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Key Points:

- Effect of neutral wind on ANN TEC model is less beyond the northern crest of EIA
- Response of ANN TEC models to neutral wind is less during autumnal equinox than vernal equinox
- During high solar activity period, neutral wind effects on ANN TEC models are more pronounced

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Response of data-driven artificial neural network-based TEC models to neutral wind for different locations, seasons, and solar activity levels from the Indian longitude sector

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Abstract The perturbations imposed on transionospheric signals by the ionosphere are a major concern for navigation. The dynamic nature of the ionosphere in the low-latitude equatorial region and the Indian longitude sector has some specific characteristics such as sharp temporal and latitudinal variation of total electron content (TEC). TEC in the Indian longitude sector also undergoes seasonal variations. The large magnitude and sharp variation of TEC cause large and variable range errors for satellite-based navigation system such as Global Positioning System (GPS) throughout the day. For accurate navigation using satellite-based augmentation systems, proper prediction of TEC under certain geophysical conditions is necessary in the equatorial region. It has been reported in the literature that prediction accuracy of TEC has been improved using measured data-driven artificial neural network (ANN)-based vertical TEC (VTEC) models, compared to standard ionospheric models. A set of observations carried out in the Indian longitude sector have been reported in this paper in order to find the amount of improvement in performance accuracy of an ANN-based VTEC model after incorporation of neutral wind as model input. The variations of this improvement in prediction accuracy with respect to latitude, longitude, season, and solar activity have also been reported in this paper.

1. Introduction

The maximum ionization density in Earth's ionosphere is observed inside the regions covering ±30° magnetic dip. Transionospheric satellite signals experience perturbations in the form of range error and range rate error for a major part of the day and amplitude and phase scintillations during postsunset hours before being received by the ground receiver. The GPS signals suffer group delay which is proportional to total electron content (TEC). It is important to note that the first-order effects of TEC present in ionosphere causing range error could be accounted for using dual frequency GPS receivers. Higher-order ionospheric effects, which are increasingly becoming important for high precision applications such as aviation, remain an unresolved issue. The observed "Fountain Effect" [*Appleton*, 1946; *Hanson and Moffett*, 1966] causes anomalous distribution of ionization in the low-latitude ionosphere. Enhancement of electron density near the 20°N and 20°S geomagnetic latitude and subsequent decrement of electron density near geomagnetic equator causes the equatorial ionization anomaly (EIA).

The EIA in the equatorial region causes sharp latitudinal gradient of TEC. The highly dynamic ionosphere results in large day-to-day TEC variations [*Rastogi and Klobuchar*, 1990; *Klobuchar et al.*, 2001; *Paul et al.*, 2011; *Das et al.*, 2014]. The variations of EIA anomaly crest location and intensity have also been reported in the literature [*Huang et al.*, 1989; *Rastogi and Klobuchar*, 1990]. Sharp latitudinal variability of TEC in the Indian longitude sector has been reported in *Paul et al.* [2011] and *Das et al.* [2014]. Solar cyclic and seasonal variations of TEC have been reported in various literatures such as *Rama Rao et al.* [1977, 1985], *Bhuyan* [1992], and *Bhuyan and Borah* [2007]. The longitudinal variability of low latitudes has been reported by *Su et al.* [1996]. The globally accepted ionospheric TEC models such as the International Reference Ionosphere (IRI), parameterized ionospheric model (PIM), and NeQuick, are not sufficiently accurate in the low-latitude region [*Bittencourt and Chryssafidis*, 1994; *Shastri et al.*, 1996; *Ezquer et al.*, 1998; *Orus et al.*, 2002; *Ezquer et al.*, 2004; *Paul et al.*, 2005; *Bhuyan and Borah*, 2007; *Kenpankho et al.*, 2011; *Sur and Paul*, 2013; *Sur et al.*, 2015]. In the equatorial region, prediction of TEC can be improved by real-time data-driven models [*Orus et al.*, 2002; *Paul et al.*, 2005; *Sur and Paul*, 2013; *Sur et al.*, 2015].

Vertical TEC (VTEC) prediction models have been developed using measured VTEC with the help of artificial neural network (ANN) based models for 77°E, 88°E, and 121°E longitude in the low-latitude regions for different solar activity periods. The developments of these models have been reported in *Sur and Paul* [2013] and *Sur et al.* [2015].

In the present paper, the effects of incorporation of neutral wind as model inputs to the accuracy of ANN-based VTEC models have been analyzed in different locations and geophysical conditions in the Indian longitude sector (low- to middle-latitude regions in Northern Hemisphere). Neutral wind effects on the accuracy of ANN-based VTEC models have been studied with respect to (i) latitudinal variation, (ii) seasonal variation, (iii) variation of solar activity periods (daily sunspot number), and (iv) longitudinal variations. The TEC data used to develop ANN-based models in this paper have been summarized in the following section.

2. Description of Data Set

All the ANN-based VTEC models reported in the present paper have been developed using GPS VTEC measured at different stations in the Indian longitude sector. These ANN-based VTEC models are designed by using feed forward backpropagation technique. Inputs of all the VTEC models reported in the present paper are (i) day of the year, (ii) time of the day (UT), (iii) 350 km subionospheric latitude, (iv) 350 km subionospheric longitude, and (v) daily sunspot number. It has been assumed that the mean h_mF_2 (maximum ionization altitude for F_2 layer from ground) is 350 km. This assumption is valid in Indian longitude sector for satellites having elevation angle at or over 50° [*Rama Rao et al.*, 2006]. The point, where the raypath from satellite to ground receiver intersects the ionosphere at an altitude of 350 km, is known as ionospheric pierce point. The projection of this point on the ground is called 350 km subionospheric point. The latitude and longitude of that point are referred as 350 km subionospheric latitude and longitude, respectively. The ANN-based VTEC models produce VTEC at the output in 1 min intervals. Data sets are trained and tested separately to avoid data biasing in all ANN models described in this paper. Only geomagnetic quiet days ($Dst \geq -50$ nT) are used for model training and testing. TEC above an elevation mask of 50° have been used for model training and testing in order to avoid multipath error. VTEC values are expressed in TEC Unit (TECU, 1 TECU = 10^{16} el m^{-2}) in this paper. Equivalent VTEC can be obtained from slant TEC (STEC) using equations (1) and (2) [*Breed et al.*, 1997; *Nava et al.*, 2007].

$$\text{slanting factor} = \frac{1}{\sqrt{\left[1 - \{A\cos\alpha/(A+h)\}^2\right]}} \tag{1}$$

$$\text{equivalent VTEC} = \frac{\text{equivalent STEC}}{\text{slanting factor}} \tag{2}$$

h =height of the point of maximum electron density from ground (350 km), meter.
A =radius of the Earth, meter.
α =elevation angle of GPS from the receiver position, degree.

Equation (1) is derived from the single layer model of the Earth's ionosphere assuming that no horizontal VTEC gradients exist. These developed ANN-based models were tested alongside the standard ionospheric models such as IRI, PIM, and NeQuick, to understand their applicability in low-latitude region. Measured data-driven ANN-based VTEC models show better performance than standard ionospheric models for most periods of time in the low-latitude Indian longitude region [*Sur and Paul*, 2013; *Sur et al.*, 2015].

It has already been reported in the literature that the components of neutral wind such as meridional wind and zonal wind affect the generation and distribution of the electron density in the ionosphere [*Fesen et al.*, 1989; *Alken et al.*, 2008; *Drob et al.*, 2008; *Balan et al.*, 2009; *Zhang et al.*, 2011]. In order to observe the effects of neutral wind on performance accuracy of VTEC models, meridional wind and zonal wind have been incorporated as model inputs [*Sur et al.*, 2015]. The magnitudes of meridional and zonal wind velocities

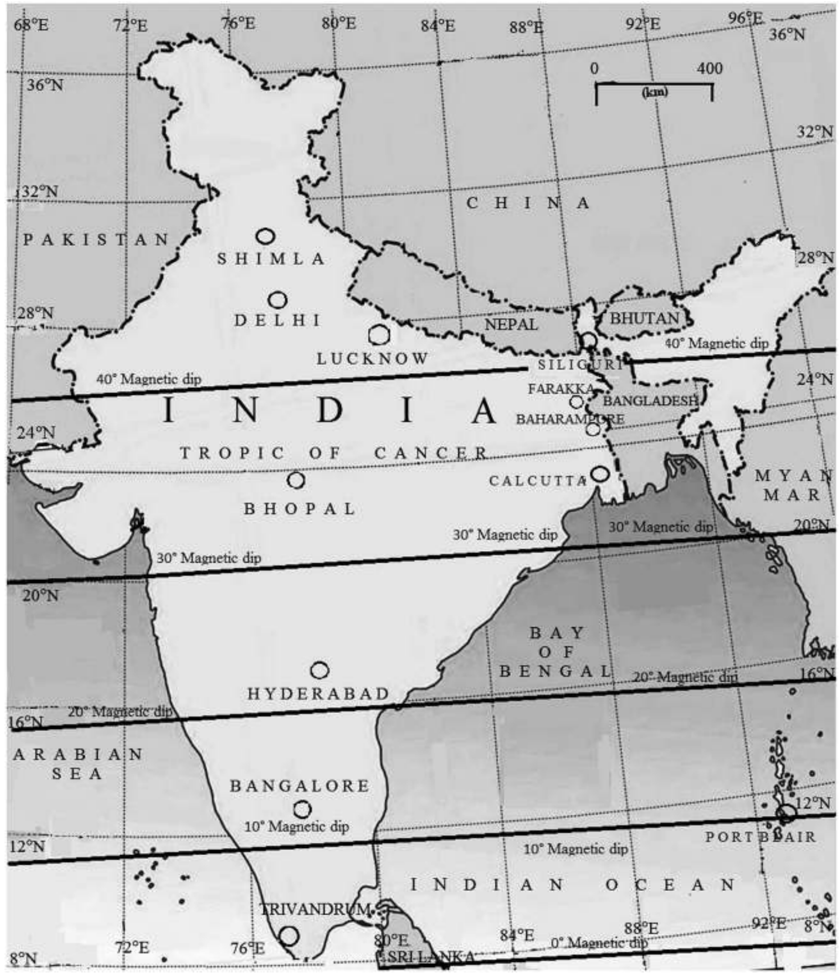

Figure 1. Map of Indian subcontinent to demonstrate the geographic and geomagnetic coordinates of the GPS TEC receiver stations used.

for all the models described in this paper are obtained from the horizontal wind model (HWM07) [*Drob et al.*, 2008; *Alken et al.*, 2008]. It has been observed that the performances of the VTEC models with neutral wind are better in most of the cases than those of the models without neutral wind components as model input.

The data set used for training and testing of the ANN-based VTEC models is described in this section.

2.1. Data for Testing VTEC Models at Different Latitudes

In this paper, it has been studied whether there is any improvement in prediction accuracy at different latitudes after incorporation of neutral wind. Details of these observations have been described in sections 4 and 5 for April and October 2005, respectively. Description of the data set for these observations is presented in this subsection. The study has been conducted through 7°N to 29°N latitudes and for almost same longitude of 77°E. The GPS TEC data are obtained from dual frequency GPS-Aided Geo-Augmented Navigation (GAGAN) GPS-TEC receivers during January 2004 to October 2005 in 1 min intervals. This wide range of latitudes is composed of dynamically sensitive Indian longitude sector from locations near geomagnetic equator to regions beyond the northern crest of EIA. The GPS VTEC data set from January 2004 to March 2005 is used as a training data set for the ANN-based VTEC model (IRPE-TEC-77E). The GPS VTEC data set of April and October 2005 is used for model testing. In order to observe the effects of neutral wind on this model, meridional wind and zonal wind components have been added as model inputs. The neutral wind coupled model is named IRPE-TEC-77E(HWM). The locations of all GPS TEC receiver stations are shown in Figure 1. The names of the stations are indicated below alongside their inclination angle and declination angle for the year 2005.

