global resolution. ~~The study reveals the influence of solar cycle, which facilitates the contraction and expansion of plasma bubbles across the complete altitude range.~~ Meanwhile, these EPBs which are provoked by PRE show a strong dependence on the periodic variation in the solar activity with a larger altitude extent as we proceed towards the high solar activity. In principle, we observe that, throughout the global analyses, the annual EPBs occurrence have a strong dependency on solar activity, which was additionally compared with the sunspot cycle. Overall, the GPS-RO technique seems favorable in understanding the EPBs and could be used as a complementary technique in analyzing such ionospheric irregularities because of its unique measurements as a result of vertical scans.

Appendix A

A1

5 *Competing interests.* The authors declare that they have no conflict of interest.

Disclaimer. TEXT

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