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How uncertainty in the neutral wind limits the accuracy of ionospheric modeling and forecasting

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Key Points:
- Physics based ionospheric models propagate uncertainties associated with their inputs
- The HWM14 neutral wind model is known to have a ±37 m/s uncertainty
- Driving the TDIM with HWM14 leads to a ±20 to 30% uncertainty in midlatitude, TEC

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How uncertainty in the neutral wind limits the accuracy of ionospheric modeling and forecasting

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Abstract One of the most important input fields for an ionospheric model is the horizontal neutral wind. The primary mechanism by which the neutral wind affects ionospheric densities is the inducement of an upward or downward ion drift along the magnetic field lines; this affects the rate at which ions are lost through recombination. The magnitude of this effect depends upon the dip angle of the magnetic field; for this reason, the impact of the neutral wind is somewhat less in polar regions than at mid-latitudes. It is unfortunate that observations of the neutral wind are relatively scarce, as compared for example with observations of the Earth's electric field or auroral precipitation, and that the existing climatological models of the neutral wind are thus sharply limited in theirresolution. The observational data base of thermospheric winds is not sufficient to adequately constrain a three-dimensional model across a variety of conditions such as solar cycle, season, geomagnetic activity, and so on. Using the physics-based Time Dependent Ionospheric Model (TDIM) of Utah State University, we look for a quantitative answer to this question: How severe is the limitation imposed on ionospheric models by an uncertain specification of the neutral wind? We find that ionospheric modeling depends upon a detailed specification of the neutral wind to the extent that, if a climatologically averaged wind model is being used as a driver, this will lead to unavoidable uncertainties of 20-30% in the modeled F-region densities or Total Electron Content (TEC).

1. Introduction

An outstanding challenge in ionospheric modeling is the determination of a model's sensitivity to uncertainties in its input parameters. In modeling the *F* region ionosphere, the neutral wind is one of the most important inputs, especially at midlatitudes; unfortunately, there is a relative scarcity of observational data, and the neutral wind is difficult to model on basic principles. In this study we ask this question: given that our knowledge of the neutral wind is relatively poor, how severely does this limit the accuracy of our efforts at modeling or forecasting the *F* region ionosphere?

There is a community-wide effort to improve the capability of physics-based ionospheric models. Uncertainty in the ionosphere is the leading source of error that obstructs the capacity for precision in geolocation and also has important ramifications for HF communication and over-the-horizon radar. In this study we show where a large part of the error in ionospheric modeling comes from, namely, the neutral winds. Any effort to improve ionospheric modeling will rely on a better knowledge of the neutral winds.

The most readily available neutral wind models are empirically based climatological models; over the past 40 years they have evolved by the inclusion of more observations [*Murphy et al.*, 1976; *Hedin et al.*, 1988; *Drob et al.*, 2008; *Emmert et al.*, 2008; *Drob et al.*, 2015]. Unfortunately, the base of observational data is too sparse to adequately constrain a three-dimensional thermospheric wind model for different seasons, solar cycles, and levels of geomagnetic activity. Observations of the neutral winds are hard to come by for several reasons. Direct ground-based techniques rely on Fabry-Perot measurements of the Doppler shifts of naturally occurring emissions from the thermosphere/ionosphere, but these can only be carried out in clear-sky nighttime conditions. In situ measurements of the wind also involve FP measurements, but these involve long line-of-sight integrations. Local measurement using accelerometers or wind instruments is a technique still under development.

David et al. [2014] carried out a study in which four wind model variations were used when simulating the *F* region ionosphere with the Utah State University Time Dependent Ionospheric Model (TDIM); the results of these simulations were compared with a ground-truth of ionosonde observations from five midlatitude stations distributed in longitude. No single model could be identified as the "best," as certain models performed better under certain conditions, and the outcome was seen to be dependent upon the particular configuration of the ionospheric model in use at the time. The model that appeared to give the best overall agreement was one that specified zero wind on the dayside, which, of course, is contrary to what is known about the thermosphere.