(i) Shimla (31.09°N, 77.07°E geographic; magnetic dip 47.43°; and magnetic declination 1.21°), (ii) Delhi (28.58°N, 77.21°E geographic; magnetic dip 43.5°; and magnetic declination 0.68°), (iii) Bhopal (23.28°N, 77.34°E geographic; magnetic dip 33.95°; and magnetic declination −0.26°), (iv) Hyderabad (17.44°N, 78.47°E geographic; magnetic dip 21.9°; and magnetic declination −1.15°), (v) Bangalore (12.95°N, 77.68°E geographic; magnetic dip 11.69°; and magnetic declination −1.82°), and (vi) Trivandrum (8.47°N, 76.91°E geographic; magnetic dip 0.9°; and magnetic declination −2.59°)

2.2. Data for Testing VTEC Models During Different Seasons

In order to observe the seasonal variation of the effects of neutral wind on the performance of ANN-based VTEC models in the Indian longitude sector, IRPE-TEC-77E and IRPE-TEC-77E(HWM) models are tested for April and October 2005 for moderate to low solar activity periods. The vernal (February–April) and autumnal (August–October) equinoxes have been selected for analysis in this paper as these are the seasons when ionization densities and consequently the TEC are highest in the Indian longitude sector. The minimum ionization densities are usually found during the summer solsticial months of May to July. The performance variations for VTEC models with and without neutral wind have been discussed in section 4 for April 2005 and in section 5 for October 2005.

2.3. Data for Testing VTEC Models During Different Solar Activity Periods

The effects of neutral wind on the performance of ANN-based VTEC models in different solar activity periods (based on daily sunspot number) have been observed in moderate solar activity periods (October 2005) and high solar activity periods (October 2014) from Bangalore (12.95°N, 77.68°E geographic; magnetic dip 11.69° in year 2005 and 13.57° in 2014; and magnetic declination −1.82° in 2005 and −1.43° in 2014). The small variations of geomagnetic inclination and declination values with respect to time for this station have also been taken into consideration. ANN-based VTEC models IRPE-TEC-77E and IRPE-TEC-77E(HWM) have been used to study the effects of neutral wind in October 2005.

The ANN-based VTEC model for the high solar activity periods of 2014 has been designed using the International Global Navigation Satellite Systems Service (IGS) (website: http://sopac.ucsd.edu/) data from Bangalore. The training data set for the model (IRPE-TEC-BANGALORE) comprises the IGS TEC data set during September 2012 to September 2014. The model has been tested for October 2014. The inputs and output of the models are mentioned at the beginning of section 2. Neutral wind components such as (i) meridional wind and (ii) zonal wind are added (obtained from HWM07) in the model to observe the effects of neutral wind on percentage accuracy of VTEC model during high solar activity periods in the Indian longitude region. The neutral wind coupled model is named IRPE-TEC-BANGALORE(HWM).

The effects of neutral wind on ANN-based TEC models in different solar activity periods have also been studied by using data from Calcutta (22.58°N, 88.38°E geographic, magnetic dip 33.09° in year 2009 and 33.48° in 2012; and magnetic declination −0.51° in 2009 and −0.45° in 2012). Calcutta is situated near the northern crest of EIA. The study has been conducted during February–April 2009 (low solar activity periods) and during February–April 2012 (high solar activity periods).

The ANN-based VTEC models used during February–April 2009 are trained by using the GPS-TEC data set from Calcutta. The dual frequency GPS receiver in Calcutta is operated by the Institute of Radio Physics and Electronics (IRPE), University of Calcutta under the international Scintillation network decision aid (SCINDA) program. The processed plots of GPS TEC and S_4 data are available online to authorized users at http://capricorn.bc.edu/scinda/india. The data set training period for this GPS TEC station ranges from 1 January 2007 to 31 December 2008. One VTEC model is designed without neutral wind as model input (IRPE-TEC-CALCUTTA), and another model is designed after addition of neutral wind as model input (IRPE-TEC-CALCUTTA(HWM). The data during February–April 2009 are used for model testing which is outside the duration of model training periods.

The models designed to predict VTEC during February–April 2012 are IRPE-TEC-88E (model without neutral wind as input) and IRPE-TEC-88E(HWM) (model with neutral wind as model input). GPS TEC data set used to design these models is mentioned below.

1. Calcutta: The data set training period for this station ranges from 1 January 2007 to 15 September 2011. The details of this station have been discussed above.

2. Baharampore (24.09°N, 88.25°E geographic, magnetic dip 36.35° in 2012; geomagnetic declination angle −0.30° in 2012): This dual frequency GPS TEC receiver is located at K. N. College, Baharampore. The time period of data from this station used for generation of the model ranges from March 2011 to 15 September 2011.

The models have been tested during February–April 2012.

2.4. Data for Testing VTEC Models at Different Longitudes

A study has been conducted in order to observe any variation of the effects of neutral wind on ANN-based VTEC models with the variation of longitude. In this regard, VTEC from stations located almost along same latitude but separated in longitude are used to test the ANN-based VTEC models with and without neutral winds. For this purpose, GPS-TEC data from stations near geomagnetic equator, Bangalore (12.95°N, 77.68°E geographic; magnetic dip 13.57°; and magnetic declination −1.43°) and Port Blair (11.64°N, 92.71°E geographic; magnetic dip 9.72°; and magnetic declination −0.95°) have been used for comparison during October 2014. The geomagnetic inclination and declination angles for these stations are indicated for the year 2014. ANN-based models used for prediction of VTEC from Bangalore are IRPE-TEC-BANGALORE and IRPE-TEC-BANGALORE(HWM). The detailed discussion about data set of IRPE-TEC-BANGALORE and IRPE-TEC-BANGALORE(HWM) for testing periods of October 2014 has already been done in section 2.3.

ANN-based VTEC model at Port Blair is developed by using IGS GPS TEC data from this station. The training data set for the model (IRPE-TEC-PORT BLAIR) is taken from the periods of September 2012 to September 2014. The model has been tested during all the geomagnetic quiet days of October 2014. The model has been redesigned with addition of neutral wind inputs such as (i) meridional wind and (ii) zonal wind. The new model is named (IRPE-TEC-PORT BLAIR(HWM)).

A study has also been conducted in order to observe longitudinal variability of the effects of neutral wind on ANN-based VTEC models at latitudes beyond the northern crest of EIA in the Indian longitude sector. For this purpose, data from GPS TEC receiver stations Lucknow (26.91°N, 80.96°E geographic; magnetic dip 42°; and geomagnetic declination angle 0.58°) and Siliguri (26.72°N, 88.39°E geographic; magnetic dip 41.54°; and geomagnetic declination angle 0.07°) have been used to design and test ANN-based VTEC models. The geomagnetic inclination and declination angles are mentioned for the year 2016 for these two stations. The geographic latitude, geomagnetic inclination angle, and declination angle for these stations are almost identical. However, these two stations are separated by geographic longitude.

ANN-based VTEC model at Lucknow has been designed using IGS GPS TEC data recorded during September 2015 to February 2016 (IRPE-TEC-LUCKNOW). GPS TEC data set of March 2016 is used for test data set during only geomagnetic quiet days. Neutral wind coupled VTEC model (IRPE-TEC-LUCKNOW(HWM)) has been developed by adding meridional and zonal wind velocities to the network as model inputs. The neutral wind coupled model is tested along with the model without neutral wind in order to see any improvement in prediction accuracy of an ANN-based VTEC model during March 2016.

ANN-based VTEC models without and with neutral wind inputs at Siliguri (IRPE-TEC-88E and IRPE-TEC-88E(HWM), respectively) are designed using TEC data from a chain of GPS TEC receiver stations with almost same longitude 88.5°E and same geomagnetic declination angle for a range of latitudes (20°N–28°N). The training database for these models is described in section 2.3. Additional GPS TEC data set has been added to the training database from the following stations.

1. Farakka (24.79°N, 87.89°E geographic, magnetic dip 38.15° in 2016; and geomagnetic declination angle −0.09° in 2016): Dual frequency GPS TEC receiver was operated at Bharat Sevasram Sangha, Farakka. Data during April 2012 were used from this station to train the ANN-based VTEC model.
2. Siliguri (26.72°N, 88.39°E geographic; magnetic dip 41.54° in 2016; and geomagnetic declination angle 0.07° in 2016): Software-based dual frequency GPS TEC receiver has been installed with data sampling rate of 50 Hz at University of North Bengal, Siliguri. GPS TEC data at Siliguri have been incorporated as training database into the model (IRPE-TEC-88E) from September 2011, April 2012, September 2012, April 2013, and September 2013 through equinoctial campaign mode. Though the data acquisition frequency of the receiver is 50 Hz, the time resolution of data has been converted to an interval of 1 min before

