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Key Points:

- The UPC GIM has been analyzed over both poles during 1.5 solar cycles confirming its slightly better performance compared to other IGS GIMs
- It presents realistic VTEC features over two poles, in agreement with previous higher resolution works and using non-GNSS measurements
- The climatology of the main VTEC polar features is obtained by means of the learning vector quantization (LVQ) unsupervised technique

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Polar Electron Content From GPS Data-Based Global Ionospheric Maps: Assessment, Case Studies, and Climatology

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Abstract The electron content distribution of the north and south polar ionosphere from 2001 to the beginning of 2019 is analyzed by using the UQRG global ionospheric map (GIM) of vertical total electron content (VTEC), computed every 15 min by UPC-IonSAT with a tomographic-kriging combined technique. We first show that the accuracy of UQRG GIM is slightly better than that of the GIMs of other analysis centers on the whole and also over both poles. Second, we show examples of polar VTEC features in UQRG GIM, previously reported by different authors and with higher-resolution techniques. Third, by means of an unsupervised clustering algorithm, learning vector quantization, we characterize the main features of the ionospheric electron content climatology, separately for the north and south polar regions.

1. Introduction

This paper focuses on studying the climatology of polar ionospheric features from electron content distribution, in both the north and south polar hemispheres including polar caps (hereinafter NP and SP). One example, deserving high interest in the recent years, is the tongue of ionization (TOI) and its associated patches.

It is believed that TOIs are plasma enhancements in the high-latitude F region. Along their edges form steep electron density gradients, which can lead to degradation in HF radio communications and disturbance in satellite navigation and communication systems. Therefore, the study of the occurrence of TOI and polar cap patches helps better understand the signature of the polar ionosphere. Despite the efforts of several researchers (Buchau et al., 1983, 1985; Chartier et al., 2018; Coley & Heelis, 1998; Dandekar, 2002; David et al., 2016; Liu et al., 2017; Noja et al., 2013; Sojka et al., 1994; Spicher et al., 2017), no agreement has been reached regarding the dependence factors of TOI or polar cap patches occurrence. This is due in part to the fact that data from diverse instruments (such as optical, HF and incoherent radar, and ionosonde) have limited spatial coverage or limited time span, or imperfect model simulation and partly due to different algorithms. Table 1 summarizes different dependence characteristics on polar cap patches. For instance, David et al. (2016) used high-resolution TEC maps from the Madrigal Database of Haystack Observatory to determine that the Northern Hemisphere TOI or patches have universal time (UT) and seasonal dependence. However, whether polar patches are a seasonal or annual phenomenon is called into question by the finds of Chartier et al. (2018). They used in situ plasma density observations and topside TEC data to detect TOI and found that TOI is not only a winter phenomenon but also occurs in the Southern Hemisphere summer.

A new data source to study TOI and other polar ionospheric features is the global ionospheric map (GIM) of vertical total electron content (VTEC). They are computed from Global Navigation Satellite Systems (GNSS), specifically from Global Positioning System (GPS) measurements by UPC-IonSAT with a tomographic-kriging technique (UQRG GIM), on a daily basis with latency of 1 day. This study is performed with the full UQRG data sets from 2001 to beginning of 2019, that is, more than 600,000 GIMs during the most recent one and half solar cycles.

Table 1
Studies on Occurrence Dependence of TOI and Polar Patches

Measurement/model source	Area	Dependence				Ref.
		Annual/ seasonal	UT/ MLT(LT)	Geomag./ IMF	Solar Cycle	
Digisonde	NH	x	UT	x	Solar Cycle	(Buchau et al., 1985)
The Utah State University time-dependent ionospheric model (TDIM) ^a	NH	Seasonal	UT	x	x	(Sojka et al., 1994)
The retarding potential analyzer (RPA), the ion drift meter (IDM), and the Langmuir probe aboard the DE 2 spacecraft	NH	Seasonal	UT	IMF	x	(Coley & Heelis, 1998)
foF2 data from Digital Ionospheric Sounding Systems at stations Sondrestromfjord and Qaanaaq	NH	Seasonal	MLT	IMF(weak)	Solar Cycle	(Dandekar, 2002)
9-years CHAMP TEC data	NH, SH	Annual	MLT	IMF	Solar Cycle	(Noja et al., 2013)
Madrigal GPS TEC maps (high-resolution)	NH	Seasonal	UT	x	x	(David et al., 2016)
The National Center for Atmospheric Research Thermosphere-Ionosphere Electrodynamics General Circulation Model (TIEGCM)	NH, SH hemispheric Asymmetry of TOI intensity	Seasonal dependence of UT Effects on TOI intensity	UT	IMF	x	(Liu et al., 2017)
Swarm: in situ plasma density measurements	NH, SH	Seasonal	x	IMF	x	(Spicher et al., 2017)
Swarm: in situ electron dens. by Langmuir probe and TEC from POD GPS receiver	NH, SH	Annual	x	Kp-independent	x	(Chartier et al., 2018)

^aSwitch between the A and DE patterns every 30 min with constant inputs: (a) The auroral oval parameters, specifically the electron energy flux and average energy, were obtained from (Hardy et al., 1987) model. (b) A solar maximum condition was assumed, represented by an F10.7 index of 210.

First, we will justify the selection of UQRG GIM, showing that it is the most accurate GIM also on polar regions. Then we will briefly describe examples of several types of polar ionospheric events observed from GIMs, which had already been studied by other authors. Finally, we will present the comprehensive results of unsupervised clustering of polar VTEC maps, showing the most frequent electron content patterns, and the key occurrence characteristics. As main conclusion, we answer the following question affirmatively: Can the GIMs provide reliable information on the polar ionospheric electron content distribution to allow the characterization of the climatology of polar ionospheric phenomena? It should be taken into account that the characterization is done in spite of the reduced number of permanent receivers, and in spite of the limited spatial resolution, that is, 5° in longitude and 2.5° in latitude (as pointed out, e.g., in Liu et al., 2014).