In the present study an alternative approach is adopted, to see how an uncertainty in the neutral wind input will propagate through an ionospheric model to result in an uncertainty in the ion density parameters produced by the model. We have chosen to represent the *F* region output of the model with the parameter TEC, that is, vertical total electron content, as this is perhaps the most useful and well-known ionospheric parameter. The Horizontal Wind Model, originally developed by *Hedin et al*. [1988] and now updated by *Drob et al*. [2015] and known by the name HWM14, is used as a baseline wind distribution. The uncertainty associated with the wind values in HWM14 is about ± 37 m/s [*Drob et al*. [2015]]. This uncertainty may come from at least three different sources: a relative scarcity of wind observations, error or uncertainty in those observations which do exist, and day-to-day thermospheric weather (as opposed to climatology). All three factors make a contribution to the total uncertainty in the wind model, with the day-to-day variability contributing perhaps the largest share. In this study it is immaterial what is the source of the uncertainty; we just want to find out how much error in a physics-based ionospheric model's output may be attributed to uncertainty in the neutral wind input model. We study three regions in the Northern Hemisphere separately: the midlatitude dayside, the midlatitude nightside, and the polar region. (The TDIM is not suitable for use in equatorial regions.)

The result we obtain is the outcome of basic ionospheric physics: the relationship between the neutral wind and the magnetic field results in the raising or lowering of the *F* layer and hence the increase or decrease of the ion densities. While we employ here only one ionospheric model, the TDIM, we expect that other physics-based ionospheric models would yield a very similar overall result. It is true that a model using a detailed specification of the Earth's magnetic field, such as IGRF, would very likely show some difference in the response to the neutral wind at specific locations, but we believe the large-scale, overall picture would be much the same as the one we have obtained with the TDIM. In other words, our imperfect knowledge of the neutral wind imposes a fundamental limitation on ionospheric modeling, which cannot be overcome by refining or polishing the ionospheric models themselves.

2. Ionospheric Model

The Utah State University Time-Dependent Ionospheric Model (TDIM) is a three-dimensional, high-resolution, multi-ion model of the ionosphere in the altitude range from 90 to 800 km at midlatitude and high latitude [*Schunk*, 1988; *Sojka*, 1989; *Schunk et al*., 1986]. It is a first-principles model with over three decades of research development; *Sojka et al*. [2013] and references therein provide a detailed description of the model's development and usage. *David et al*. [2014] carried out a TDIM study contrasting four neutral wind models as drivers for the ionospheric model; the interface between the TDIM and the climatological neutral wind models is described in that article.

In addition to the thermospheric wind, which is the focus of this study, the TDIM requires several other global inputs, including the neutral atmospheric densities and temperatures, the convection electric field, and the particle precipitation pattern. All of these are sources of uncertainty in ionospheric modeling and may be subjected to the same type of analysis in upcoming publications that we here devote to the neutral winds. The topside downward electron flux is kept at its default value of zero. The "PRIMO" adjustments [see *Anderson et al*., 1998], including the Burnside factor, are not incorporated. For the neutral atmosphere densities and temperatures we have used NRLMSISE-00 [*Picone et al*., 2002]. The *Hardy et al*. [1987] model is used to specify the auroral electron precipitation, and the *Heppner and Maynard* [1987] model is used to describe plasma convection.

For a baseline specification of the neutral wind, as needed by the ionospheric model, we use the latest version of the Horizontal Wind Model; see *Drob et al*. [2015]. The wind model is referred to as HWM14; it provides a climatological representation of the Earth's horizontal neutral wind as a function of geographic location, local time, season, altitude, and geomagnetic activity level. It is based on satellite, rocket, and ground-based wind measurements.

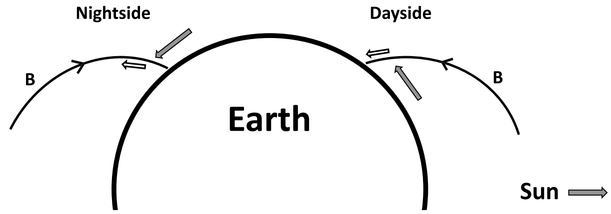

Figure 1. A diagram showing the mechanism by which a horizontal neutral wind may affect the ionosphere by either raising or lowering the *F* layer. The larger arrows represent a horizontal wind, that is, parallel to the Earth's surface, and the shorter arrows represent its component along the line of the magnetic field (labeled "B"). The wind shown is antisunward, that is, poleward on the dayside, driving charged particles downward to lower altitudes; and equatorward on the nightside, lifting the ions upward.