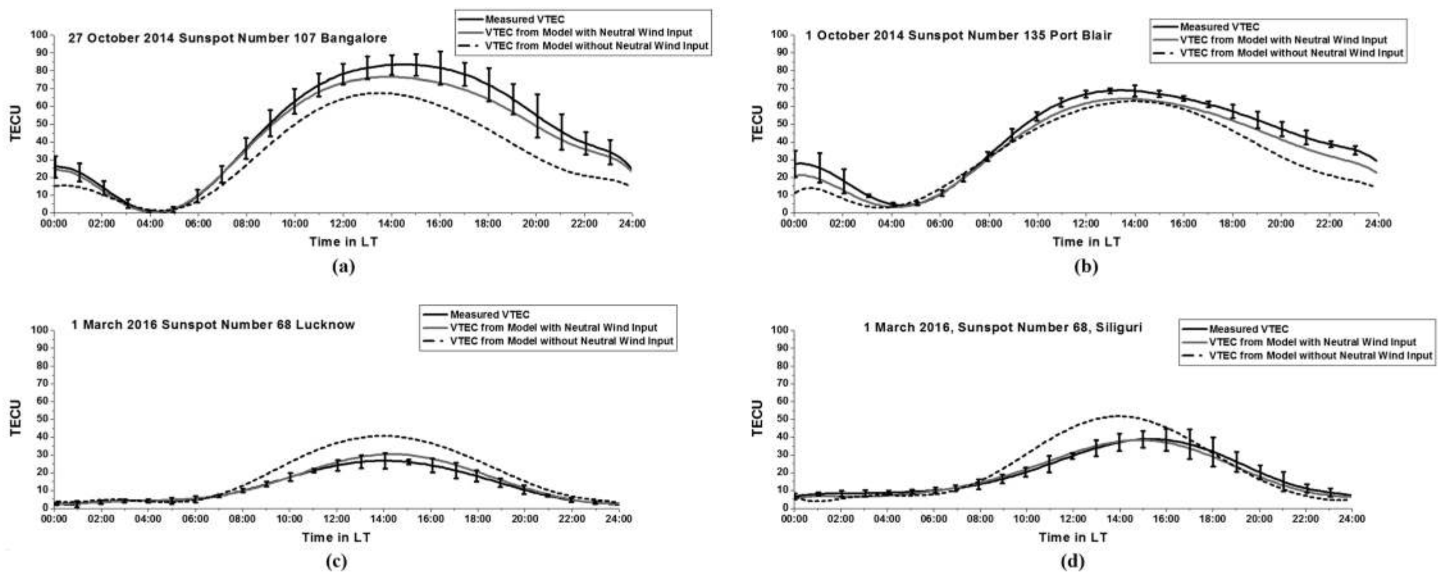

Figure 2. (a) Diurnal comparison of predicted VTEC from IRPE-TEC-BANGALORE(HWM) and IRPE-TEC-BANGALORE alongside measured VTEC at Bangalore (12.95°N, 77.68°E geographic; magnetic dip 13.57°; and magnetic declination −1.43°) on 27 October 2014. The $\pm 1\sigma$ standard deviation is shown in hourly basis over measured VTEC. (b) Diurnal comparison of predicted VTEC from IRPE-TEC-PORT BLAIR(HWM) and IRPE-TEC-PORT BLAIR alongside measured VTEC at Port Blair (11.64°N, 92.71°E geographic; magnetic dip 9.72°; and magnetic declination −0.95°) on 1 October 2014. The $\pm 1\sigma$ standard deviation is shown in hourly basis over measured VTEC. (c) Diurnal comparison of predicted VTEC from IRPE-TEC-LUCKNOW(HWM) and IRPE-TEC-LUCKNOW alongside measured VTEC at Lucknow (26.91°N, 80.96°E geographic; magnetic dip 42°; and magnetic declination 0.58°) on 1 March 2016. The $\pm 1\sigma$ standard deviation is shown in hourly basis over measured VTEC. (d) Diurnal comparison of predicted VTEC from IRPE-TEC-88E(HWM) and IRPE-TEC-88E alongside measured VTEC at Siliguri (26.72°N, 88.39°E geographic; magnetic dip 41.54°; and magnetic declination 0.07°) on 1 March 2016. The $\pm 1\sigma$ standard deviation is shown in hourly basis over measured VTEC.

feeding the data into the model. The model have been tested during March 2016 from Siliguri. Another model (IRPE-TEC-88E(HWM)) has been designed by adding neutral wind inputs such as meridional wind and zonal wind as model inputs. These models are used to see the effects of neutral wind on VTEC models in these longitudinally separated regions.

3. Some Case Studies of Diurnal Variations of Predicted VTEC From ANN-Based VTEC Models

It has already been observed that ANN-based data-driven VTEC models produce more accurate predictions than standard ionospheric models (IRI, PIM, and NeQuick) [*Sur and Paul*, 2013]. Further improvements in prediction accuracies of these ANN-based VTEC models have been observed after incorporation of neutral wind as model input [*Sur et al.*, 2015]. Performances of ANN-based VTEC models at Bangalore and Port Blair have been observed during all geomagnetic quiet days of October 2014. Performances of ANN-based VTEC models at Lucknow and Siliguri have been observed during all geomagnetic quiet days of March 2016. The diurnal performance of ANN-based VTEC models from Bangalore, Port Blair, Lucknow, and Siliguri is shown in Figure 2 for four arbitrarily chosen geomagnetic quiet days from the entire test periods. Predicted VTEC from the ANN-based VTEC model at Bangalore is shown in Figure 2a for 27 October 2014. Predicted VTEC from the ANN-based VTEC model at Port Blair is shown in Figure 2b for 1 October 2014. Similar observation from Lucknow and Siliguri is shown in Figures 2c and 2d, respectively, for 1 March 2016. It has been observed from Figures 2a–2d that ANN-based VTEC models with neutral wind input show close correspondence with the measured VTEC for a major part of these tested days compared to the model without neutral wind. Similar model testing is performed during other geomagnetic quiet days of the test months from these stations. From these results, it has been observed that the percentage accuracy of ANN-based VTEC models has been increased after inclusion of neutral wind for almost throughout each day. The effects of neutral wind on the performance of ANN-based VTEC models for different latitudes, seasons, longitudes, and solar activity have been observed in the following sections.

4. Effects of Neutral Wind on ANN-Based VTEC Models at Different Latitudes

Any improvement in accuracy after inclusion of neutral wind has been expressed in percentage. The percentage accuracy is calculated by equation (3).

$$\text{percentage accuracy} = [(\text{measured VTEC}{\sim}\text{predicted VTEC})/\text{measured VTEC}] \times 100\% \quad (3)$$

$$\begin{aligned}&\text{The increment of percentage accuracy after addition of neutral wind}\\&\quad = \text{percentage accuracy from the ANN} - \text{based VTEC model with neutral wind}\\&\quad = \text{percentage accuracy from the ANN} - \text{based VTEC model without neutral wind}\end{aligned} \quad (4)$$

$$\text{Absolute predicted VTEC error} = \text{measured VTEC}{\sim}\text{predicted VTEC}, \text{VTEC is expressed in terms of TECU.} \quad (5)$$

In this section, the effects of neutral wind on ANN-based VTEC models at different latitudes of the Indian longitude sector have been observed. The neutral wind coupled model (IRPE-TEC-77E(HWM)) is compared with the model without neutral wind (IRPE-TEC-77E) for two separate equinoctial periods of 2005 (April 2005 and October 2005) in order to observe the effect of neutral wind on the models at different latitudes and during different seasons. Increment or decrement of accuracy after incorporation of neutral wind has been computed for each hour. The results have been shown in Figure 3 for both April and October 2005. Monthly median values of absolute predicted VTEC error during every hour are also shown in Figure 3. Diurnal median increment of percentage accuracy of models and diurnal reduction of absolute error VTEC (TECU) after inclusion of neutral wind during every test periods throughout this manuscript are shown in Figure 6.

The effects of neutral wind on performance accuracy of VTEC model from Delhi (station beyond the northern crest of EIA) during different hours of April 2005 are shown in Figure 3a. The maximum increments in accuracy after incorporation of neutral wind are observed during 06:00 LT (39.28%) and 22:00 LT (40.16%) at Delhi. The maximum decrement of performance accuracy after incorporation of neutral wind is observed during 19:00 LT (26.64%). Diurnal median increment of model accuracy after incorporation of neutral wind from Delhi in April 2005 is 8.21% (Figure 6a). The monthly absolute VTEC prediction errors during every hour obtained from VTEC models before and after inclusion of neutral wind are shown in Figure 3b. The reduction of absolute error VTEC after incorporation of neutral wind is observed during every hour of each day. The absolute error has been reduced after addition of neutral wind during most of the hours of each day. The diurnal median reduction of absolute error VTEC after inclusion of neutral wind is 1.53 TECU (Figure 6b).

The effects of neutral wind on the performance accuracy of an ANN-based VTEC model from Bhopal (situated near the northern crest of EIA) in April 2005 are shown in Figure 3c. It is found that the performance has been improved after incorporation of neutral wind during different hours of April 2005 except during 21:00 LT. The highest increments of performance accuracy are observed during 06:00 LT (59.70%), 07:00 LT (63.10%), 11:00 LT (62.24%), and 13:00 LT (56.91%). Diurnal median improvement of percentage accuracy after incorporation of neutral wind during April 2005 is 25.87% (Figure 6a). The monthly prediction errors during every hour in terms of absolute VTEC from models before and after inclusion of neutral wind are shown in Figure 3d. The absolute error VTEC has been reduced after incorporation of neutral wind throughout the majority part of each day during April 2005. The diurnal median reduction of absolute error VTEC after inclusion of neutral wind is 5.05 TECU at Bhopal during April 2005 (Figure 6b).

The same comparison has been performed at Hyderabad, a station situated between geomagnetic equator and northern crest of EIA. The results are shown in Figure 3e. From Figure 3e, it is found that the highest improvements of performance accuracy have occurred during 06:00 LT (52.81%) and during 20:00 LT (44.56%) after inclusion of neutral wind. The ANN model with neutral wind shows better accuracy almost throughout the day except during 00:00–01:00 LT. During 00:00–01:00 LT, the model without neutral wind shows better accuracy than the model with neutral wind. Diurnal improvement of accuracy after incorporation of neutral wind during April 2005 at this station is 12.29% (Figure 6a). The hourly absolute VTEC errors before