This paper is distributed in four sections, following section 1 and before section 6, *References*, and *Acknowledgments*:

- Introduction to UQRG GIM, performance, and topside electron content fraction byproduct.
- Six case studies of polar ionospheric events, comparing the GIM TEC footprints with the results from other authors, including those from higher-resolution regional VTEC models and different techniques.
- Summary of the learning vector quantization (LVQ) unsupervised clustering algorithm used to perform the climatological study of the polar ionospheres.
- Summary of the polar VTEC climatology, including some VTEC features discussed in the previous case studies.

2. The UQRG GIM Ionospheric Data Source: Performance and the Topside Electron Content Fraction μ_2 Byproduct

The GIMs have been computed since 1998.5 in the context of the International GNSS Service (IGS). They have become a reliable and open source of ionospheric information (VTEC), as it is shown in Hernández-Pajares et al. (2009, 2011, 2017).

UPC-IonSAT is one of the presently seven IGS ionospheric analysis centers. One product provided by UPC is UQRG GIM, with time resolution of 15 min and latency of 1–2 days. The long-term external assessment

Figure 1. Simplified layout of the dual-layer voxel-based tomographic model of the ionospheric electron content, directly estimated from the actual dual-frequency GNSS carrier phase measurements only, by applying a Kalman filter.

comparison of UQRG with other GIMs of UPC and the GIMs of CODE, JPL, ESA, NRCAN, CAS, and WHU shows that UQRG is slightly more accurate in both VTEC and slant total electron content (STEC), as it can be seen in Roma-Dollase et al. (2018). The UQRG GIM is based on a combined tomographic estimation and kriging interpolation technique applied to the measurements from 150–250 worldwide distributed GPS receivers.

The first step is the estimation of the mean electron density $(N_e)_{i,j,k}$ of the voxels providing a certain ionospheric partition $\{(i,j,k): i = 1, \dots, M_I, j = 1, \dots, M_J, k = 1, \dots, M_K\}$, which is 3-D distributed (see Figure 1) in two layers from the ground-based dual-frequency GNSS carrier phase data only, the L_1 and L_2 in length unit, as

$$L_I - (\lambda_1 - \lambda_2) \cdot \phi = \alpha \sum_{i=1}^{M_I} \sum_{j=1}^{M_J} \sum_{k=1}^{M_K} (N_e)_{i,j,k} \cdot \Delta l_{i,j,k} + B_I, \quad (1)$$

where for each pair GNSS transmitter-receiver, the ionospheric combination of carrier phases $L_I = L_1 - L_2$ is known (measured), and the wind-up correction term due to the relative rotation ϕ of transmitter and receiver antenna is also known and corrected for permanent receivers, considering as well the ray-path-length inside each illuminated voxel (i,j,k) , $\Delta l_{i,j,k}$, which is computed by the very good approximation of straight-line propagation; finally, $\alpha \simeq 1.05 \text{ m/TECU}$ is the scaling factor derived from the Appleton-Hartree equations (see, for instance, Hernández-Pajares, 2010; Hernández-Pajares et al., 2011).

The unknowns are estimated by the TOMION-v1 software, developed by the first author, by implementing a forward scalar Kalman filter, modeling the mean electron densities as random walk processes in a Sun-fixed reference frame and the ambiguities as random variables (“constants”). It yields more accurate and precise results because (1) it significantly reduces the modeling error associated to the fixed-height single-layer models, as it was demonstrated in Hernández-Pajares et al. (1999), and (2) it avoids the usage of dual-frequency ionospheric pseudorange combination, strongly affected by the multipath and thermal noise.

The second step is the interpolation to fill the gaps of measurements, due to the lack of a full coverage of GNSS receivers, especially important over the oceans, the Southern Hemisphere, Siberia, central Africa, and partially in the south polar region (see in this case its difference of illumination coverage regarding the north polar region at μ_2 plots in Figures 5 and 6). The input data of interpolation are the individual VTEC values obtained from each measurement, after subtracting the best estimation of the carrier phase ambiguity value in equation (1). This is typically the last one of the continuous-phase transmitter-receiver arc, available in postprocessing, which is the case of UQRG GIM computation. Afterward, the slant TEC S is obtained as $S = (L_I - (\lambda_1 - \lambda_2) \cdot \phi - B_I) / \alpha$ and converted to VTEC with the single-layer mapping function with constant height at 450 km (see Hernández-Pajares et al., 2011), adopted in IGS by the different ionospheric computation centers. Finally, the kriging technique is applied on such individual VTEC estimations, which efficiently takes into account the ionospheric model error decorrelation lengths in the interpolation process (Orús et al., 2005).

Figure 2. Distribution of the daily standard deviation values between the GIM VTEC and the 9,647,398 direct VTEC measurements available from TOPEX, JASON-1, and JASON-2 altimeters, around the north pole (latitude greater than 50°) between Day 7 of year 2002 and Day 360 of year 2018. They correspond, from left to right and from top to bottom, to the CODG, ESAG, IGSG, JPLG, UPCG, and UQRG GIMs.

2.1. UQRG GIM Also Performs Slightly Better Than Other GIM Products on Polar Regions

As it has been mentioned previously, the UQRG GIM behaves better than other GIMs at global scale (Roma-Dollase et al., 2018), but previously, no specific comparison has been made restricted to the polar regions. It can be seen in Figures 2 and 3 the distribution of daily standard deviations of the difference between the reference direct VTEC altimeter measurements (TOPEX, JASON-1, and JASON-2) and the corresponding interpolated GIM VTEC values, from 2002 to 2018, for the north and south polar regions (latitudes above +50° and below −50°, respectively). Table 2 shows that UQRG has a performance slightly better, for instance, in terms of average of the daily standard deviation of the altimeter and GIM VTEC difference, than the performance of the final GIMs of the IGS analysis centers and their combination, in both NP and SP: See in Table 2 the first and second better behaving GIMs emphasized in bold and underline, respectively, for both distribution mode and average. And this is mostly due to the technique being used, rather than the higher temporal resolution of UQRG (15 min) compared with the final GIMs (2 hr), as it was demonstrated in section 3.1 of Roma-Dollase et al. (2018). Hence, we conclude that the UQRG GIM time series is an appropriate candidate to attempt to detect significant polar TEC features and to extract the polar electron content climatology, as indicated in next sections.