3. Neutral Wind and the Ionosphere

Through collisional interaction, the horizontal momentum of neutral particles may be transferred to ions. Since the ions are constrained to move along a magnetic field line and cannot simply move horizontally, there will be a resulting vertical component to the movement. The amount of vertical motion depends on the inclination angle of the magnetic field; see *Schunk and Nagy* [2009].

Whether the induced vertical ion drift is upward or downward depends on the relativity of the angled field line and the direction of the wind (see Figure 1). On the dayside, a wind blowing toward the pole, or antisunward, will be the norm, except in cases of geomagnetic storm conditions. (A wind direction toward the pole is labeled as positive by the HWM14 model, and we follow that convention.) When the horizontal wind is broken down into meridional and zonal components, it is the meridional component that is most geoeffective in this way; a zonally directed wind will have little effect in moving charged particles up or down the magnetic field lines. (The TDIM uses a tilted dipole magnetic field, whose tilt is 11.4°, with the longitude of the north magnetic pole being 71°W.)

The significance of the upward or downward motion of ions lies in the fact that loss of ions due to recombination into neutral species occurs most rapidly at the lower altitudes. Therefore, if the ions are lifted upward, this will serve to inhibit loss of ions. If the ions are pushed downward, recombination will occur more rapidly and the *F* region ion densities will be decreased. Thus, the typical effect of the neutral wind during quiet-to-moderate geomagnetic conditions is that dayside ion densities will be reduced by the wind, while on the nightside, the wind will tend to maintain the *F* layer. The magnitude of the induced vertical transport depends upon the angle of inclination *I* through the product sin(*I*)cos(*I*); therefore, we may expect the neutral wind to have a more direct effect on ion densities at midlatitudes than in the polar regions. (As stated previously, the TDIM is not suitable for use at low latitudes.)

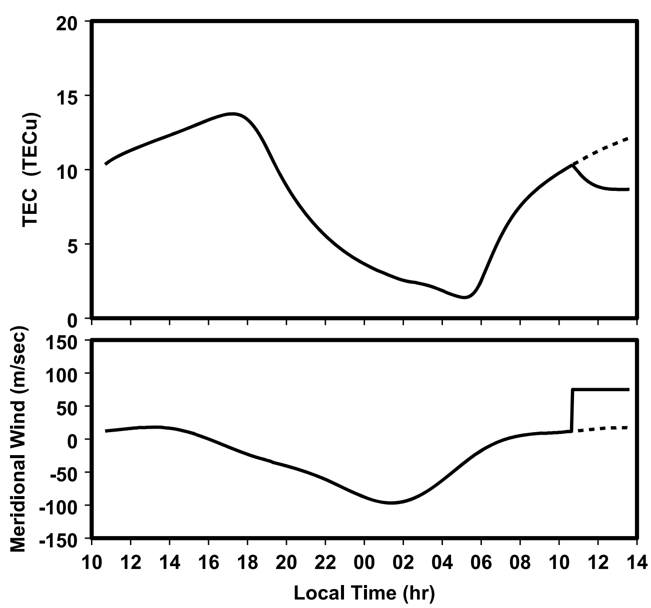

Figure 2. Output of a midlatitude dayside TDIM model simulation. (top) Total Electron Content (TEC); (bottom) the meridional component of the horizontal neutral wind as specified by the HWM14 model. During the last 3 h of the run, the wind has been set to a fixed value of 75 m/s (solid line), thereby causing TEC to be reduced by about 30%. The dashed curve shows the model run with the unchanged HWM14 wind input.

4. Midlatitude Dayside

At midlatitudes, under conditions of low or moderate geomagnetic activity, we may reasonably assume that the ionosphere is corotating with the earth; this introduces considerable simplicity into our method. We begin by selecting a ground location; for our first test case we shall use the location of Millstone Hill, Massachusetts, USA, situated at approximately 42°N and 288°E geodetic coordinates, with a magnetic latitude of 54°. For a given set of conditions, for example,