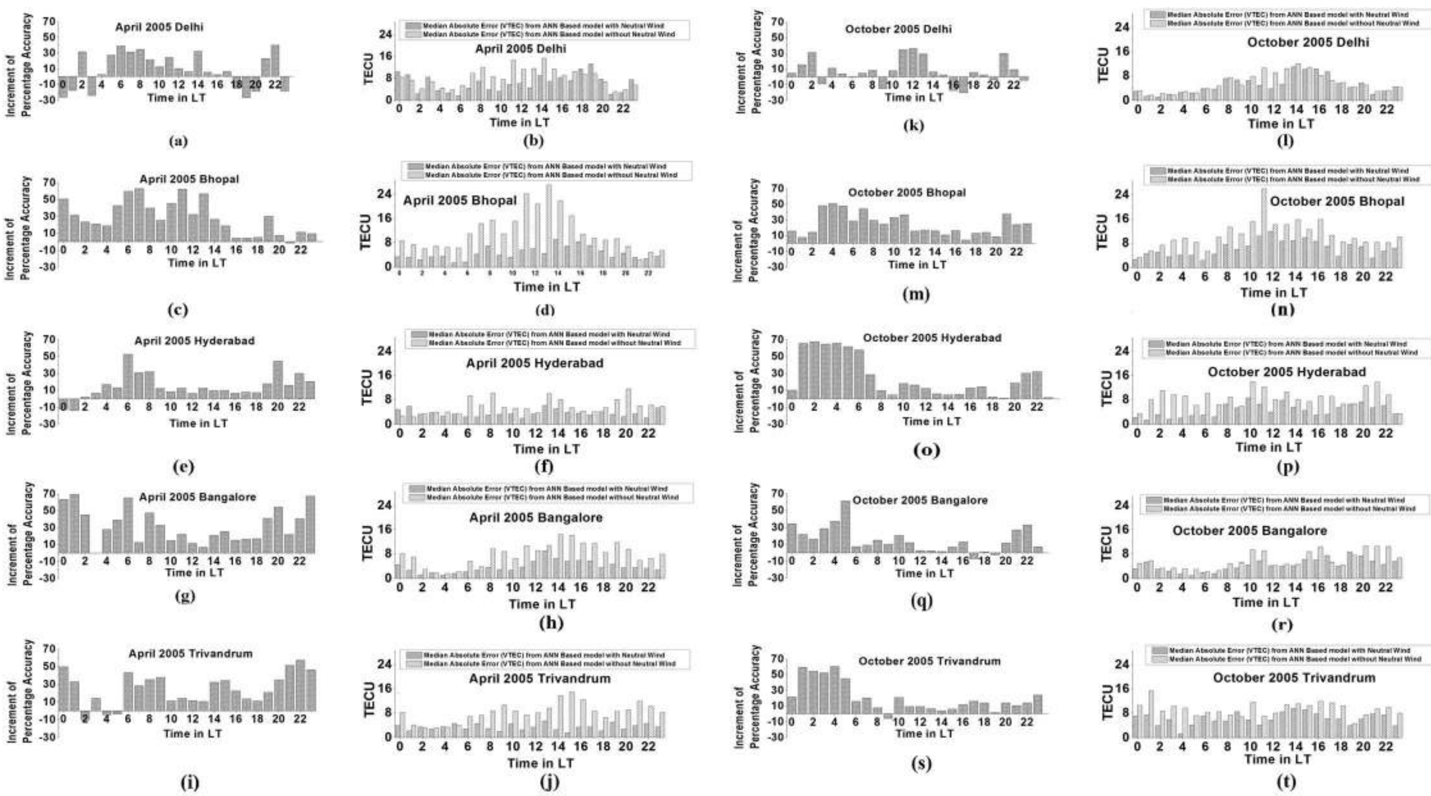

Figure 3. (a) Hourly median increment of percentage accuracy obtained from IRPE-TEC-77E(HWM) over IRPE-TEC-77E at Delhi (28.58°N, 77.21°E geographic; magnetic dip 43.5°; and magnetic declination 0.68°) during April 2005. Monthly mean sunspot number: 38.7. (b) Hourly absolute VTEC errors obtained from IRPE-TEC-77E(HWM) and IRPE-TEC-77E at Delhi during April 2005. (c) Hourly median increment of percentage accuracy obtained from IRPE-TEC-77E(HWM) over IRPE-TEC-77E at Bhopal (23.28°N, 77.34°E geographic; magnetic dip 33.95°; and magnetic declination −0.26°) during April 2005. Monthly mean sunspot number: 38.7. (d) Hourly absolute VTEC errors obtained from IRPE-TEC-77E(HWM) and IRPE-TEC-77E at Bhopal during April 2005. (e) Hourly median increment of percentage accuracy obtained from IRPE-TEC-77E(HWM) over IRPE-TEC-77E at Hyderabad (17.44°N, 78.47°E geographic; magnetic dip 21.9°; and magnetic declination −1.15°) during April 2005. Monthly mean sunspot number: 38.7. (f) Hourly absolute VTEC errors obtained from IRPE-TEC-77E(HWM) and IRPE-TEC-77E at Hyderabad during April 2005. (g) Hourly median increment of percentage accuracy obtained from IRPE-TEC-77E(HWM) over IRPE-TEC-77E at Bangalore (12.95°N, 77.68°E geographic; magnetic dip 11.69°; and magnetic declination −1.82°) during April 2005. Monthly mean sunspot number: 38.7. (h) Hourly absolute VTEC errors obtained from IRPE-TEC-77E(HWM) and IRPE-TEC-77E at Bangalore during April 2005. (i) Hourly median increment of percentage accuracy obtained from IRPE-TEC-77E(HWM) over IRPE-TEC-77E at Trivandrum (8.47°N, 76.91°E geographic; magnetic dip 0.9°; and magnetic declination −2.59°) during April 2005. Monthly mean sunspot number: 38.7. (j) Hourly absolute VTEC errors obtained from IRPE-TEC-77E(HWM) and IRPE-TEC-77E at Trivandrum during April 2005. (k) Hourly median increment of percentage accuracy obtained from IRPE-TEC-77E(HWM) over IRPE-TEC-77E at Delhi (28.58°N, 77.21°E geographic; magnetic dip 43.5°; and magnetic declination 0.68°) during October 2005. Monthly mean sunspot number: 13.2. (l) Hourly absolute VTEC errors obtained from IRPE-TEC-77E(HWM) over IRPE-TEC-77E at Delhi during October 2005. (m) Hourly median increment of percentage accuracy obtained from IRPE-TEC-77E(HWM) over IRPE-TEC-77E at Bhopal (23.28°N, 77.34°E geographic; magnetic dip 33.95°; and magnetic declination −0.26°) during October 2005. Monthly mean Sunspot Number: 13.2. (n) Hourly absolute VTEC errors obtained from IRPE-TEC-77E(HWM) over IRPE-TEC-77E at Bhopal during October 2005. (o) Hourly median increment of percentage accuracy obtained from IRPE-TEC-77E(HWM) over IRPE-TEC-77E at Hyderabad (17.44°N, 78.47°E geographic; magnetic dip 21.9°; magnetic declination −1.15°) during October 2005. Monthly mean sunspot number: 13.2. (p) Hourly absolute VTEC errors obtained from IRPE-TEC-77E(HWM) over IRPE-TEC-77E at Hyderabad during October 2005. (q) Hourly median increment of percentage accuracy obtained from IRPE-TEC-77E(HWM) over IRPE-TEC-77E at Bangalore (12.95°N, 77.68°E geographic; magnetic dip 11.69°; and magnetic declination −1.82°) during October 2005. Monthly mean sunspot number: 13.2. (r) Hourly absolute VTEC errors obtained from IRPE-TEC-77E(HWM) over IRPE-TEC-77E at Bangalore during October 2005. (s) Hourly median increment of percentage accuracy obtained from IRPE-TEC-77E(HWM) over IRPE-TEC-77E at Trivandrum (8.47°N, 76.91°E geographic; magnetic dip 0.9°; and magnetic declination −2.59°) during October 2005. Monthly mean sunspot number: 13.2. (t) Hourly absolute VTEC errors obtained from IRPE-TEC-77E(HWM) over IRPE-TEC-77E at Trivandrum during October 2005.

and after incorporation of neutral wind in VTEC model are shown in Figure 3f. The diurnal median decrement of absolute error is 1.80 TECU after inclusion of neutral wind from Hyderabad during April 2005 (Figure 6b).

The performance of neutral wind incorporated ANN VTEC model from Bangalore (a station located between the geomagnetic equator and northern crest of EIA) is shown in Figure 3g. ANN-based VTEC model with neutral wind shows better accuracy than ANN-based model without neutral wind almost throughout the day except during 03:00 LT in April 2005. The highest improvements in percentage accuracy are observed during 00.00–01:00 LT, 06:00 LT, and 23:00 LT (63.45% to 69.53%). Diurnal median improvement in percentage accuracy after addition of neutral winds during April 2005 is 26.68% (Figure 6a). The absolute errors before and after addition of neutral winds in VTEC model have been shown in Figure 3h. The diurnal median of the reduction of absolute VTEC error after inclusion of neutral wind is 4.07 TECU from this location (Figure 6b).

The effects of neutral wind on performance accuracy of ANN VTEC model from Trivandrum (located near the geomagnetic equator) during April 2005 is shown at Figure 3i. It can be seen from Figure 3i that the model with neutral wind shows better accuracy than the model without neutral wind almost throughout the day except during 02:00 LT, 04:00 LT, and 05:00 LT in April 2005. The highest improvements in prediction accuracy after incorporation of neutral wind are observed during 00:00 LT and 21:00–23:00 LT (46.33% to 57.20%). The rate of improvement of prediction accuracy after incorporation of neutral wind had decreased during 02:00–05:00 LT (−10.41% to 14.03%), 10:00–13:00 LT (10.62% to 14.14%), and during 17:00–18:00 LT (10.97% to 13.54%). The negative symbol indicates that incorporation of neutral wind has degraded the performance accuracy during that particular interval. Diurnal median improvement of percentage accuracy after inclusion of neutral wind during April 2005 is 25.39% (Figure 6a). The absolute VTEC prediction errors from models with and without neutral wind from Trivandrum during April 2005 are shown in Figure 3j. The absolute VTEC prediction error has been reduced for most of the times in each day after incorporation of neutral wind. The diurnal median reduction of absolute error after addition of neutral wind is 4.48 TECU (Figure 6b).

The effects of neutral wind on the ionosphere of this equatorial region to EIA crest (Trivandrum to Bhopal) may be explained by the induced electric field by neutral wind in this region [*Rishbeth*, 1997; *Heelis*, 2004; *Fang et al.*, 2009]. This electric field is generated due to zonal drift of ions and electrons in the equatorial region. An electric current is generated due to this electric field. This wind induced electric field (E_w = wind velocity × magnetic flux density) increases the total electric field. The addition of an electric field also adds to the conventional $E \times B$ drift velocity of F region ions and electrons. These changes in $E \times B$ upward ion drift due to E and F region neutral wind flow have already been established [*Rishbeth*, 1997]. The effects of F region zonal wind to the $E \times B$ ion drift has been suggested by *Heelis* [2004] and *Kutiev et al.* [2007]. Neutral wind-driven electric field enhances the $E \times B$ ion drift during daytime at geomagnetic equator [*Immel et al.*, 2006]. The increment of daytime eastward electric field and current because of the flow of neutral wind through E region has also been reported in *Maute et al.* [2012]. The influence of neutral wind in nighttime equatorial ionization is suggested by *Rishbeth* [1981], *Crain et al*. [1993], *Fesen et al*. [2000], and *Jin et al.* [2008]. This additional electric field may strengthen the upward $E \times B$ ion drift in this equatorial region. This may be a possible reason for the influence of neutral wind on performance accuracy of an ANN-based VTEC model at regions close to magnetic equator to EIA crest. From the above observations, it can be concluded that the least diurnal median improvement among Trivandrum to Bhopal is observed at Hyderabad during April 2005. These variations do not conclusively support the mechanism mentioned above regarding the effects of neutral wind on $E \times B$ ion drift.

For the region from northern crest of EIA to region beyond northern crest of EIA (Bhopal to Delhi), it has been observed that the diurnal median increment of percentage accuracy after incorporation of neutral winds has been reduced at Delhi (located beyond the northern crest of EIA). The minimum reduction of absolute error after inclusion of neutral wind is also observed from Delhi (between Bhopal and Delhi). The diurnal median of reduction of the absolute error from Delhi is 1.53 TECU. This can be explained by equation (6) [*Zhang et al.*, 2011].

$$v = -v_z \text{ sine } (\beta) \text{ cosine } (\delta) \tag{6}$$

v =Earth's magnetic field line aligned ionization drift velocity (conventionally positive for upward drift), m/s

v_z =zonal wind velocity can be obtained from HWM07 model (conventionally positive for eastward direction), m/s

β =local magnetic declination angle (conventionally positive for eastward magnetic field), degree

magnetic declination is zero for magnetic north.

δ =local magnetic inclination angle (conventionally positive for downward magnetic field), degree.

Magnetic inclination is zero at the horizontal.

The growth of Earth's magnetic field line aligned ionization drift velocity depends on the zonal wind of that region at that local time, local magnetic inclination angle, and declination angle. The direction of each component determines the final direction of ionization drift velocity (upward or downward). When the ionization moves upward, this reduces the rate of ion recombination and thus increases TEC of that region. In case of downward movement, the recombination rate increases and the TEC of that region decreases. This may be a possible explanation of how zonal wind can be correlated with TEC. All the stations tested for April 2005 are situated almost along same longitudes and very close declination angles. Among the stations from northern crest of EIA to region beyond northern crest of EIA, Delhi is situated at a location with high geographic latitude and magnetic inclination angle. If the inclination angle increases, the cosine component of inclination angle will subsequently be decreased. This reduces the Earth's magnetic field line aligned ionization drift velocity. Thus, the effect of zonal wind on the development of TEC is decreased. This can be a possible explanation of reduced increment of prediction accuracy at ANN-based VTEC model after incorporation of neutral wind at Delhi (situated beyond the northern crest of EIA).

It should be noted that the effects of zonal wind on the developed VTEC models have been observed from five stations extending from Trivandrum and Bangalore, near the magnetic equator through Hyderabad, located between magnetic equator and the northern crest of EIA, to Bhopal, situated at the northern crest and Delhi, located beyond the northern crest. Possible explanation for observed effect on the lines of ionospheric electrodynamic mechanism following *Zhang et al.* [2011] could be effectively applied for two stations, Bhopal and Delhi.

