Space Weather

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Key Points:

• An ionospheric climate index (ICI) is established for representing the general state of the ionosphere based on Global Navigation Satellite System.

• Solar EUV irradiation, geomagnetic activity, and upper atmospheric wind field contribution to ICI are quantitatively determined.

• A multiple linear regression model is built for reconstruction of ICI and extending historical data of ICI back 60 years.

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Abstract The ionospheric total electron content (TEC) is a significant parameter for scientific studies of the ionosphere and space weather. Ground-based Global Navigation Satellite System (GNSS) station network provides an opportunity for modeling the ionospheric TEC with high accuracy. Based on global ionospheric TEC maps, by using data from the International GNSS Service (IGS) stations for 21 years (from 1998 to 2018), we establish an ionospheric climate index (ICI) for representing the general state of the ionosphere. In addition, we build a multiple linear regression model for fitting ICI using the SSN, \( F_{10.7} \), \( Ap \), and \( Dst \) indices and upper atmospheric wind field. We quantitatively analyze the contribution of these factors to ICI time series. ICI during the past six solar cycles, namely, from 1958 to 2018, are presented, which are assigned as the adjectives (cold, cool, mild, warm, hot, and sizzling) for ionospheric climatology studies. This new index is a very promising representative of day-to-day variations of middle- and low-latitude ionosphere.

1. Introduction

As a part of the Earth’s upper atmosphere, the ionosphere plays an important role in solar-terrestrial space environment and space weather. Performance of the satellite-land systems, such as satellite navigation, space-based synthetic aperture radar, and satellite altimetry, are affected by the ionospheric propagation effects (Bilitza, 1992; Komjathy, 1997; Lei et al., 2005; Makela et al., 2000; Matteo & Morton, 2010; Sobral et al., 2003). The ionospheric total electron content (TEC) is one of the significant parameters for physical studies of the ionosphere and practical applications mentioned above. The Global Navigation Satellite System (GNSS) with dual-frequency observations has been an effective way to monitor the ionospheric TEC for several decades (Feltens & Schaer, 1998; Hernández-Pajares et al., 2014; Mandrake et al., 2005; Wang et al., 2016, 2017). The International GNSS Service (IGS) has been providing observations of hundreds of GNSS stations since 1998 (Hernández-Pajares et al., 2009; Roma-Dollase et al., 2018; Wang et al., 2019), which are beneficial for ionospheric TEC modeling on the global scale.

Several indices like solar 10.7 cm radio flux, sunspot number, and \( Ap \) and \( Dst \) indices are widely used in expression the state of solar and geomagnetic activity. Recently, a thermospheric climate index was proposed to represent the global thermal state of the thermosphere based on the Sounding of the Atmosphere using RF Technique (SABER) (Mlynczak et al., 2015, 2016).

A number of ionospheric indices have been proposed during the last few decades. Based on foF2 measurements from ionosonde, several indices have been developed, such as the IG index (Liu et al., 1983), which has been widely used in practical applications such as the management of high-frequency (HF) radio systems, the IF2 index (Minnis & Bazzard, 1960), and the MP2 index (Mikhailov & Mikhailov, 1995). Ionospheric \( T \) index, which is adopted by National Centers for Environmental Information (NCEI), U.S. National Oceanic and Atmospheric Administration (NOAA), is derived from observed values of critical frequency and scaled onto the sunspot number-maximum frequency relationship. Although these indices derived from foF2 can be useful for ionospheric HF communication, with the development of GNSS, TEC measurements also show its potential for satellite-to-ground applications such as navigation and remote sensing, as well as ionospheric research. Global electron content (GEC) was proposed as a new index of solar activity, since it correlates very well with solar extreme ultraviolet (EUV) radiation and solar 10.7 cm radio flux (Afraimovich et al., 2008).

In this contribution we perform the global ionospheric TEC modeling with spherical harmonics (SH) function by using several hundreds of IGS stations and generate the daily global ionospheric maps (GIMs) from...
1998 to 2018 (Cheng et al., 2018; Wang et al., 2016). An ionospheric climate index (ICI) is derived from daily GIMs, which is helpful to describe the general state of the ionosphere. Due to the fact that variations of the ionosphere are mainly driven by the solar EUV irradiation and geomagnetic activity, the ICI time series derived from GNSS for 21 years can be modeled with a multiple linear regression by using sunspot number (SSN), solar 10.7 cm radio flux (F10.7), Ap index,Dst index, and upper atmospheric wind field (hereinafter referred to as Wind). Based on the regression model, we can quantitatively analyze the contribution of each independent variable to the dependent variable ICI. In addition, the ICI model could be used for reconstruction of the historical data of ICI back to 1958. Using the long-term ICI time series of 61 years (from 1958 to 2018), we assign the adjectives cold, cool, mild, warm, hot, and sizzling to represent the global ionospheric climate during the past six solar cycles (SCs).