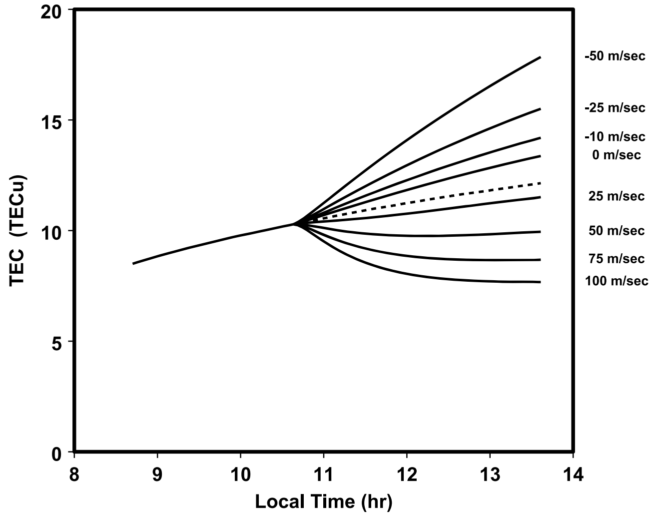

Figure 3. Output of TDIM model runs showing the TEC for one corotating midlatitude dayside location with different wind scenarios, as described in section 4. A fixed value of the meridional component of the horizontal neutral wind is imposed for the last 3 h of each simulation; the values used are shown at the right. The dotted curve is for the unaltered HWM14 wind model.

Equinox, solar medium, and $Kp = 2$, the TDIM will follow the corotating *F* region ionosphere above this location for a 24 h period, using the HWM14 model as the driver for the horizontal neutral wind. Then, for a 3 h period centered on local noon, we continue following the corotating ionosphere, but now we impose a fixed value for the meridional component of the neutral wind. In order to determine the range of values for the meridional wind that might be reasonably used, we look to the HWM14 model to see what range it provides on the dayside at midlatitudes for quiet conditions, and we find that to be roughly −50 to +100 m/s. We do TDIM runs with wind values (for 3 h) of −50, −25, −10, 0, +25, +50, +75, and +100 m/s. Then we compare the values of total electron content (TEC) that result from these values of the wind. Our goal is to make a quantitative statement that relates the uncertainty in the wind input to the resulting uncertainty in the ionospheric model output. We will call these uncertainties ΔWind and ΔTEC; it will be seen later (Figures 5, 7, and 9) that there is a linear relationship between them.

Figure 2 shows an example in which this method has been employed. We have started a TDIM simulation on the dayside at 0830 h local time at the location of Millstone Hill and followed the corotating plasma through the night until it comes round to 1030 h local time. (It is important that the TDIM follows a trajectory for about 24 h, in order to allow initial conditions to settle out.) At 1030 local time, and for the 3 h following, we no longer use the wind from the HWM14 model but, instead, fix the meridional component to a specified level, in this case, +75 m/s. This step function in the wind can be seen in Figure 2 (bottom) (the dashed curve there shows the HWM14 wind). The positive sign indicates a direction toward the pole; on the dayside this means that a downward ion drift is induced, resulting in a lowering of ion densities and a corresponding reduction in TEC. This downward drift is the typical case on the dayside, except in times of considerable geomagnetic disturbance. The dashed curve in Figure 2 (top) shows the TEC that results from the use of the wind from the HWM14 model, while the solid line shows that which results from the imposed meridional wind of +75 m/s; as soon as the *F* layer is forced downward there is an immediate drop in ion density.

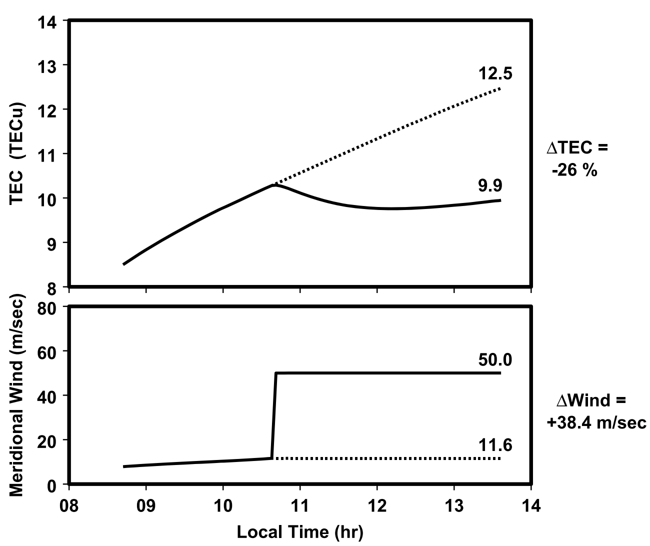

Figure 4. A TDIM run is used as an example for illustrating the definition and computation of the parameters we have named "ΔWind" and "ΔTEC," as explained in section 4.