5. Effects of Neutral Wind on ANN-Based VTEC Models During Different Seasons

In order to observe seasonal variation of the effects of neutral wind on the performance of ANN-based VTEC models in the Indian longitude sector, IRPE-TEC-77E and IRPE-TEC-77E(HWM) models are tested for April and October 2005 during moderate to low solar activity periods. The performances of VTEC models in April 2005 have been discussed in section 4. Similar testing of models has been conducted during October 2005, and the results have been discussed in this section.

The ANN-based VTEC models IRPE-TEC-77E and IRPE-TEC-77E(HWM) are tested for Delhi (GPS-TEC receiver station located beyond the northern crest of EIA) during the periods of October 2005. The results are shown in Figure 3k. The highest increments of accuracies have been observed during 02:00 LT, 11:00–13:00 LT, and 21:00 LT (29.46% to 36.21%) after inclusion of neutral wind. Diurnal median increment of percentage accuracy is 5.31% during October 2005 (Figure 6a). Diurnal increment of percentage accuracy after incorporation of neutral wind at Delhi during April 2005 is 8.21% (section 4). Thus, the increment rate of percentage accuracy of ANN-based VTEC models after inclusion of neutral wind at Delhi has been reduced during autumnal equinox compared to that during vernal equinox in 2005. Absolute prediction errors from models with and without neutral wind are shown in Figure 3l for every hour during October 2005. It has been observed that the absolute error has been reduced significantly after inclusion of neutral wind almost during every hour in October 2005 except during 03:00 LT, 09:00 LT, 16:00–17:00 LT, 20:00 LT, and 23:00 LT. The diurnal median of reduction of absolute error VTEC after inclusion of neutral wind at Delhi during October 2005 is 0.25 TECU (Figure 6b). The same is higher during April 2005 (1.53 TECU) than during October 2005.

The models have been tested during October 2005 from Bhopal, located near the northern crest of EIA (Figure 3m). From these results, it could be seen that the model based on neutral wind shows better accuracy than the model without neutral wind during different hours of October 2005. The maximum improvement of percentage accuracies after incorporation of neutral wind has been found during 03:00 LT, 04:00 LT, 05:00 LT, and 07:00 LT (44.03% to 50.80%). Diurnal median of the improvement in accuracy observed is 20.58% during October 2005 (Figure 6a). Diurnal median of the improvement in accuracy after incorporation of neutral wind during April 2005 is 25.87% (section 4). The effect of neutral wind on prediction accuracies of ANN-based VTEC models has been decreased in October 2005 during 00:00–02:00 LT, 06:00–15:00 LT, 17:00 LT, and 19:00 LT compared to April 2005. Thus, it can be concluded that the improvement of percentage accuracies of ANN-based VTEC models after inclusion of neutral wind has been decreased during autumnal equinoctial periods compared to that during vernal equinox at Bhopal in 2005. The absolute VTEC prediction error before and after addition of neutral wind at Bhopal during October 2005 are shown in Figure 3n. The diurnal median reduction of the absolute errors from Bhopal is 4.72 TECU after addition of neutral wind during October 2005 (Figure 6b) which is lesser than that during April 2005 (5.05 TECU).

The effects of neutral wind on prediction accuracy of ANN-based VTEC models have also been studied during October 2005 at Hyderabad (Figure 3o). Hyderabad is situated between the magnetic equator and the northern crest of EIA. It has been observed that the model with neutral wind produces higher accuracy toward TEC prediction during October 2005. The highest increments of accuracies after inclusion of neutral wind in ANN-based VTEC model have been observed during 01:00–06:00 LT (57.78% to 67.59%). Diurnal median improvement in percentage accuracy after inclusion of neutral wind during October 2005 is 15.13% (Figure 6a). Diurnal median percentage increment of accuracy observed during April 2005 after inclusion of neutral wind is 12.29%. So it can be concluded that the effect of neutral wind on the percentage accuracy of an ANN-based VTEC model has been increased in autumnal equinox compared to that during vernal equinox at Hyderabad during 2005. From Figure 3p, the absolute error VTEC from models before and after inclusion of neutral wind can be observed. The diurnal median decrement of absolute VTEC error after inclusion of neutral wind is 3.99 TECU during October 2005 TECU (Figure 6b). This is higher than that observed during April 2005 (1.80 TECU) from the same location.

The same observation has been performed from Bangalore, located between magnetic equator and northern crest of EIA (Figure 3q). From Figure 3q, it can be observed that the model coupled with neutral wind shows better accuracy than the model without neutral wind during different hours during October 2005 at Bangalore except during 17:00 LT and 19:00 LT. The highest increment of percentage accuracy has been observed during 05:00 LT (61.37%) after addition of neutral wind as model inputs. Diurnal median increment during October 2005 is 11.80% after incorporation of neutral wind (Figure 6a). This is lesser than the diurnal median increment of percentage accuracy during April 2005 (26.68%) after incorporation of neutral wind as model input at Bangalore. After observing performances during individual hours, it can be concluded that the effects of neutral wind on percentage accuracies of ANN-based VTEC model have been decreased during 00:00–02:00 LT, 06:00–09:00 LT, 11:00–20:00 LT, and 22:00–23:00 LT in autumnal equinox compared to that during vernal equinox in 2005 at Bangalore. Absolute prediction error VTEC has been computed for each hour, and the variation of this has been observed before and after incorporation of neutral wind (Figure 3r). The diurnal median reduction of absolute error throughout the day at Bangalore during October 2005 is 1.45 TECU after addition of neutral wind as model input (Figure 6b). This is lesser than that obtained during April 2005 from the same location (4.07 TECU).

The effects of neutral wind on performance accuracy of ANN-based VTEC models at Trivandrum (station near the geomagnetic equator) are shown in Figure 3s for October 2005. From Figure 3s, it has been observed that the model with neutral wind produces more accurate results than the model without neutral wind for almost the entire day except during 09:00 LT in October 2005. The increment of the accuracy after incorporation of neutral wind maximizes during 01:00–04:00 LT (52.17%–60.61%). Diurnal median increment of performance accuracy during October 2005 is 13.90% after inclusion of neutral wind inputs (Figure 6a). Diurnal median increment of percentage accuracy obtained from model with neutral wind at Trivandrum during April 2005 is 25.39%. After observing the effects of neutral wind during individual hour, it can be observed that the effect of neutral wind on prediction accuracies of ANN-based VTEC model has been decreased in autumnal equinox during 00:00 LT, 06:00–09:00 LT, 11:00–16:00 LT, and 19:00–23:00 LT compared to that during vernal equinox at Trivandrum in 2005. So it can be summarized that the overall effect of incorporation of neutral winds on ANN-based VTEC model has been reduced during autumnal equinox compared to that during vernal equinox in 2005 at Trivandrum. The diurnal variation of absolute error VTEC before and after addition of neutral wind is shown in Figure 3t. The diurnal median decrement in error VTEC after inclusion of neutral wind during October 2005 at this station is 2.87 TECU (Figure 6b). This is lesser than that obtained from same location during April 2005 (4.48 TECU).

Thus, it has been observed (Figures 3a–3t) that the total median increment of performance accuracy after incorporation of neutral wind at Delhi is less than that at the other stations tested in both equinoxes. Figure 3k also indicates that the largest overall improvement in accuracy after inclusion of neutral wind has been observed at Delhi during 12:00–13:00 LT in October 2005. It is important to note that these observations do not conclusively satisfy the explanation given in terms of field-aligned ion drift mechanism.

From Figures 3a–3t and 6a and 6b, it can be concluded that the effects of neutral wind on ANN-based real-time data-driven VTEC models have been lesser during autumnal equinox than that during vernal equinox except Hyderabad in 2005. This can be explained by equinoctial asymmetry of ionization. It has been observed that N_mF_2 and TEC in vernal equinox are higher than that those in autumnal equinox during solar minimum [*Akala et al.*, 2013]. The difference of ionization between two equinoxes is referred as equinoctial asymmetry [*Titheridge*, 1973; *Essex*, 1977; *Titheridge and Buonsanto*, 1983; *Balan et al.*, 1997, 1998; *Kawamura et al.*, 2002; *Liu et al.*, 2010, 2011]. This asymmetry intensifies near EIA crest [*Balan et al.*, 2000]. Asymmetric distribution of ionization during different equinoctial periods has also been observed from other locations [*Balan et al.*, 1997, 1998, 2000; *Bailey et al.*, 2000; *Unnikrishnan et al.*, 2002]. The asymmetry of ionization may be explained by variation of neutral wind velocities during different seasons. The variation of *F* region plasma drift due to zonal wind is very high during vernal equinox [*Fejer*, 1991, 2011; *Valladares et al.*, 1996; *Akala et al.*, 2013]. This variation of plasma drift velocity of zonal wind increases its influence over VTEC during vernal equinoxes more prominently than during autumnal equinox. The variation in the magnitude of neutral wind during different equinoctial periods has also been reported in *Aruliah et al.* [1996] and *Kawamura et al.* [2002]. The relation between variation of neutral wind velocities and asymmetrical distribution of ionization process during different seasons has also been reported in other literatures [*Wright*, 1963; *Torr and Torr*, 1973; *Millward et al.*, 1996; *Rishbeth et al.*, 2000; *Zou et al.*, 2000; *Richards*, 2001; *Mendillo et al.*, 2005; *Pavlov and Pavlova*, 2005; *Liu et al.*, 2007, 2010; *Oliver et al.*, 2008]. The strong correlation between these ionization asymmetries during two equinoxes with variation of neutral winds has also been established by *Balan et al.* [1997, 1998]. The bottomside ionization asymmetry is observed due to the change of the ratio of oxygen atom and nitrogen molecule which is stronger during autumnal equinoxes. The topside ionization asymmetry during two equinoctial periods occurred because of the variation of magnitude and direction of neutral winds. The geomagnetically directed component of neutral wind causes sharp upward plasma drift during daytime. This causes asymmetry near the ionization peak. This asymmetry is stronger than the bottomside asymmetry. This phenomenon intensifies during the vernal equinox causing high ionization during this equinox. [*Balan et al.*, 1997, 2000; *Kawamura et al.*, 2002; *Liu et al.*, 2010]. The sharp influence of neutral wind on the generation of high VTEC values during vernal equinoxes could be a possible explanation of this higher increment in accuracy of VTEC models during vernal equinox than that during autumnal equinox after inclusion of neutral wind as model input.

It can be observed that (Figures 3a–3t) the increase in percentage accuracies after incorporation of neutral wind reduces during diurnal peak VTEC time in most of the cases during both equinoxes. It is because all the percentage accuracies are calculated relative to the actual VTEC (which is higher at diurnal peak time). Thus, the percentage accuracies decrease during diurnal peak time for most of the days. But the reduction of absolute VTEC error after inclusion of neutral wind maximizes around diurnal peak time in most of the cases.