Table 2

Summary of Daily Standard Deviations of GIMs Versus Direct Altimeter VTEC Measurements, in TECUs, in NP (With Latitudes Above 50N) and SP (With Latitudes Below 50S), and from 2002 to 2018

GIM Id.	Daily std. dev. vs. altimeter VTEC			
	NP		SP	
	Mode	Average	Mode	Average
CODG	1.8	2.0	2.2	3.0
ESAG	1.8	2.4	2.2	3.6
IGSG	1.5	1.8	1.8	<u>2.7</u>
JPLG	1.7	2.0	2.1	2.6
UPCG	<u>1.6</u>	<u>1.9</u>	<u>2.0</u>	2.8
UQRG	1.5	1.8	<u>2.0</u>	2.6

Note. It summarizes the detailed results described in Figures 2 and 3.

Figure 3. Distribution of the daily standard deviation values between the GIM VTEC and the 33,115,960 direct VTEC measurements available from TOPEX, JASON-1, and JASON-2 altimeters, around the south pole (latitude lower than -50°) between Day 7 of year 2002 and Day 360 of year 2018. They correspond, from left to right and from top to bottom, to the CODG, ESAG, IGSG, JPLG, UPGC, and UQRG GIMs.

2.2. The Topside Electron Content Fraction μ_2 Byproduct

The GIM is not the only product obtained from this approach. Before the interpolation step, the fraction of topside electron content, μ_2 parameter, can be derived from the tomographic run. It is defined as follows from the two simultaneously estimated mean electron density values, $(N_e)_{i,j,1}$ and $(N_e)_{i,j,2}$, at mean heights of 450 and 1,130 km, respectively (see Figure 1), and for the same horizontal voxel index (i,j) :

$$(\mu_2)_{i,j} = \frac{(N_e)_{i,j,2}}{(N_e)_{i,j,1} + (N_e)_{i,j,2}}. \quad (2)$$

As it has been commented above, the dual-layer model of the ionospheric electron content is necessary for a more accurate determination of VTEC from ground GNSS data, compared to single-layer models, as shown in Hernández-Pajares et al. (1999). However, this is still a simplification by which estimations need to be interpreted properly, especially in atypical cases when μ_2 can be

- Slightly negative, when the $P_2 = (N_e)_{i,j,2} \cdot \Delta h$ the partial electron content of the second layer with thickness Δh is slightly negative. This happens when almost all the electron content is placed below the effective height of the first layer (450 km).
- Slightly larger than one (with $P_1 = (N_e)_{i,j,1} \cdot \Delta h$ the partial electron content of the first layer slightly negative, when almost all the electron content is placed above the effective height of the second layer (1,130 km).

It can be demonstrated from the following approximation:

$$STEC = M_1 \cdot P_1 + M_2 \cdot P_2 = M \cdot V. \quad (3)$$

The mapping function M_1 , M_2 , and M depend on the effective height. The greater the effective height is, the smaller the mapping function is. H_1 and H_2 are defined as 450 and 1,130 km, the central height for each layer, corresponding to M_1 and M_2 . And H represents the real effective height, corresponding to M .

When H is greater than H_2 , for example, during the nighttime when most of the electron density is distributed in the plasmasphere, then $H > H_2 > H_1$ and thus $M_1 > M_2 > M$. Equation (3) can be written as

$$(M_1 - M) \cdot P_1 = (M - M_2) \cdot P_2. \quad (4)$$

Figure 4. VTEC maps in NP (left) and SP (right) at 1700 UT on 5 November 2012. The VTEC scale is given in 0.1 TECUs, the same as the remaining VTEC GIMs in this section. The red star represents the corresponding magnetic pole.

It can be seen that $M_1 - M$ is positive and $M - M_2$ is negative, which means that P_1 and P_2 have opposite signs. Since $V = P_1 + P_2$ must be positive and $|P_2| > |P_1|$, so we get positive P_2 and $P_2 > V$. Therefore, $\mu_2 = P_2/V$ is greater than 1.

In the case that most of the electron density is distributed below 450 km, positive P_1 and negative P_2 can be similarly deduced by means of equation (4), thus negative μ_2 .

The negative P_1 and P_2 seem unreasonable at the first glance based on their definition. But from the point of view of modeling, it is consistent with the assumption of the two layers where electron density is homogeneously distributed. So from real data and the simplified dual-layer model, whether μ_2 is negative or greater than 1, both cases can be derived and represent realistic electron density distribution.

To avoid negative values of μ_2 in the plots, $\mu_2^* = \mu_2 + 1$ will be represented instead of μ_2 , which is obtained from the direct estimation in the tomographic model, and stored internally at UPC premises for the daily global runs performed since 1998.5 within IGS. μ_2 is not only an indicator of the relative vertical distribution of free electrons as we will see below, but it is also a useful driver of an improved ionospheric mapping function, as it has been recently demonstrated at midlatitudes in Lyu et al. (2018).

3. UQRG GIM Reveals Relevant Features Detected With Higher-Resolution Techniques: Six Case Studies

In this section, we are going to confirm the capability of UQRG GIM to realistically detect different polar content features. This is demonstrated through some representative case studies previously reported by other authors with different and higher-resolution techniques: TOI, ionospheric trough, flux transfer event (FTE), theta-aurora, ionospheric convection patterns, and storm-enhanced density (SED).

3.1. TOI

As it has been mentioned in section 1, the TOI and associated patches are special features of the polar ionosphere, which are believed are plasma enhancements in the high-latitude F region.