We carry out the same procedure for a set of wind values ranging from −50 to +100 m/s; in Figure 3 we show

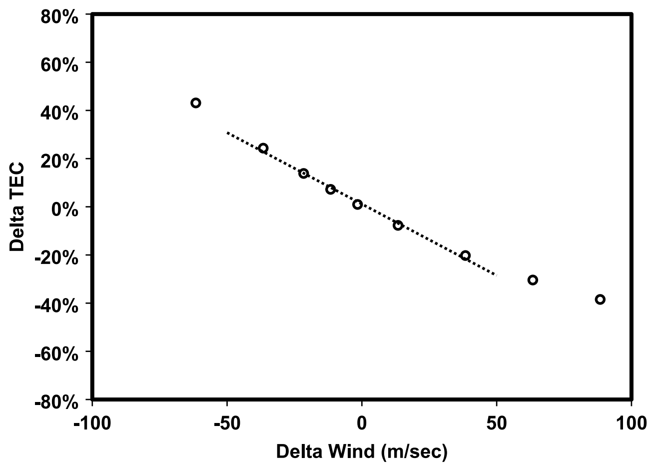

Figure 5. Uncertainty in the simulated TEC values (ΔTEC) is plotted against the uncertainty in the meridional component of the horizontal neutral wind (ΔWind). ΔTEC and ΔWind are defined in section 4 and illustrated in the previous figure. The TDIM runs shown here were done for solar medium, low activity, equinox conditions, at the location of Millstone Hill near local Noon (1330 MLT).

the last 5 h of the TDIM trajectories with these imposed winds. The dashed curve is a model run done with the continuing use of HWM14. The TDIM values of TEC that result from these winds range from about 7 to 18 TECu: a spread over a factor of 2½.

In order to make a quantitative statement about the uncertainty in TEC that results from a given uncertainty in the input wind, we need to define the two parameters that we call ΔWind and ΔTEC (see the illustration in Figure 4). When the corotating plasma reaches 1030 local time, the value of the meridional component of the neutral wind from the HWM14 model at that point is noted (11.6 m/s in this example), and the "baseline" TDIM simulation (dashed curve) uses that as a fixed value for the neutral wind during the following 3 h. ΔWind for any given TDIM run is then defined as the difference between the imposed meridional wind value used for that run (+50 m/s in this case) and the baseline value. Then ΔTEC is the difference between the computed TEC values for those two runs expressed as a percentage, taken 3 h after the wind change began. We use these "delta" values to represent the uncertainty in the input field for the neutral wind and the resulting uncertainty in the modeled values of TEC.

In Figure 5, we plot all the ΔWind values with their corresponding ΔTEC values for the set of model runs that were shown in Figure 3. A clear linear relationship exists between the uncertainty in the wind and the resulting uncertainty in the modeled TEC. We may fit a straight line to the points in the middle of the graph, where the ΔWind values are most reasonable and calculate the slope of the line which allows us to make a quantitative statement of the kind alluded to above. In this case, the slope of the line is −0.59, and therefore, $\Delta TEC = -0.59 * \Delta Wind$.

Drob et al. [2015] state that the typical uncertainty in the HWM14 model is about ± 37 m/s. With a preference for round numbers, we will use 40 m/s to represent the level of uncertainty in the neutral wind. When −40 and +40 are used in the equation for the straight line, we get ΔTEC values of 25 and −23%. In other words, given our present level of uncertainty in the neutral wind specification, whether due to imprecision in observations, scarcity of observations, and/or day-to-day variability, we may say that ionospheric modeling efforts for TEC in the midlatitude dayside region cannot be more accurate than to be within about ± 25%, just due to uncertainties in the neutral wind input. Of course, there are also other uncertain factors that will add to that figure.