2. Methodology

2.1. Modeling of Global Ionospheric TEC

The IGS Ionosphere Associate Analysis Centers (IAACs) produce their GIMs routinely with different models and software. Five of seven IAACs basically use SH function as the main algorithm for modeling the global ionospheric TEC (Roma-Dollase et al., 2018). In this study, we also use the SH function for global ionospheric modeling and producing the daily GIMs by using GNSS dual-frequency observations. The basic equation is given by Equation 1:

\[
\tilde{P}_1 - \tilde{P}_2 = \frac{40.3(f_2^2 - f_1^2)}{f_2^2} \cdot mf(z) \cdot VTEC + c(\text{DCB}_r + \text{DCB}_s)
\]

where \(\tilde{P}_1\) and \(\tilde{P}_2\) are the carrier smoothed code measurements; \(f_1\) and \(f_2\) indicate the carrier frequencies of the L1 and L2 signals; \(mf\) is the mapping function, which depends on the zenith distance \(z\) at the station; \(VTEC\) is the vertical TEC at the ionospheric pierce point (IPP); \(c\) is the speed of light in vacuum; and \(\text{DCB}_r\) and \(\text{DCB}_s\) are the differential code biases (DCB) of receiver and satellite, respectively.

The SH function is used for fitting VTEC referred to a solar geomagnetic frame as shown in Equation 2:

\[
VTEC(\phi, \lambda) = \sum_{n=0}^{n_{\text{max}}} \sum_{m=0}^{m_{\text{max}}} \tilde{P}_{nm}(\sin \phi)(a_{nm}\cos(m\lambda) + b_{nm}\sin(m\lambda))
\]

where \(\phi\) and \(\lambda\) are the geomagnetic latitude and Sun-fixed longitude of IPP, respectively; \(n\) and \(m\) are the degree and order of the model, respectively; \(\tilde{P}_{nm}\) is the normalized associated Legendre function; and \(a_{nm}\) and \(b_{nm}\) are the SH coefficients to be estimated.

In this study, GNSS observations of more than 200 IGS stations are collected for modeling. The SH expansions are up to a degree and order of 15. A minimum elevation cutoff of 10° is configured to avoid particularly noisy measurements. Figure 1 shows the geographical distribution of the IGS stations which provide daily GNSS observations. It should be noted that the number of stations is not fixed. The stations which have low signal-noise rate observations or have large residual errors will be eliminated in the actual data processing, in order to ensure objectivity and accuracy of the modeling results. The DCBs of satellites and receivers are estimated along with SH parameters by using the least squares method. The daily GIMs (named BUAG) of more than 21 years (from 1998 to now) are available for public access via our FTP (ftp://pub.ionosphere.cn/product/).

2.2. Establishment of ICI

We use the daily GIMs to establish an ICI for representing the daily global ionospheric climate. Since the Sun’s perpendicular rays migrate from 23.5°S latitude to 23.5°N latitude of the Earth, solar radiation is strongest in this region. Consequently, this region of the ionosphere would be more ionized. Solar EUV irradiation appears strongest from 10 a.m. to 2 p.m. The Sun’s perpendicular rays are at 12 a.m. The peak TEC
value is typically at 2 p.m. Taking into consideration ionospheric hysteresis, we collect the grid point VTEC values as basic data at low dip latitudes (<30°) during the period of the day from 2 p.m. to 4 p.m. on local time. Subsequently, the ICI value is obtained by averaging of these VTEC values. Finally, we get the ICI time series on a daily basis from 1998 to 2018. It should be noted that ICI is essentially a physical parameter of TEC, and its unit is total electron content unit (TECU). We could get an overview of the ionosphere by ICI value on a daily basis.