6. Effects of Neutral Wind on Performance of ANN-Based VTEC Models During Different Solar Activity Periods

In order to observe the effects of neutral wind on the performance accuracy of ANN-based VTEC models during different solar activity periods in the Indian longitude sector, models with and without neutral wind are tested during moderate solar activity periods (October 2005) and high solar activity periods (October 2014) from Bangalore (12.95°N, 77.68°E geographic; magnetic dip 11.69° in year 2005 and 13.57° in 2014; and magnetic declination −1.82° in 2005 and −1.43° in 2014). IRPE-TEC-77E(HWM) and IRPE-TEC-77E models have been used to observe the effects of neutral wind on VTEC models at Bangalore during October 2005. The increment of percentage accuracy of VTEC model after inclusion of neutral wind during October 2005 has earlier been shown in Figure 3q. The absolute prediction errors from models with and without neutral wind from Bangalore during October 2005 are shown in Figure 3r. These figures have been shown again in Figures 4a and 4b, respectively. It has been shown in section 5 that except during 17:00 LT and 19:00 LT, neutral wind coupled model shows better accuracy than the model without neutral wind (Figure 4a) in October 2005 from Bangalore. The increment in accuracy is maximum during 05:00 LT (61.37%) after incorporation of neutral winds. The diurnal median increment is 11.80% during October 2005. The diurnal median reduction of absolute error after inclusion of neutral wind at Bangalore during October 2005 is 1.45 TECU (Figure 4b).

The corresponding models for the high solar activity periods of 2014 have been designed using IGS GPS TEC (IRPE-TEC-BANGALORE and IRPE-TEC-BANGALORE(HWM)) data from Bangalore. The details of training and testing data have been discussed in section 2. The increment of percentage accuracy after incorporation of neutral wind as model input is shown in Figure 4c for October 2014. It can be observed from Figure 4c

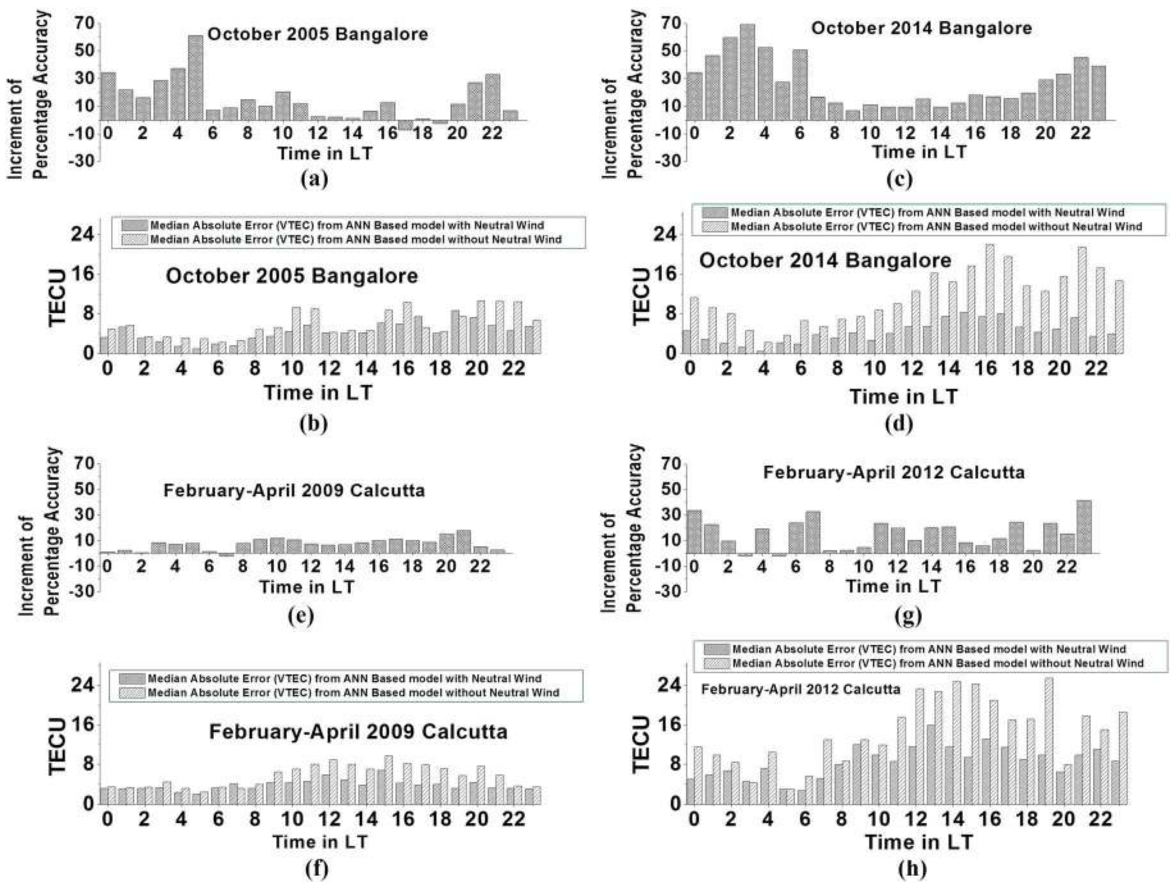

Figure 4. (a) Hourly median increment of percentage accuracy obtained from IRPE-TEC-77E(HWM) over IRPE-TEC-77E at Bangalore (12.95°N, 77.68°E geographic; magnetic dip 11.69°; and magnetic declination −1.82°) during October 2005. Monthly mean sunspot number: 13.2. (b) Hourly absolute VTEC errors obtained from IRPE-TEC-77E(HWM) over IRPE-TEC-77E at Bangalore during October 2005. (c) Hourly median increment of percentage accuracy obtained from IRPE-TEC-BANGALORE(HWM) over IRPE-TEC-BANGALORE at Bangalore (12.95°N, 77.68°E geographic; magnetic dip 13.57°; and magnetic declination −1.43°) during October 2014. Monthly mean sunspot number: 90. (d) Hourly absolute VTEC errors obtained from IRPE-TEC-BANGALORE(HWM) over IRPE-TEC-BANGALORE at Bangalore during October 2014. (e) Hourly median increment of percentage accuracy obtained from IRPE-TEC-CALCUTTA(HWM) over IRPE-TEC-CALCUTTA at Calcutta (22.58°N, 88.38°E geographic, magnetic dip 33.09°; and magnetic declination −0.51°) during February–April 2009. Monthly mean sunspot number for February 2009: 1.2, March 2009: 0.6, and April 2009: 1.2. (f) Hourly absolute VTEC errors obtained from IRPE-TEC-CALCUTTA(HWM) over IRPE-TEC-CALCUTTA at Calcutta during February–April 2009. (g) Hourly median increment of percentage accuracy obtained from IRPE-TEC-88E(HWM) over IRPE-TEC-88E at Calcutta (22.58°N, 88.38°E geographic, magnetic dip 33.48°; and magnetic declination −0.45°) during February–April 2012. Monthly mean sunspot number for February 2012: 47.8, March 2012: 86.6, and April 2012: 85.9. (h) Hourly absolute VTEC errors obtained from IRPE-TEC-88E(HWM) over IRPE-TEC-88E at Calcutta during February–April 2012.

that the model with neutral wind provides improved accuracy during all the hours of each day in October 2014. The highest increments in accuracies are observed during 02:00–04:00 LT and 06:00 LT (50.86% to 69.17%). Diurnal median increment in accuracy after inclusion of neutral wind is 18.63% (Figure 6c). The corresponding value for October 2005 is 11.80%. From Figures 4a and 4c, it can be noted that the overall increment of accuracy after inclusion of neutral wind components is higher during October 2014 than in October 2005 for throughout the day except during 05:00 LT and 08:00–11:00 LT. Absolute prediction errors from models before and after addition of neutral wind have been computed for October 2014 at Bangalore. These results have been shown in Figure 4d. From Figure 4d, it has been observed that the error has been reduced after inclusion of neutral wind throughout each day in October 2014. The diurnal median reduction of absolute errors from ANN-based VTEC models after inclusion of neutral wind is 6.80 TECU during October 2014 (Figure 6d). The same for October 2005 is 1.45 TECU. Thus, it can be summarized that the effects of neutral wind on prediction accuracy of ANN-based VTEC models show improvement for most part of the day during high solar activity periods than that during moderate solar activity periods at Bangalore, located between northern crest of EIA and geomagnetic equator. The overall daily median increment of effects of neutral wind also improves during high solar activity periods.

The effects of neutral wind on ANN-based VTEC model during different solar activity periods have also been observed from Calcutta (22.58°N, 88.38°E geographic, magnetic dip 33.09° in year 2009 and 33.48° in 2012; and magnetic declination −0.51° in 2009 and −0.45° in 2012). This station is located near the northern crest of EIA. The study has been conducted for low solar activity periods (February–April 2009) and for high solar activity periods (February–April 2012). IRPE-TEC-CALCUTTA and IRPE-TEC-CALCUTTA(HWM) are used for VTEC prediction during February–April 2009. IRPE-TEC-88E and IRPE-TEC-88E(HWM) are used for the same during February–April 2012. During February–April 2009, the model with neutral wind provides more accuracy than the model without neutral wind almost throughout the day except during 07:00 LT (Figure 4e). The maximum improvement of accuracy after incorporation of neutral wind is observed during 21:00 LT (17.81%). Diurnal median improvement of accuracy after incorporation of neutral wind during February–April 2009 is 7.65% (Figure 6c). The hourly absolute VTEC errors obtained from models with and without neutral wind are shown in Figure 4f. The prediction error is reduced after incorporation of neutral wind as model input for majority part of each day during February–April 2009 at Calcutta. The diurnal median of the reduction of error after inclusion of neutral wind is 2.38 TECU (Figure 6d).

During February–April 2012, model with neutral wind provides more accuracy than the model without neutral wind almost throughout the day except 03:00 LT and 05:00 LT (Figure 4g). The maximum improvement of accuracy after inclusion of neutral wind during February–April 2012 is 41.45% (23:00 LT). Diurnal median improvement of accuracy after inclusion of neutral wind is 17.27% (Figure 6c). Absolute errors are computed for models with and without neutral wind during February–April 2012 for each hour of each day (Figure 4h). The error is reduced after addition of neutral wind as model input for majority part of each day during February–April 2012 at Calcutta. The diurnal median reduction of absolute errors during each day after addition of neutral wind is 6.10 TECU (Figure 6d). This is higher than the same obtained during the periods of February–April 2009 (2.38 TECU).

From Figures 4e–4h and 6c and 6d, it is observed that the increment of percentage accuracy of VTEC models after inclusion of neutral wind has been increased during February–April 2012 compared to February–April 2009 for almost throughout the day except during 03:00 LT, 05:00 LT, 08:00–10:00 LT, 16:00–17:00 LT, and 20:00 LT. The diurnal median improvement of percentage accuracy after inclusion of neutral wind during February–April 2012 is also higher (17.27%) than that during February–April 2009 (7.65%).

These conclusions may be explained by the correlation of increase in VTEC with solar activity [*Akala et al.*, 2013]. The effects of neutral wind vary with different solar activity level. The dependency of the variation of the magnitude of the neutral wind with solar activity levels has already been reported [*Buonsanto*, 1990, 1991; *Igi et al.*, 1999]. The daytime wind velocities are stronger during solar maximum periods, while the nighttime wind velocities are stronger during solar minimum periods [*Hagan*, 1993; *Igi et al.*, 1999]. The mean meridional wind decreases in Millstone Hill with decreasing solar activity level [*Babcock and Evans*, 1979]. Neutral wind across geomagnetic field produces a slow positive ion drift along perpendicular direction of wind velocity as well as geomagnetic field [*Rishbeth*, 1971]. This ion drift affects the total ionization in this equatorial region. It has already been reported that the *F* region zonal plasma drift velocities near the equator (nighttime drift velocities) increase during solar maximum [*Fejer et al.*, 1985; *Fejer*, 2011]. The zonal wind plays a pivotal role to generate *F* region dynamo [*Rishbeth*, 1971; *Heelis et al.*, 1974]. Thus, the variation of neutral wind during different solar activity periods can affect the total ionization in low-latitude region. Atmosphere heating by solar EUV rays causes upward lifting of neutral components to upper atmosphere. During high solar activity periods, the intensity of heating and ionization by EUV rays increases due to increased intensity of 10.7 cm solar flux. This causes upward lifting of neutral components to upper atmosphere [*Hedin*, 1987; *Fuller Rowell*, 1998]. This may cause variation in ionization. Thus, these reasons may provide a suitable explanation for the increment of performance accuracy of VTEC model after incorporation of neutral winds with increase in solar activity.