To put this 25% uncertainty into context, we may consider the day-to-day variability of TEC in the dayside midlatitude region. *Soicher and Gorman* [1985] studied three different month-long periods, looking at TEC values from Fort Monmouth, NJ, USA, throughout each day of 3 months. They expressed the day-to-day variability in terms of the coefficient of variation, e.g., the standard deviation divided by the mean. Their findings, taken from their Figure 3, were as follows: summer (August), 15–25%; winter (February), 15–25%; and spring (May), 35–45%.

Table 1. The Geodetic Coordinates and Magnetic Latitudes of Four Midlatitude Locations

	Geodetic Latitude	Geodetic Longitude	Magnetic Latitude	Dip Angle (Dipole Field)
Boulder	40°	255°	49°	66°
Millstone Hill	43°	288°	54°	70°
Slough	51°	359°	54°	70°
Yakutsk	62°	130°	51°	68°

Table 2. Uncertainties in Modeled Dayside Midlatitude TEC Values

	Equinox	Summer	Winter	
Solar Cycle				
Min	30%	22%	31%	Boulder
Med	34%	27%	35%	
Max	34%	28%	36%	
Min	21%	17%	22%	Millstone Hill
Med	24%	20%	25%	
Max	24%	22%	26%	
Min	22%	22%	24%	Slough
Med	26%	27%	28%	
Max	28%	28%	29%	
Min	22%	17%	24%	Yakutsk
Med	26%	20%	27%	
Max	26%	21%	28%	

Does this uncertainty of 25% in the midlatitude dayside ionosphere have a dependence on conditions such as solar activity level, geodetic longitude, or season? To address the question, we carry out the same procedure for a variety of different conditions, including solar maximum and solar minimum; winter, summer, and equinox; and four different ground locations distributed longitudinally around the Northern Hemisphere, all having a geomagnetic latitude of about 50° (see Table 1). Results are summarized in Table 2; the numbers represent the model uncertainty expressed as a percentage (the "ΔTEC") for each set of conditions; each single number is the average of the absolute values of the ΔTEC for the two ΔWind values of +40 and −40 m/s. It is evident from the similarity of the numbers in the table that there is no strong dependence on the various conditions or longitudes tested. (There is a systematic increase of about 4–5% in solar maximum, but this is small compared with the 25% effect we are focusing on.) The overall average of the numbers in Table 2 is 25.6%. The meaning of this number is that our inability to specify the neutral wind with a higher degree of accuracy imposes an error bar of (at least) ± 25% on our ionospheric modeling at midlatitudes. It does not mean that 25% of the ionospheric model's error is due to uncertainty in the neutral wind but that a ± 25% uncertainty in the modeled TEC inevitably follows from the postulated ± 40 m/s uncertainty or variance in the neutral wind.

5. Nightside, Midlatitudes

As in the previous section, we limit our model simulations to conditions of low-to-moderate geomagnetic activity, and we may therefore consider the ionosphere to be corotating. The procedure is identical with that used on the dayside, with the exception that instead of the 3 h period of imposed wind being centered on local noon, it will be centered on midnight; the imposed wind begins at a local time of 2230 and continues for 3 h. Again, we will use the location of Millstone Hill as a test case.

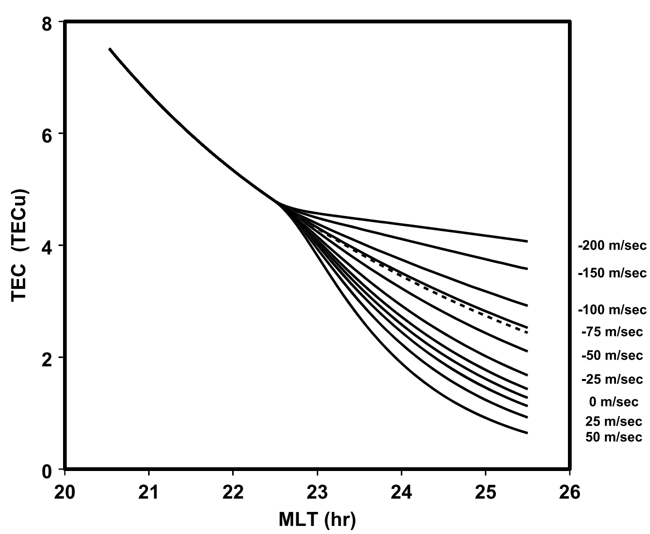

Figure 6. TDIM model runs on the nightside; similar to Figure 3, but centered on local midnight. The TEC for one nightside midlatitude corotating location is plotted for different wind scenarios, as described in section 5. A fixed value of the meridional component of the horizontal neutral wind is imposed for the last 3 h of each simulation; the values used are shown at the right. The dotted curve is for the unaltered wind from the HWM14 model.