The UQRG GIM VTEC map at 1700 UT on 5 November 2012, when the NP TOI was reported in David et al. (2016), is shown at the left-hand plot of Figure 4. This is fully consistent in extension, shape, and VTEC level (up to around 20 TECU in the TOI) with Figure 2 of David et al. (2016), obtained with a higher-resolution VTEC mapping technique. In addition, a simultaneous TOI happened in the SP, which can be seen at the right-hand plot of Figure 4.

Another interesting feature about TOIs in SP is that most of the TOIs cross or direct to the south magnetic pole (see four examples at different UT times in Figure 5), which is located in the range (136° E–138° E, 63° S–64° S) from 1998 to 2015. The frequent appearance of this feature shows the TOI bends from its origin at the daylight hemisphere side toward the magnetic pole. It is noticeable that the μ_2 values within the TOIs

Figure 5. Four typical SP VTEC maps showing TOIs, and the associated μ_2 distribution, corresponding to the year-DOY-UT: 2001-079-1745, 2001-148-1345, 2002-047-1545, and 2012-288-2145 (from left to right and from top to bottom). The white area in all the VTEC maps of this context represents VTEC values greater than 40 TECU. In the right panel of each subplot, the values in colorbar are $\mu_2^* = \mu_2 + 1$. The red star represents the corresponding magnetic pole.

are typically smaller than those in the surrounding night polar ionosphere, for example, the case at 1745 UT of day of year (DOY) 079, 2001 in Figure 5, showing μ_2 in the TOI around [0.3, 0.8] compared to the range approximately between 1.0 and 1.5 in the rest of nightside ionosphere. The smaller μ_2 values represent the associated electron content being distributed significantly lower in height. While, when TOI and the daylight areas are compared, the μ_2 values change slightly. It indicates that the ionospheric effective height, where the free electron can be considered concentrated in a simplified view, almost keeps constant in the TOI from the dayside part. This agrees with the result obtained from Digisonde that the virtual heights in the ionograms did not change during transit of the arcs through the zenith (Buchau et al., 1983).

3.2. Trough and Dawnside Drifting Structure

An ionospheric trough is a region of depleted ionization, limited in width but extended in the east-west direction, with more intense regions to the north and south (Hunsucker & Hargreaves, 2007). Taking 1745 UT on DOY 041, 2003 (Figure 6) as an example, from the left panel, it is easy to see the midlatitude trough

Figure 6. VTEC and μ_2 NP maps at 1745 UT on DOY 041, 2003, from UQRG GIMs. In the right panel, the values in colorbar are $\mu_2^* = \mu_2 + 1$. The red star represents the corresponding magnetic pole.

Figure 7. IMF B_y and B_z components on DOY 041, 2003, downloaded from the website (https://omniweb.gsfc.nasa.gov/ftpbrowser/wind_swe_2m.html).

(in purple), also called as the main ionospheric trough, in the nightside sector. And the right panel shows that μ_2 values in the trough are above 0.8 (corresponding to the represented values of $\mu^* = \mu_2 + 1 > 1.8$), greater than those in the surrounding area. Big μ_2 , implying high ionospheric effective height, corresponds to decrease in concentration of O+ and a typical midlatitude trough feature- enhanced electron temperature. According to the proportional relationship between temperature and scale height, the high temperature would increase the scale height in the topside part, resulting in slow decay of electron density above the peak, thus increasing the ionospheric effective height. Apart from the trough, the ring-like enhanced ionization area is clear in VTEC map of Figure 6, which will be confirmed in the polar climatology summarized in section 5 (see, for instance, the third and second columns of Figure 16). In this case study, at 1745 UT, the interplanetary magnetic field (IMF) y component, B_y , is negative and the z component, B_z , is switching from northward to southward (see Figure 7). The convection theory (Sojka et al., 1993) suggests that, for negative B_y when IMF is southward, the flow is across the duskside of the polar cap. While the structure in the VTEC map appears to be dawnside, thus the convection pattern needs to be further investigated by theoretical model.

3.3. FTE

On 13 February 2001, the transpolar propagation of large-scale traveling ionospheric disturbances (TIDs) from the nightside source region to the dayside was reported by Cai et al. (2011). On 14 February, the magnetospheric FTEs are observed by Cluster spacecraft (Wild et al., 2001, 2003). As demonstrated in Table 2, UQRG can provide good VTEC estimation with the kriging interpolation technique, in spite of the limited number of permanent receivers during these early times especially in SP. The VTEC maps in both hemispheres (see Figures 8 and 9) show the ionospheric response to these events. NP VTEC Maps from 11 February (DOY 041) to 17 February (DOY 047) 2001 have been closely examined. It is worth mentioning that only a series of VTEC maps from 1900 UT of DOY 044 to 0500 UT of DOY 045 with 2-hr interval has been shown in figures to avoid excessive length. TOI occurred and lasted for around 4 and 5 hr after 1500 UT for DOY 041 and 042, respectively. From 2330 UT of DOY 043 to 0100 UT of DOY 044, two-TOI-like structure presented, which is similar to that in the bottom-left plot of Figure 8. Afterwards, between 1700 UT of DOY 044 and 0200 UT of DOY 045, very strong TOI appeared, then drifting to the duskside and back to the dawnside later, and gradually forming a loop and then separating into two-TOI-like structure again. In the second half day of DOY 045, TOI was formed from 1315 UT to 1730 UT. Whereas, on both DOY 046

Figure 8. From left to right and from top to bottom: NP VTEC maps from UQRG GIMs, showing the development of TOI and patches each 2 hr from 13 February 1900 UT to 14 February 0500 UT, 2001. The red star represents the corresponding magnetic pole.

and 047, no obvious TOI showed up. From SP VTEC maps, TOI appeared in two time slots [0600 UT, 0730 UT] and [2145 UT, 2330 UT] on DOY 044, 2001, 3 days before which no TOI showed up. What is interesting is a swan-shape structure, which is drifted TOI, occurred around 0200 UT on DOY 045, 2001. And on the same day, TOI can also be seen from 1130 UT to 1500 UT. The specific NP feature that two-TOI-like structure appeared and merged later on might be related to FTE or directly to the geomagnetic disturbance caused by FTE. The mechanism is still unknown, and it is worth investigating with other measurements.