2.3. Multiple Linear Regression Fitting of ICI

Based on the GNSS-derived ICI time series of 21 years (covering nearly two SCs), we use several solar and geomagnetic indices (including SSN, $F_{10.7}$, $Ap$, and $Dst$) and upper atmospheric wind field ($Wind$) to establish a multiple linear regression model for reconstruction of ICI time series. The basic expression for the modeling is shown in Equation 3:

$$ICI = a_0 + a_1 \times SSN + a_2 \times F_{10.7} + a_3 \times Ap + a_4 \times Dst + a_5 \times Wind$$

(3)

where $[a_0, a_1, a_2, a_3, a_4, a_5]$ are the coefficients to be estimated. ICI is in units of TECU. $F_{10.7}$ is in solar radio flux units (sfu). Units of $Ap$ and $Dst$ index are in nanotesla (nT). $Wind$ is in meter per second (m/s). On the account of these independent variables having different temporal resolution, a daily average of each independent variable is calculated and taken into the regression modeling. By applying the least squares solution to Equation 3, the estimated coefficients $a_0$, $a_1$, $a_2$, $a_3$, $a_4$, and $a_5$ are $63.86$, $-0.047$, $0.57$, $-0.17$, $-0.12$, and $-1.17$, respectively.

The $Wind$ data are the composite of meridional and zonal wind vectors, which are derived from the Earth’s upper atmospheric horizontal wind fields model (HWM14) (Drob et al., 2015). Several studies have shown that neutral wind is one of the primary drivers of the variation of the ionosphere (Bagiya et al., 2009; Balan et al., 2018; Drob et al., 2015). The upper atmospheric wind field has a great influence on the neutral composition and O/N$_2$ ratio which plays an important role in driving the TEC variation in different seasons, especially in low latitudes (Bagiya et al., 2009; Balan et al., 2018; Bhuyan & Borah, 2007; Olwendo et al., 2013). Therefore, we also perform the modeling without wind field to investigate the importance of this factor. The details will be presented in next section. The HWM model can easily provide the wind field anywhere in the world by giving several common input parameters (including year, day of year, seconds of day, local time, latitude, and longitude). $Ap$ index is also an essential input parameter for the HWM model.

3. ICI

3.1. ICI Time Series and Analysis

According to the proposed method, the daily ICI is derived by GNSS from 1998 to 2018. Figure 2 shows the daily values of ICI time series, as well as solar and geomagnetic indices and upper atmospheric wind speed. Overall, the solar and geomagnetic indices (SSN, $F_{10.7}$, $Ap$, and $Dst$) present a strong correlation with solar activity cycle. The absolute values of these indices are apparently larger at higher solar activity than those at lower solar activity. However, the upper atmospheric wind speed shows little correlation with solar activity, but strongly depends on seasons. Basically, ICI time series shows periodic fluctuations with solar activity on a large scale. In addition, ICI time series presents seasonal periodic characteristics.

A multiple linear regression model is established by using solar and geomagnetic indices, as well as upper atmospheric wind field for fitting the ICI time series of 21 years. Figure 3 shows the ICI time series derived from GNSS and the regression model on a daily basis from 1998 to 2018, respectively. The $R^2$ value 0.82 indicates that the multiple linear regression model has the advantage of high goodness of fit and satisfactory effect. The established model can reproduce the large-scale periodic fluctuations and seasonal periodic variations of ICI time series. However, the $R^2$ value is 0.76 if the wind field is not introduced when modeling. Also, as shown in Figure 3b, the model without wind field has large discrepancy with the ICI time series during low solar activity. It is obvious that the model could not represent the seasonal variation of ICI in 2008, 2009, 2010, 2017, and 2018.
Figure 2. Daily values of ICI, SSN, $F_{10.7}$, $Ap$, and $Dst$ indices and upper atmospheric wind field from 1998 to 2018.

Figure 3. The daily ICI time series derived from GNSS (blue curve) and the multiple linear regression models (red curve and green curve) using SSN, $F_{10.7}$, $Ap$, and $Dst$ indices and (a/b) with/without upper atmospheric wind field, respectively.
While modeling of ICI time series, standardized regression coefficients (SRC) of each solar and geomagnetic indices and upper atmospheric wind intensity could also be calculated according to Equation 4:

$$\tilde{a}_i = \frac{a_i \cdot SD(x_i)}{SD(Y)}$$

where $\tilde{a}_i$ is the SRC; $a_i$ is the estimated regression coefficient by Equation 3; SD is the function to compute standard deviation; $x_i$ is the independent variable ($SSN$, $F_{10.7}$, $Ap$, $Dst$, and $Wind$); $Y$ is the dependent variable (ICI).