To determine what range of wind values to use, we sample the HWM14 model on the nightside at or near 50° magnetic latitude throughout a variety of seasons and universal times, and we find that the numbers seen are roughly in the range −200 to +50 m/s. Figure 6 shows how the nightside TEC responds to a three-hour period of imposed meridional wind in this range. A positive value means the wind is directed toward the pole, therefore on the nightside, a positive meridional wind will decrease the ion densities by driving the plasma downward into the altitude region of faster recombination, and a negative wind will lift the F-layer and will serve to maintain the nighttime densities.

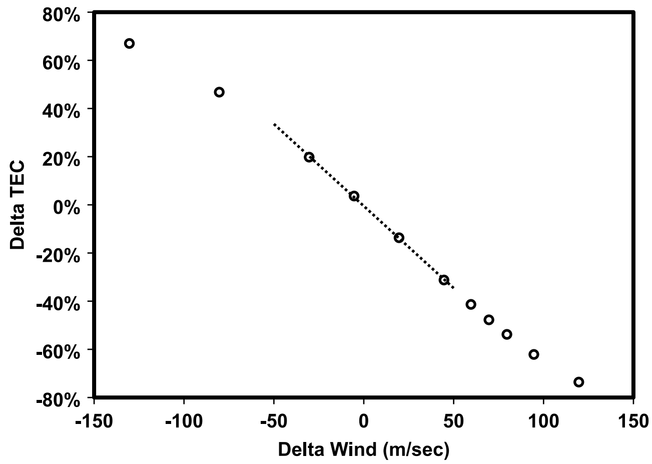

Figure 7. Uncertainty, as a percentage, in the simulated TEC values (ΔTEC) is plotted against the uncertainty in the meridional component of the horizontal neutral wind (ΔWind). ΔTEC and ΔWind are defined in section 4 and illustrated in Figure 4. The TDIM runs shown here were done for solar medium, low activity, equinox conditions, at the location of Millstone Hill near local Midnight (0130 MLT).

No amount of wind will cause the ion density to increase at night, as there is virtually no source of production. (In times of strong geomagnetic activity this might not be true.) We see in Figure 6 that even a meridional wind of −200 m/s, which induces an upward ion drift of about 60 m/s, is not sufficient to fully maintain the nighttime ion densities.

With ΔWind and ΔTEC as defined in the previous section, in Figure 7 we plot the uncertainty expressed as a percentage in the modeled TEC values vs the uncertainty in the wind. As before, there is a clear linear relationship. The slope of this line allows us to state that for ΔWinds of −40 and +40 m/s, the ΔTEC is 27% and −28% respectively; slightly higher than was the case on the dayside.

We have carried out the same procedure for a variety of conditions, including solar medium, minimum, and maximum; as well as equinox, winter, and summer conditions; for four different midlatitude locations representing a distribution of longitudes around the globe. Table 3 shows these ΔTEC values, expressed as a percentage. As before, the single numbers represent the average of the absolute values of ΔTEC for the two ΔWind values of +40 and −40 m/s. For the most part, we see that there is no significant dependence on the conditions or longitudes tested here; however, at the location of Slough the ΔTEC percentages are higher, and at Yakutsk during summer the values are lower. Theses anomalies are probably due to certain particularities in the baseline wind model (HWM14), such that the winds at Slough tend to be only about half as strong as those at either Millstone Hill or Boulder, and the wind in summer at Yakutsk is given as much higher than during equinox or winter conditions. The overall average of the ΔTEC numbers for the midlatitude nightside cases is 29.3%; this may be compared with the average of 25.6% for the dayside cases.