3.4. Theta-Aurora VTEC Observation in SP

During 1638–2000 UT of 15 September, Day 258 of year 2005, direct observations of closed magnetic flux, in correspondence with a small and thin transpolar arc over SP, were taken by the FUV Wideband Imaging Camera of the IMAGE satellite (see Figure 4a in Fear et al., 2014). We have detected the formation of a sort of transpolar arc, longer and thicker, during this day, before the pass of the satellite. It can be seen at bottom of Figure 10, in the SP VTEC snapshots at 1115 UT and 1515 UT, with two associated depletions at both sides. Moreover, a ring of enhanced electron content was very clearly formed at 1515 UT (see bottom-right plot in Figure 10). During the IMAGE satellite pass at 1915 UT, this VTEC feature obtained from UQRG GIM was weaker but still present and consistent as it is shown in Figure 11. It was located around the south magnetic pole, about 138° E, 64° S at such a time, with a radius of 15° approximately, in concordance with the above-mentioned figure of Fear et al. (2014). The aforementioned features together with a midtranspolar arc can be considered as part of such “theta-aurora” happened during northward IMF as explained in the same reference.

3.5. GIM Footprint of Ionospheric Convection Patterns

In Figure 12, we can see how clearly a typical two-cell convection pattern of VTEC is captured by UQRG GIM. This result is fully consistent with the convection patterns found by means of the large-scale coverage of the flows provided by the Super Dual Auroral Radar Network (SuperDARN) radars and with the GPS-based VTEC patches reported in NP and approximately at the same times in Figure 2 of Zhang et al. (2015). Although this event happened during southward IMF, that is, during its reconnection with the geomagnetic field (see in Zhang et al., 2015, additional details, including the full Dungey convection cycle

Figure 9. From left to right and from top to bottom: SP VTEC maps from UQRG GIMs, showing the development of TOI and patches each 2 hr from 13 February 1900 UT to 14 February 0500 UT, 2001. The red star represents the corresponding magnetic pole.

context), the fact that the corresponding representative normalized VTEC map shows a similar feature (see Figure 17, fifth row and third column plot corresponding to NP at 2145UT) would suggest the possibility that this two-cell convection pattern might happen in different conditions too, in spite of its occurrence (see the first row and third column plot in Figure 18) being lower close to solar cycle maximum conditions of Figure 12.

3.6. SED

During geomagnetic storms, F-region ionospheric plasma from lower latitudes in the afternoon sector is transported polewards. Consequently, a latitudinally narrow region of SED and increased TEC is carried toward higher latitudes in the noon sector (Foster, 1993). The distribution of NP VTEC during major geomagnetic storms, including Halloween Storms of 2003 and the other two cases with K_p index around 7 and 8.7, respectively, is shown in Figure 13. The feature that the enhanced TEC plumes are concentrated in the premidnight and postnoon sector (Foster et al., 2005) can be seen in these four examples on Halloween Storms of 2003, DOY 324, 2003, and DOY 150, 2005.

4. The Unsupervised Clustering Algorithm of Polar Ionospheric Maps: LVQ

In order to better perform a first systematic analysis of the polar VTEC climatology from the large UQRG GIMs database, we have selected an unsupervised clustering system that enables to find representative prototypes of the VTEC maps directly extracted from the GIMs. This will also allow to characterize the occurrence of its predominant morphology and features. To carry out this analysis, we have chosen the LVQ algorithm, (Kohonen, 2012) and (Murtagh & Hernández-Pajares, 1995). The reason for selecting the LVQ algorithm instead of other clustering algorithms, such as k -means or LBG (Linde et al., 1980), lies in the fact that it is an adaptive algorithm and does not require any a priori categorization that might bias the analysis, as it was shown, for instance, in classification of astronomical populations (Hernández-Pajares, 1993) or in GNSS ionospheric determination (Hernández-Pajares et al., 1997).

As it was detailed in Hernandez-Pajares and Floris (1994), the aim of this unsupervised classifier is to find a smaller set of $C = \{c_1, \dots, c_p\}$ of p centroids that provides a good approximation of the original set S of

Figure 10. SP VTEC during 15 September, Day 258, of year 2005 at 0715 UT, 1115 UT (the first row), 1515 UT, and 1915 UT (the second row), extracted from UQRG GIM. The red star represents the corresponding magnetic pole.

n ionization-level-independent, that is, normalized polar VTEC map (input space) with m attributes, that is, the number of pixels, encoded as vectors $\mathbf{x} \in S$. Intuitively, this means that for each $\mathbf{x} \in S$, the distance $\|\mathbf{x} - \mathbf{c}_{f(\mathbf{x})}\|$ between $\mathbf{x}$ and the closest centroid $\mathbf{c}_{f(\mathbf{x})}$ should be small.