7. Effects of Neutral Wind on ANN-Based VTEC Models Across Different Longitudes

Longitudinal variability (if any) of the effects of neutral wind on ANN-based VTEC models is observed from VTEC models at Bangalore (12.95°N, 77.68°E geographic; magnetic dip 13.57°; and magnetic declination −1.43°) and Port Blair (11.64°N, 92.71°E geographic; magnetic dip 9.72°; and magnetic declination −0.95°). These stations are situated almost along the same geographic latitude and geomagnetic declination angle but separated by geographic longitude and geomagnetic inclination angle. The study has been conducted during high solar activity periods (October 2014). The effects of neutral wind on performance accuracy of VTEC models from Bangalore have already been discussed in section 6 and shown in Figures 4c and 4d (redrawn in Figures 5a and 5b, respectively).

VTEC models have been tested from another station (Port Blair) which is situated almost at same latitude but separated from Bangalore by longitude (Figure 1). The percentage increment of accuracy for neutral wind coupled ANN-based VTEC model (IRPE-TEC-PORT BLAIR(HWM)) is compared with the performance of model without neutral wind (IRPE-TEC-PORT BLAIR) during October 2014. The comparison is shown in Figure 5c. From Figure 5c, it could be observed that the inclusion of neutral wind consistently increases the prediction accuracy of ANN-based VTEC models during different hours of October 2014. The highest increments in percentage accuracies after inclusion of neutral wind have been observed during 02:00–05:00 LT and 23:00 LT (46.98% to 64.65%). Similar studies have been conducted from Bangalore (Figure 5a). By comparing Figures 5a and 5c, it can be found that the increment of percentage accuracy of ANN-based VTEC models after incorporation of neutral wind is higher at Port Blair than at Bangalore for almost throughout the day in October 2014 except during 01:00–04:00 LT, 06:00 LT, 10:00–13:00 LT, 16:00–17:00 LT, and 22:00 LT. Diurnal median increment of percentage accuracy observed at Port Blair after inclusion of neutral wind is 21.91% during October 2014 (Figure 6e). The same observed at Bangalore is 18.63% during October 2014 (section 6). Thus, median increment in percentage accuracy has been increased by 3.28% after inclusion of neutral winds in Port Blair than Bangalore. Absolute prediction errors from models with and without wind are computed in Figure 5d at Port Blair during October 2014. The error has been decreased after addition of neutral wind to the model during October 2014. The diurnal median decrement of absolute error after addition of neutral wind is 7.31 TECU (Figure 6f). The same for Bangalore during the same period is 6.80 TECU.

A possible explanation of this difference could lie in this fact that longitudinal variability of ionization at region close to geomagnetic equator is strongly correlated with the variation of neutral wind velocities [*West and Heelis*, 1996]. The effects of neutral winds on longitudinal variability of ionization have also been reported by *Maute et al.*, 2012. The variation of vertical plasma drift at different longitudes of equatorial region depends on the variation of the velocities of neutral wind as well as variation of geomagnetic declination [*Vichare and Richmond*, 2005, *Maute et al.*, 2012]. Neutral wind components cause upward or downward movement of ions or electrons. This causes variation of peak height of *F* region. The effects of meridional wind are maximized during solstice periods, whereas the effects of zonal wind become prominent in equinoxes. The effects of zonal wind also maximize with high declination angles in the equatorial region [*West and Heelis*, 1996]. The declination angles of Bangalore and Port Blair are not very high ($-1.43°$ and $-0.95°$, respectively). The zonal wind velocity during equinoctial month October 2014 at Bangalore varies between 104.54 m/s eastward to 140.58 m/s westward. The same for Port Blair is 104.65 m/s eastward to 144.99 m/s westward. The narrow variation of declination angles and zonal wind velocities between Bangalore and Port Blair may be a reason of the small variation of effects of neutral wind on ANN-based VTEC models during this equinoctial period (October 2014). This longitudinal variability of the effect of neutral wind on ANN-based VTEC model is less pronounced between these two stations than latitudinal and solar variabilities observed in different regions of the Indian longitude sector during different periods. The longitudinal variability of the effects of neutral wind on VTEC models could be further improved if the difference between zonal wind velocities flowing between these two stations and declination angles of these two stations is relatively higher.

Longitudinal variability of the effects of neutral wind on VTEC models in regions beyond the northern crest of EIA has been observed using GPS TEC receiver stations at Lucknow (26.91°N, 80.96°E geographic; magnetic dip 42°; and geomagnetic declination angle 0.58°) and at Siliguri (26.72°N, 88.39°E geographic; magnetic dip 41.54°; and geomagnetic declination angle 0.07°) during March 2016. These two stations are situated in almost same geographic latitude but separated by geographic longitude.

Comparison of test results of neutral wind coupled VTEC model (IRPE-TEC-LUCKNOW(HWM)) and model without neutral wind inputs (IRPE-TEC-LUCKNOW) from Lucknow is conducted during all geomagnetic quiet days of March 2016. The comparison results are shown in Figure 5e. From Figure 5e, it could be seen that neutral wind-based VTEC model shows improvement in prediction accuracy over VTEC model without

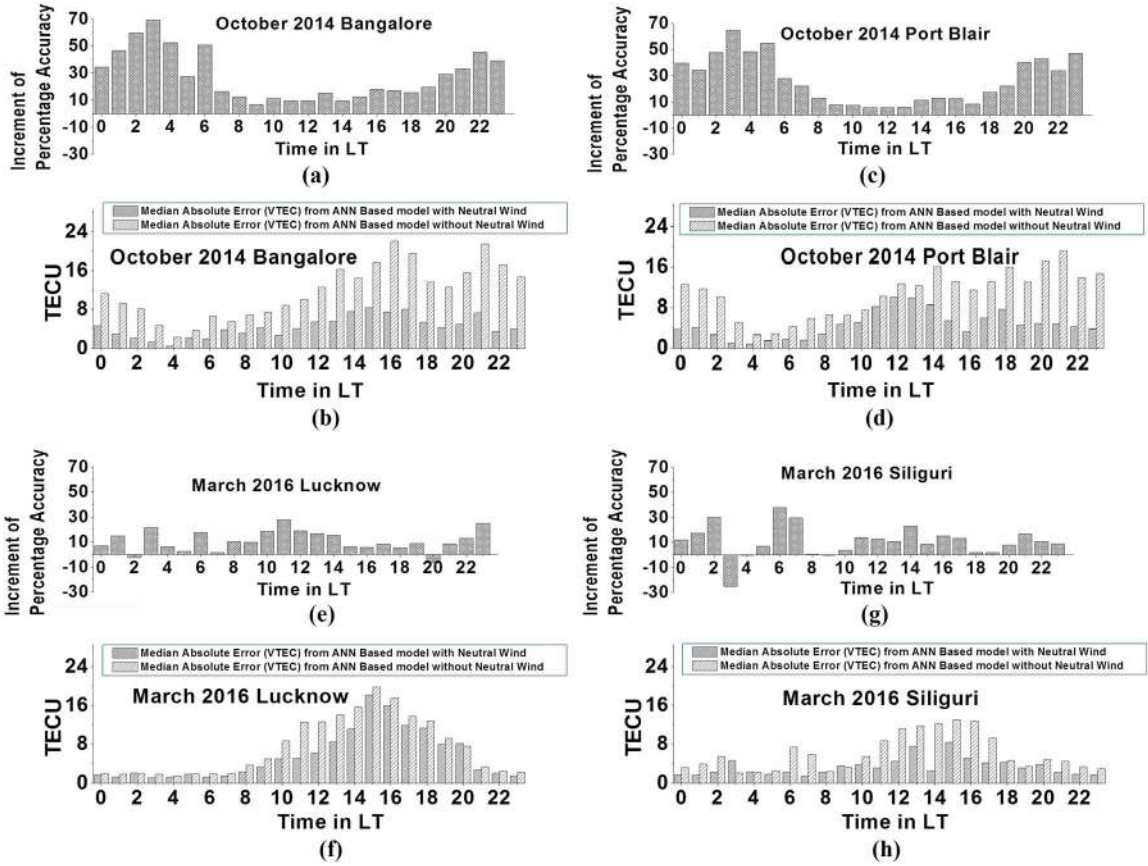

Figure 5. (a) Hourly median increment of percentage accuracy obtained from IRPE-TEC-BANGALORE(HWM) over IRPE-TEC-BANGALORE at Bangalore (12.95°N, 77.68°E geographic; magnetic dip 13.57°; and magnetic declination −1.43°) during October 2014. Monthly mean sunspot number: 90. (b) Hourly absolute VTEC errors obtained from IRPE-TEC-BANGALORE(HWM) over IRPE-TEC-BANGALORE at Bangalore during October 2014. (c) Hourly median increment of percentage accuracy obtained from IRPE-TEC-PORT BLAIR(HWM) over IRPE-TEC-PORT BLAIR at Port Blair (11.64°N, 92.71°E geographic; magnetic dip 9.72°; and magnetic declination −0.95°) during October 2014. Monthly mean sunspot number: 90. (d) Hourly absolute VTEC errors obtained from IRPE-TEC-PORT BLAIR(HWM) over IRPE-TEC-PORT BLAIR at Port Blair during October 2014. (e) Hourly median increment of percentage accuracy obtained from IRPE-TEC-LUCKNOW(HWM) over IRPE-TEC-LUCKNOW at Lucknow (26.91°N, 80.96°E geographic; magnetic dip 42°; and geomagnetic declination angle 0.58°) during March 2016. Monthly mean sunspot number: 54.1. (f) Hourly absolute VTEC errors obtained from IRPE-TEC-LUCKNOW(HWM) over IRPE-TEC-LUCKNOW at Lucknow during March 2016. (g) Hourly median increment of percentage accuracy obtained from IRPE-TEC-88E(HWM) over IRPE-TEC-88E at Siliguri (26.72°N, 88.39°E geographic; magnetic dip: 41.54°; and geomagnetic declination angle 0.07°) during March 2016. Monthly mean sunspot number: 54.1. (h) Hourly absolute VTEC errors obtained from IRPE-TEC-88E(HWM) over IRPE-TEC-88E at Siliguri during March 2016.

neutral winds almost throughout a day in March 2016 except during 02:00 LT and 20:00 LT. The maximum improvements in prediction accuracy after incorporation of neutral winds are observed during 11:00 LT and 23:00 LT (24.82%–27.73%). Diurnal median improvement in accuracy after inclusion of neutral wind as model input is 9.37% (Figure 6e). Absolute errors obtained from IRPE-TEC-LUCKNOW(HWM) and IRPE-TEC-LUCKNOW are computed for each hour during March 2016 (Figure 5f). The error is decreased after inclusion of neutral wind during the major part of each day in March 2016. The diurnal median decrement of absolute error after incorporation of neutral wind during this period is 0.99 TECU (Figure 6f).