The SRCs of $SSN$, $F_{10.7}$, $Ap$, $Dst$, and $Wind$ are $-8.344 \times 10^{-2}$, $9.810 \times 10^{-1}$, $-8.070 \times 10^{-2}$, $-8.538 \times 10^{-2}$, and $-2.117 \times 10^{-1}$, respectively. The absolute value of SRC (ASRC) determines the strength of the effect of each individual independent variable to the dependent variable. We calculate the ASRC of each independent variable and proportion of their ASRC. The corresponding proportion of $SSN$, $F_{10.7}$, $Ap$, $Dst$, and $Wind$ are 5.78%, 67.98%, 5.59%, 5.92%, and 14.67%, respectively. It indicates that solar EUV irradiation plays the most significant role in ionospheric climate. The upper atmospheric wind field also has a great influence on ICI time series. At the same time, geomagnetic activity accounts for more than 10% of the total effects on ionospheric climate. Figure 4 shows the annual proportion of each independent variable from 1998 to 2018.

Overall, the solar 10.7 cm radio flux and upper atmospheric wind field make up more than 80% of the contributions to ionospheric climate. It indicates that wind field is necessary and important once again. Also, the $F_{10.7}$ index shows a strong correlation with solar activity. However, there is remarkable negative correlation between upper atmospheric wind field and solar activity. Additionally, as another index of solar activity, sunspot number has little contributions of approximately 5% to ionospheric climate. The geomagnetic activity contributes more than 10% during different years, having not much variations along with solar activity.

### 3.2. Long-Term ICI Time Series

According to the established multiple linear regression model, we calculate the ICI on a daily basis with solar and geomagnetic indices (available back to 1958) and upper atmospheric wind speed. Figure 5 shows the long-term ICI time series of 61 years (from 1958 to 2018), which is covering almost six SCs, from the peak of SC 19 to the bottom of SC 24. From the ICI time series depicted in Figure 5, the ICI values are obviously smaller during the much weaker SC 20 and SC 24 than those during other SCs. In addition, we divide the ICI time series into six groups, which are separated by 30, 45, 60, 75, and 100 TECU, respectively. The colored horizontal dotted lines in Figure 5 define the six quintiles of the distribution
of ICI time series. Also, we assign several adjectives (cold, cool, mild, warm, hot, and sizzling) to describe the corresponding ionospheric climate. From the ICI time series during the past six SCs, we can see that there are only a few sizzling days during SC 20 and SC 24.

4. Summary and Conclusions

An ionospheric climatology index is established based on global GNSS-TEC measurements, which is very promising for representing the general state of the ionosphere. A multiple factor linear regression model is built for fitting the ICI time series of 21 years (from 1998 to 2018) with solar and geomagnetic indices ($F_{10.7}$, SSN, Ap, and $Dst$) as well as upper atmospheric wind field. From the model, we realize the relative contributions of solar EUV irradiation, geomagnetic activity, and upper atmospheric wind field into the middle- and low-latitude ionospheric climatology. Among these factors, the solar EUV irradiation plays the most significant role in ionospheric climate. The upper atmospheric wind field is also an important factor, which has a great influence on ionospheric climate, especially during low solar activity. Additionally, the model provides an opportunity to reconstruct a long-term ICI time series back to 1958. Based on the 61 years of ICI historical data, we divide the ionospheric climate into six categories. They are cold, cool, mild, warm, hot, and sizzling. During the past six SCs, there are only a few sizzling days during the weaker SC 20 and SC 24. Therefore, solar activity plays a decisive role in the variation of ionospheric climate. The proposed ICI based on GNSS is capable of characterizing the day-to-day variability of the middle and low ionosphere. It provides a direct description of ionospheric climate that could not be expressed by existing individual indices. In addition, ICI gives quick and general information of the ionospheric status, which can improve the operational use of communication and navigation systems. In further work, we will update the ICI on a routine basis. Also, we would like to involve more variables like electron temperature in the multiple linear regression modeling for reconstruction of ICI time series with higher accuracy.

Data Availability Statement

IGS provides GNSS observations and satellites ephemeris online (ftp://cddis.gsfc.nasa.gov/gnss/data/). The Space Weather Prediction Center of NOAA provides Ap, SSN, and $F_{10.7}$ data online (https://www.swpc.noaa.gov). Kyoto University provides Dst data online (http://wdc.kugi.kyoto-u.ac.jp).

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