The LVQ clustering algorithm can be summarized as follows:

1. We define the number of centroids p and the number of times (number of epochs) for which the whole database is run through the algorithm.
2. We initialize the values $C = \{\mathbf{c}_1, \dots, \mathbf{c}_p\}$ of the p centroids from p input observations randomly selected. After training, every centroid $l \in \{1, \dots, p\}$ will represent a set of normalized polar VTEC maps, and the weight vector $\mathbf{c}_l$ will approximate to the *center of mass* of this set.
3. We initialize counter: j that denotes the iteration, that is, the updated timestamp of the centroids.
4. For iteration 1 to number of epochs:
 - (a) For each of the n training vectors of the overall database, $\mathbf{x}_i$, the following procedures are carried out:
 - i. We find the node k whose weight $\mathbf{c}_k$ best approaches $\mathbf{x}_i$ (d represents in this case the Euclidean distance in the space $\mathbf{R}^n$, where n is the number of grid values of any polar VTEC map: $d(\mathbf{c}_k, \mathbf{x}_i) \leq d(\mathbf{c}_l, \mathbf{x}_i), \forall l \in \{1, \dots, p\}$).
 - ii. We update the weight of the winning node k and its neighbors, $N_k(i)$, approaching the training vector as closely as possible:

$$\mathbf{c}_l(i) = \begin{cases} \mathbf{c}_l(i-1) + \alpha(i) [\mathbf{x}_i - \mathbf{c}_l(i-1)] & \forall l \in N_k(i) \\ \mathbf{c}_l(i-1) & \forall l \in \{1, \dots, p\} - N_k(i) \end{cases} \quad (5)$$

Figure 11. Collocated electron content distributions, obtained during September 15, 2005, 1915 UT approximately, in FUV by NASA's IMAGE satellite (kindly provided at https://www.esa.int/ESA_Multimedia/Images/2014/12/Theta_aurora_as_seen_by_NASA_s_Image_satellite_on_15_September_2005, left-hand plot) and by UQRG GIM based on GPS ground-based measurements (right-hand plot, with colorbar ranging from 0 to 10 TECU). Both depletion and the central transpolar arc can be seen in compatible positions, taken into account that the right-hand plot is oriented approximately 30° clockwise relative to the left-hand plot.

Here, $\alpha(i)$ is a suitable, monotonically decreasing sequence of scalar-valued gain coefficients, $0 < \alpha(i) < 1$. The justification of this parameter is related to the Robbins-Monro algorithm (Robbins & Monro, 1951), which guarantees the convergence of an iterative estimation of a mean parameter of a Gaussian distribution. A choice for fast convergence is, for example, a linear decrease of $\alpha(i)$ during the first 1,000 epochs in a range between 0.9 and 0.1 (ordering period). Then after this initial phase, $\alpha(i)$ should attain a final value below or equal to 0.01, with a decrease proportional to the inverse of the iteration number, that is, $\alpha(i) \propto 1/i$.

The distribution of $\{c_1, \dots, c_p\}$ is an approximation of the continuous probability density function of the vectorial input variable $\mathbf{g}(\mathbf{x})$ (actually it follows $[\mathbf{g}(\mathbf{x})]^{\frac{m}{m+2}}$; Kohonen, 1990, p. 1466).

5. Climatology of the Polar Ionospheres

We analyzed with LVQ the time series of polar VTEC maps during over 6,600 days from 1 January 2001 to 14 February 2019, from the inputs consisting of about 640,000 UQRG GIMs with a sampling time interval of 15 min.

Since the polar ionosphere has pronounced daily variations depending on universal time (David et al., 2016; Hunsucker & Hargreaves, 2007), each UT in the data set has been examined independently. The geographic coordinate system is selected to show the electron content distribution, because this can help avoid any interpolation and analyze directly the values provided by the GIMs, and by μ_2 , regardless of the level of magnetic field deviation from the standard dipolar model. It is worth noticing that both magnetic poles in the Northern and Southern Hemispheres present a slow drift during the period in question: from 81.3° N, 160.06° W and 64.6° S, 138.5° E respectively in 2001, to 86.29° N, 160.06° W and 64.28° S, 136.59° E in 2015 (see, for instance, https://en.wikipedia.org/wiki/South_Magnetic_Pole, Manda & Purucker, 2018; Witze, 2019). And this can produce a small smoothing effect, especially in the north polar region. The NP and SP were split with 45N and 45S as the respective latitudinal borders, and the GIM resolution of 5°, 2.5°, and 15 min in longitude, latitude, and time is maintained, which is high enough to detect large-scale patches with hundreds of kilometers to several thousand kilometers in the horizontal dimension, as it has been illustrated in previous section.

To study this long time period, the 1,260,000 polar VTEC maps were normalized by a L2 norm as a pre-processing step before the clustering procedure. The geomagnetic activity has not been taken into account

Figure 12. UQRG GIM VTEC in NP during 17 January 2013, during approximately the same times as those in Figure 2 in Zhang et al. (2015), in this case (from left to right and from top to bottom): 1730 UT, 1815 UT, 1930 UT, 1945 UT, 2030 UT, 2100 UT, 2130 UT, 2200 UT, and 2230 UT.

due to the relatively small percentage of significantly active days. For the period considered, that is, from 2001.0 to 2018.3, 92% of the time is free from geomagnetic storms ($K_p < 4$). So the clustering results should be considered representative of the predominant quiet-time conditions. Therefore, we are able (1) to detect the most frequent features, also with low ionization level, for example, in nighttime during minimum solar cycle conditions; the time evolution and asymmetry between both poles of corresponding mean VTEC values are shown in Figure 14, which are consistent with the VTEC annual asymmetry with higher values in January than in June (Gulyaeva et al., 2014). The cause of ionospheric annual asymmetry is still unknown, which cannot be explained by the 7% annual asymmetry in photoionization caused by the Sun-Earth distance effect. The suspected cause includes atomic oxygen production, planetary waves, gravity waves, and ionosphere-atmosphere interactions, as it can be seen, for instance, in Rishbeth and Müller-Wodarg (2006), Gulyaeva et al. (2014), and Lei et al. (2016). And (2) to use the inner product among the normalized vectors representing each polar VTEC map to derive their distance (see in Figure 15 the mean projection of every polar VTEC map regarding the corresponding cluster in both polar regions, also in agreement with higher asymmetry around south pole). The unsupervised LVQ algorithm, as indicated in the introduction,

Figure 13. Four NP cases for storm-enhanced TEC on 2 days (DOY 302 2215 UT and 303 2100 UT, 2003) of "Halloween Storms" (top), on DOY 324 1745 UT, 2003 (bottom-left), and DOY 150 1745 UT, 2005 (bottom-right), directly obtained from the corresponding UQRG GIMs. The red star represents the corresponding magnetic pole.

was applied independently for each UT and polar region on the time series of normalized polar VTEC maps, providing the corresponding clustering and representative map.