The neutral wind incorporated model (IRPE-TEC-88E(HWM)) has been compared with the model without neutral wind (IRPE-TEC-88E) at Siliguri during March 2016 and the comparison is shown in Figure 5g. From this figure, it could be observed that the inclusion of neutral wind as model input has improved the overall percentage accuracy of VTEC model almost throughout the day except during 03:00–04:00 LT and 09:00 LT in March 2016. The highest increment in percentage accuracy observed after inclusion of neutral wind is 37.81% (06:00 LT). Diurnal median increment of percentage accuracy during March 2016 after incorporation of neutral wind is 10.62% (Figure 6e). These results have been compared with the percentage accuracy of VTEC model at Lucknow during March 2016 in order to see longitudinal variability of the effects of neutral

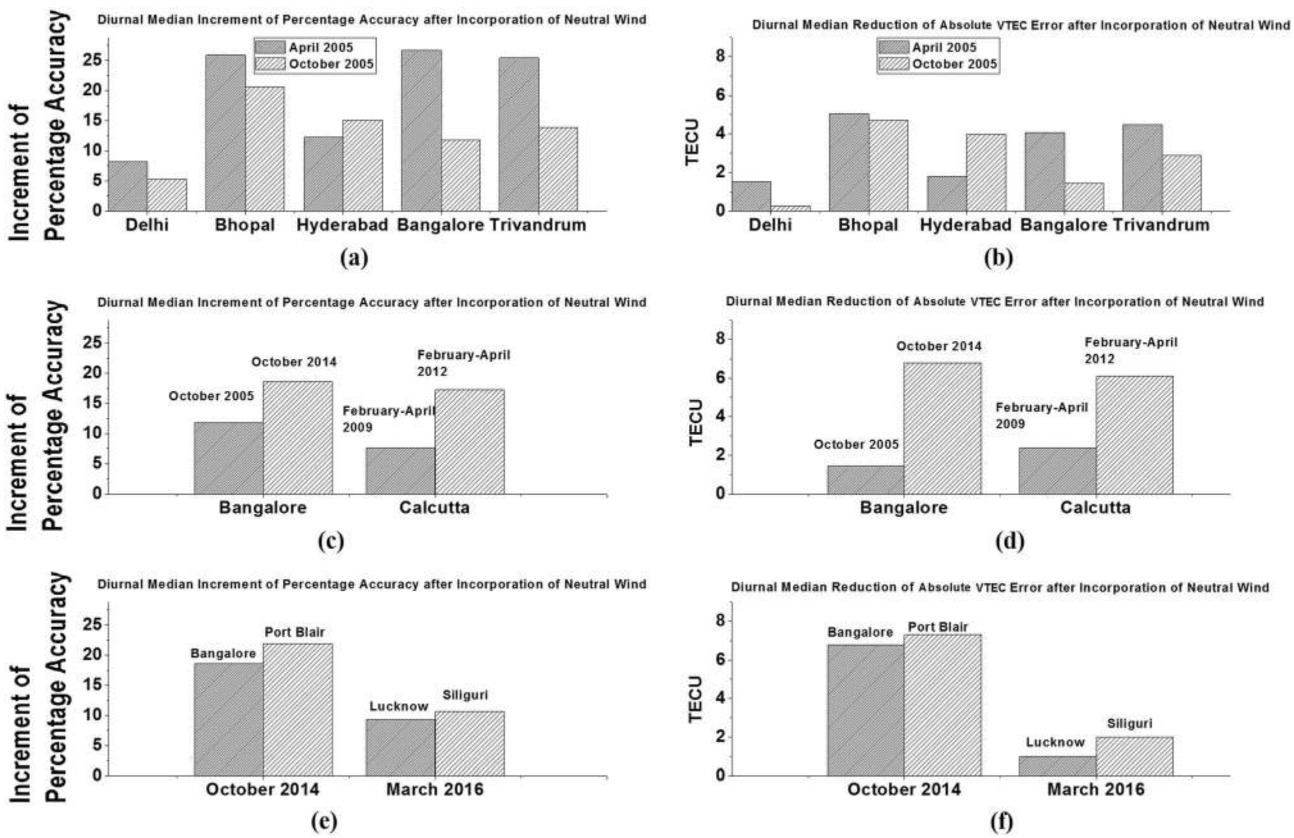

Figure 6. (a) Diurnal median increment of percentage accuracy after incorporation of neutral wind at Delhi, Bhopal, Hyderabad, Bangalore, and Trivandrum during April and October 2005. (b) Diurnal median reduction of absolute VTEC error after incorporation of neutral wind at Delhi, Bhopal, Hyderabad, Bangalore, and Trivandrum during April and October 2005. (c) Diurnal median increment of percentage accuracy after incorporation of neutral wind at Bangalore (during October 2005 and October 2014) and from Calcutta (during February–April 2009 and February–April 2012). (d) Diurnal median reduction of absolute VTEC error after incorporation of neutral wind at Bangalore (during October 2005 and October 2014) and from Calcutta (during February–April 2009 and February–April 2012). (e) Diurnal median increment of percentage accuracy after incorporation of neutral wind during October 2014 (Bangalore and Port Blair) and during March 2016 (Lucknow and Siliguri). (f) Diurnal median reduction of absolute VTEC error after incorporation of neutral wind during October 2014 (Bangalore and Port Blair) and during March 2016 (Lucknow and Siliguri).

wind on ANN-based VTEC models at regions beyond the northern crest of EIA. The absolute errors observed from IRPE-TEC-88E(HWM) and IRPE-TEC-88E during March 2016 at Siliguri are shown in Figure 5h. The error obtained from model with neutral wind is lesser than that obtained from model without neutral wind for the majority part of each day during March 2016 at Siliguri. The diurnal median reduction of absolute error after addition of neutral wind as model input from Siliguri is 1.99 TECU (Figure 6f). This is slightly higher than the same obtained from Lucknow during March 2016.

After comparing the results (Figures 5e–5h and 6e and 6f), it could be observed that the percentage accuracies of ANN-based VTEC models have improved at Siliguri more than that at Lucknow during 00:00–02:00 LT, 05:00–07:00 LT, 14:00–17:00 LT, and 20:00–21:00 LT after inclusion of neutral winds in March 2016. The performances of VTEC models show greater improvement at Lucknow than at Siliguri after incorporation of neutral wind during the remaining periods of the day. The diurnal median improvements of percentage accuracy of VTEC model after incorporation of neutral wind at Lucknow and Siliguri are 9.37% and 10.62%, respectively. From the analysis of percentage increment of accuracies and absolute errors from the models, it can be concluded that the variation of median improvement of percentage accuracies over a whole day is less pronounced between these two stations. In Siliguri, the effect of neutral wind on diurnal median increment of accuracy of VTEC model is slightly more than Lucknow in March 2016. This may be explained by the geographical positions of these two stations. The geomagnetic inclination angles for Lucknow and Siliguri are 42° and 41.54°, respectively. The declination angles for Lucknow and Siliguri are 0.58° and 0.07°, respectively. Thus, it can be noticed that the geomagnetic inclination angle and declination angles for these stations are very close. This may explain the less pronounced variation of effects of neutral winds on performance accuracies of ANN-based VTEC models between these longitudinally separated stations. From the overall analysis of longitudinal variability of effects of neutral wind on VTEC models (Figures 5a–5h and 6e and 6f), it could be noted that longitudinal variation of effects of neutral winds on performance accuracies of ANN-based VTEC models is not very much between Bangalore and Port Blair as well as between Lucknow and Siliguri. A possible explanation of the small longitudinal variation of the effects of neutral wind on VTEC models could lie in the small variations of zonal wind velocities as well as inclination and declination angle between these stations.

8. Conclusion

A study has been conducted in this paper to analyze the variation of effects of neutral wind on ANN-based feedforward backpropagation VTEC models with latitudinal, longitudinal, seasonal, and solar cyclic variations in this geophysically dynamic Indian longitude sector. The effects of neutral wind on the accuracies of ANN-based VTEC models at regions from geomagnetic equator to EIA crest can potentially be explained in terms of the effects of neutral wind over $E \times B$ ion drift. Addition of neutral wind to VTEC models improves diurnal median percentage accuracies in all the stations (between magnetic equator and northern crest of EIA) during both equinoxes of 2005. The least diurnal median improvement among Trivandrum to Bhopal is observed at Hyderabad during April 2005 and at Bangalore during October 2005. These variations of rates of improvements in different stations such as Trivandrum, Bangalore, Hyderabad, and Bhopal during different equinoxes of 2005 do not conclusively support the mechanism mentioned above regarding the effects of neutral wind on $E \times B$ ion drift.

For the regions from northern EIA crest to beyond northern crest of EIA (Bhopal and Delhi), it has been observed from the ANN VTEC models that the dependency of accuracy of VTEC models on neutral wind has been reduced for latitudes which are beyond the northern crest of EIA in 2005. A possible explanation for this observation has been suggested with the help of the relation between geomagnetic inclination angle, geomagnetic declination angle, zonal wind, magnetic field-aligned drift velocity, and rate of ionization in the local ionosphere (equation (6)) [*Zhang et al.*, 2011]. But it has also been observed that the largest overall improvement in accuracies after inclusion of neutral wind during some of the individual hours such as 12:00–13:00 LT has been observed at Delhi during October 2005. It has also been observed from the ANN-based VTEC model that the effects of neutral wind on the performance of VTEC models has been reduced during autumnal equinox compared to that during vernal equinox in 2005 at most of the stations. A possible explanation of this variation can be the equinoctial asymmetry of ionization in low latitudes. The asymmetry of ionization during different equinoxes can possibly be explained by variation of neutral wind velocities during different seasons. The variation of neutral wind velocities during different equinoxes has already been reported in different literatures. The variation of neutral wind causes variation in *F* region plasma drift. This variation intensifies during vernal equinoxes. This could be a possible explanation for variation of effects of neutral wind on the performance accuracy of VTEC models during different equinoxes. The variation of effects of neutral wind on VTEC models with variation of solar activity levels has been noticed from Bangalore in the year of 2005 (moderate solar activity periods) and 2014 (high solar activity periods). The same observation is conducted from Calcutta during February–April 2009 (low solar activity periods) and February–April 2012 (high solar activity periods). The variation of neutral wind velocities during different solar activity periods has already been established. This variation in neutral wind velocities can cause variation in plasma drift velocities at low latitudes. This plasma drift causes variation of ionization during different solar activity periods. The longitudinal variations of effects of neutral wind on performance accuracies of VTEC models have been observed from near magnetic equatorial stations (Bangalore and Port Blair) and from locations beyond the northern crest of EIA (Lucknow and Siliguri). The improvement of accuracies after inclusion of neutral wind is mildly better at Port Blair than at Bangalore. Insignificant variation of the effects of neutral wind on performance accuracies of ANN-based VTEC models has also been observed between Lucknow and Siliguri. This absence of prominent variation of effects of neutral wind on performance accuracies of VTEC models between these stations could probably be explained in terms of close geomagnetic inclination angles and declination angles of these stations. Thus, this study may provide a better picture to the ionospheric community about the variabilities of performances of ANN-based feedforward backpropagation TEC forecasting models with neutral wind over different latitudes, longitudes, seasons, and different phases of solar cycle in this highly dynamic Indian longitude sector.

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