After considering different maximum numbers of centroids in the LVQ clustering procedure of the normalized polar VTEC maps, we selected 4 because it provided more clear differences between clusters, easier to interpret. In fact, the typical clustering result of three centroids obtained in the majority of the 96 UT values (from 0000 UT, every 15 min) can be interpreted as the existence of just three main groups of GIMs, which are described below. Additionally, we have considered the polar maps of the topside electron content fraction, μ_2 , which have been helpful in some cases above to interpret VTEC features in terms of changes in the vertical electron content distribution.

The clustering representatives of the normalized GIMs defined with latitudes above 45N are shown in Figures 16 and 17 for the north polar region and in Figures 19 and 20 for the south polar one. They are shown from top to bottom every 2 hr, starting from 0145 UT, corresponding every column to each one of the three groups of clusters.

In Figures 16 and 17, it can be appreciated that the NP structures corresponding to the three groups of normalized VTEC clusters mostly rotate in function of UT, following a main local time (LT) dependence. These clear patterns are different that the SP ones that distort and change more significantly (Figures 19 and 20). This is fully consistent with the north-south asymmetry in the geomagnetic field, as described in

Figure 14. Average VTEC evolution for NP and SP (red and green points, respectively), extracted from UQRG GIMs from 2001.0 to 2019.5.

Laundal et al. (2017). The authors show how the Earth's magnetic field deviates significantly from dipolar model at ionospheric altitudes, especially in terms of magnetic field strength, and geographic-magnetic poles offset that is higher in the Southern Hemisphere (see the end of section 5.2.1 at Hunsucker & Hargreaves, 2007). This asymmetry also explains why the repeatability of μ_2 found in each group of clusters, when it is represented versus LT for a given latitude, is higher in NP (third row of Figure 18) compared with SP (third row of Figure 21).

In order to detect solar cycle- and seasonal-related patterns, the histograms of occurrence per year, and per DOY, which are very similar for the overall UTs given a group of clusters, are also represented in the first and second rows of Figures 18 and 21, for the north and south polar regions, respectively (they follow the same columnwise ordering of the corresponding groups of clusters as the same as in previous figures).

Figure 15. Mean of the projection difference of the overall analyzed UQRG GIMs from 2001.0 to 2019.5 regarding to the cluster representative for the north and south polar regions, versus the time corresponding to each independently performed LVQ.

Figure 16. Centroids of normalized NP VTEC maps (latitudes $\phi \geq 45^\circ$) in the LVQ computed with 2×2 neurons from UQRG VTEC GIMs from 2001 to the beginning of 2019 for 01.75UT (first row), 03.75UT (second row), 05.75UT (third row), 07.75UT (fourth row), 09.75UT (fifth row), and 11.75UT (sixth row).

Figure 17. Centroids of normalized NP VTEC maps (latitudes $\phi \geq 45^\circ$) in the LVQ computed with 2×2 neurons from UQRG VTEC GIMs from 2001 to the beginning of 2019 for 13.75UT (first row), 15.75UT (second row), 17.75UT (third row), 19.75UT (fourth row), 21.75UT (fifth row), and 23.75UT (sixth row).

Figure 18. Occurrence per year (first row), occurrence per day of year (second row), and μ_2 values at a latitude of 60N versus local time of the north polar region GIMs associated to the first, second, and third group of clusters (first, second, and third columns, respectively) for all the times.

The ionospheric trough can be clearly appreciated in the second group of normalized NP VTEC map clusters (second column of Figures 16 and 17). It is distributed around 0000LT to 0600LT, typically from 0015LT to 0515LT, and with latitudes around 60N (this has been determined after applying a histogram equalization technique; Gonzalez & Woods, 2002), to highlight the area of depletion in the representatives of the second group of clusters. They happen mostly during solar maximum conditions and from September to November and February to March (see the first and second rows in the second column of Figure 18). The higher value of the topside electron content fraction μ_2 at night happens in this second group of clusters, which reaches up to 0.9 coinciding with the trough occurrence at latitude 60N (see plot in the second column and the third row of Figure 18), confirming as well in climatological terms the simultaneous electron content uplift found in the trough case study summarized above (section 3.2).

It can be seen in the third group of NP clusters (third column in Figures 16 and 17) a systematic ring of relatively high electron content in the night sector, from about 55° N to 90° N and from around 2100LT to 0300LT. This happens especially from 2345 UT to 1545 UT and under solar minimum conditions and from November to February, that is, in winter and part of local fall (see occurrence histograms at the first and second rows of the third column in Figure 18). A less clear ring is also found in the second group of clusters of NP (second column of Figures 16 and 17). It appears during solar maximum conditions in a similar LT interval but mostly during the period from September to November and February to March (see plots at the first and second rows of the second column in Figure 18).

Mean relative structures of electron content resembling TOIs or partial rings, or either dual rings (see section 3.5), can be also found during the time from 1745 UT to 2145 UT in clusters, represented in columns 3 and 2 of Figures 16 and 17, mostly happening during local summer, spring, and fall seasons at any solar cycle time (Figure 18).

Figure 19. Centroids of normalized SP VTEC maps (latitudes $\phi \leq -45^\circ$) in the LVQ computed with 2×2 neurons from UQRG VTEC GIMs from 2001 to the beginning of 2019 for 01.75UT (first row), 03.75UT (second row), 05.75UT (third row), 07.75UT (fourth row), 09.75UT (fifth row), and 11.75UT (sixth row).

Figure 20. Centroids of normalized SP VTEC maps (latitudes $\phi \leq -45^\circ$) in the LVQ computed with 2×2 neurons from UQRG VTEC GIMs from 2001 to the beginning of 2019 for 13.75UT (first row), 15.75UT (second row), 17.75UT (third row), 19.75UT (fourth row), 21.75UT (fifth row), and 23.75UT (sixth row).

Figure 21. Occurrence per year (first row), occurrence per day of year (second row), and μ_2 values at a latitude of 60S versus local time of the south polar region GIMs associated to the first, second, and third group of clusters (first, second, and third columns, respectively) for all the times.

Finally, the predominant group of clusters of relative polar NP VTEC, represented in the first column of Figures 16 and 17, presents a flatter shape maximized around the Sun direction, and concentrated at any solar cycle time in local spring and summer, which seems associated to the predominant daylight conditions (first column and first and second rows in Figure 18).

As it has been mentioned above, and similar to the NP, the three main clusters obtained after the unsupervised clustering of the normalized south polar GIMs, defined with latitudes below 45S, can be seen every 2 hr from 0145 UT in the corresponding columns of Figures 19 and 20. The third group of SP clusters (third column of plots) shows a typical relative bimodal electron content depletion at night zone, especially from 2145 UT to 0545 UT, more frequent at solar minimum conditions, and from April to August, that is, within local fall and winter seasons (see the third column of Figures 19 and 20 and the first and second rows in Figure 21). A predominant single depletion is also found more frequently during solar maximum conditions in a similar UT time interval but during March–April and July–October (see the second column of plots in Figures 19 and 20 and in Figure 21 first and second rows). Other structures appear in SP during the rest of UTs, 0745 UT to 1945 UT, for the same seasons and predominant solar cycle phases in the third and second group of clusters (see above-mentioned figures): relative theta-aurora-like patterns in 1145–1575 UT (see corresponding example in previous section 3.4) and curly electron content shapes (both in third column in Figures 19 and 20 and from April to August), and TOIs (the second column) with similar solar cycle and seasonal occurrence as in 0745–1945 UT interval, that is, solar maximum conditions during March–April and July–October. The first group of SP clusters shows a flatter distribution, but with a clear mean TOI behavior during 1345–1945 UT, from November to February, that is, around local spring and summer seasons, in agreement with the results reported from Swarm measurements in Chartier et al. (2018).

6. Conclusions

In this work, we have shown that the UQRG GIM, computed by UPC-IonSAT since 1998 as IGS ionospheric analysis center, is able to provide the main VTEC climatology in both polar ionospheres in a realistic way. This statement is supported by the two main points that have been made clear in this article: First, UQRG is the slightly most accurate GIM among the IGS centers, also in polar regions; this has been shown by comparing it and the final IGS GIMs versus direct VTEC measurements of altimeters available from 2002 to 2018 (consisting of more than 6,000,000 NP and 33,000,000 SP altimeter measurements). Second, UQRG GIM is able to show the VTEC footprint of different phenomena of polar ionosphere, in terms of up to six case studies: tongues of ionization, trough and dawnside drifting structure, flux transfer event, theta-aurora SP VTEC observation, ionospheric convection patterns, and SED during infrequent major geomagnetic storms. All of them are in agreement with the results reported by other authors, with different techniques and types of measurements. The interpretation for some of these phenomena is supported as well by the topside electron content fraction, simultaneously estimated by UPC-IonSAT in the tomographic computation process of the GIM.

In addition to the two previous contributions, this paper provides the use of a tool that allows a general analysis of polar climatology: the unsupervised clustering of the normalized VTEC maps in both the south and north polar regions, provided by the LVQ neural network. The three main groups of clusters of VTEC normalized distributions have been characterized in terms of the seasonal, annual, solar cycle, and UT occurrence in the north and south polar regions. This has included the climatology of some of the main case studies previously discussed: ionospheric trough, electron content ring, transpolar arc (theta-aurora), bimodal depletion, and TOI. The discussion also covers the south polar region, with conclusions such as the clear footprint of its higher geomagnetic field asymmetry, and the confirmation of the finding that most SP TOI activity occurs in local summer.

We consider that this work can contribute as well as a first step to disclose and promote the future usage of GIMs in polar regions, for instance, in precise low-cost positioning, and to promote its further analysis in relation with different polar ionospheric phenomena. We can take advantage not only of the huge amount of information on polar ionosphere contained in the GIMs available for more than 20 years but also of the experimental GIMs that are being computed in real time in the context of IGS, including its real-time combination (Hernández-Pajares et al., 2019). They can open new scenarios of applicability, such as precise polar GNSS navigation (e.g., Hernández-Pajares et al., 2000) and space weather monitoring and warning (e.g., Béniguel et al., 2017).

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The UQRG GIMs, baseline of this work, are openly accessible from IGS server (<ftp://cddis.gsfc.nasa.gov/gps/products/ionex/YEAR/DOY/uqrqDOY0.YYi.Z>) and from UPC server (https://chapman.upc.es/tomion/rapid/YEAR/DOY_YYMMDD.15min/uqrqDOY0.YYi.Z) being YEAR and YY the four- and two-digit year identifiers, MM is month number, DD is day of month, and DOY is the day of year, all of them with leading zeros when needed (see, for instance, <ftp://cddis.gsfc.nasa.gov/gps/products/ionex/2002/003/uqrq0030.02i.Z> and https://chapman.upc.es/tomion/rapid/2002/003_020103.15min/uqrq0030.02i.Z). Any missing file can be requested from the authors, in particular from Manuel Hernández-Pajares (manuel.hernandez@upc.edu). This work has been supported by the POLarGIMs project funded by European Commission Joint Research Centre (JRC). We thank the National Space Science Data Center (NSSDC), Space Physics Data Facility (SPDF), and Principal Investigator K. W. Ogilvie at GSFC, A. J. Lazarus at MIT, and A. Aran at Universitat de Barcelona (UB), for the access of IMF data. The first author is very thankful as well with Pere Ramos, who preserved a copy of the LVQ source code developed by MHP in the above-mentioned former astronomical studies. The first author would like to dedicate this work to the memory of his mother, María Pajares-Nogales.

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