6. Polar Region

When studying the effect of the wind within the polar region, we do not have the luxury, as we did at midlatitudes, of being able to assume that the ionosphere is corotating. Therefore, we cannot follow the ionosphere above a ground location as we did before, but instead, we have to follow plasma trajectory paths that are determined by the convection electric field. We follow three such paths, which lead to locations chosen as follows: (a) a location within the tongue of ionization (when such a TOI exists, that is, a plume of high density dayside plasma convected antisunward through the cusp and across the dark polar cap); (b) a location beside the TOI; (c) an arbitrarily chosen location in the polar cap (Figure 8). (Note that the existence of a tongue of ionization depends on universal time and season.) The dip angles for our three

Table 3. Uncertainties in Modeled Nightside Midlatitude TEC Values

	Equinox	Summer	Winter	
Solar Cycle				
Min	27%	25%	18%	Boulder
Med	29%	25%	29%	
Max	24%	20%	34%	
Min	28%	27%	24%	Millstone Hill
Med	27%	27%	29%	
Max	21%	22%	25%	
Min	45%	47%	30%	Slough
Med	43%	44%	48%	
Max	35%	36%	57%	
Min	32%	16%	17%	Yakutsk
Med	32%	14%	26%	
Max	27%	11%	35%	

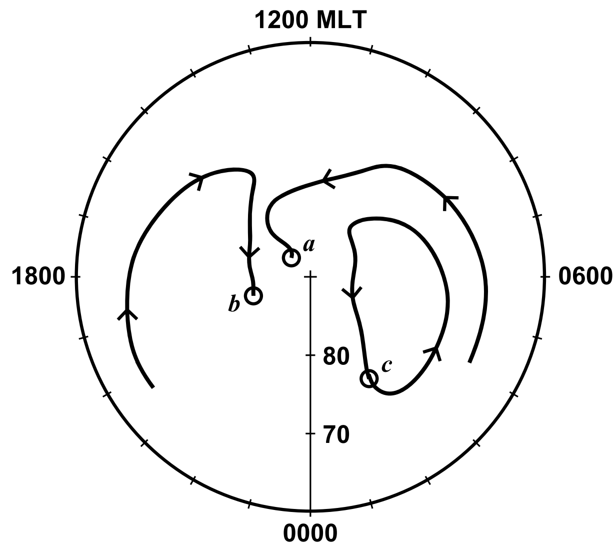

Figure 8. A dial plot in geomagnetic coordinates showing three TDIM plasma trajectory paths in the Northern Hemisphere polar cap, as discussed in section 6: (a) within the tongue of ionization; (b) beside the tongue of ionization; and (c) an arbitrary point within the polar cap. The trajectories are timed so as to reach these three points at Universal Times of 0500 and 1700.

polar cap test locations, with the dipole magnetic field used in the TDIM model, are, respectively, 88°, 86°, and 82°. Trajectory paths leading to these locations over a 24 h period are determined by the Heppner and Maynard "A" convection pattern [*Heppner and Maynard*, 1987]; we run each trajectory two separate times, such that the arrival at the endpoint will occur at universal times of 0500 and 1700. As before, for the last 3 h of the trajectory we impose a fixed value for the meridional component of the wind; within the polar cap, the HWM14 model yields meridional wind components in the range of roughly ± 200 m/s. In addition, we carry out runs for equinox, summer, and winter conditions, in order to test for a seasonal dependence.

Because the mechanism by which the neutral wind affects the ionosphere depends on the angle of the magnetic field lines, it is to be expected that the effect of the neutral wind will be less significant in polar regions than at midlatitudes, since the field lines are nearly vertical. This is well borne out by the model runs. An example is shown in Figure 9, with ΔWind and ΔTEC as defined in section 4 and illustrated in Figure 4. This is location "a," for universal times of 0500 (circles) and 1700 (crosses). At 1700 UT this location lies within the tongue of ionization, while at 0500 UT there is no TOI; this accounts for the considerable difference in the slopes of the two lines. In either case, the ΔTEC that results from a given value of ΔWind is considerably less than it was at midlatitudes on either the dayside or the nightside. If we again take ± 40 m/s as the uncertainty in the neutral wind, we get ΔTEC values of 6% and 10% for 0500 UT and 1700 UT, respectively. Table 4 contains the full listing of ΔTEC values (in percent) for the ΔWind values of ± 40. (As before, the single number given in the table is the mean of the absolute values of the two numbers that correspond to ΔWinds of +40 and −40.) The overall average of the numbers in the table is 8.7%.

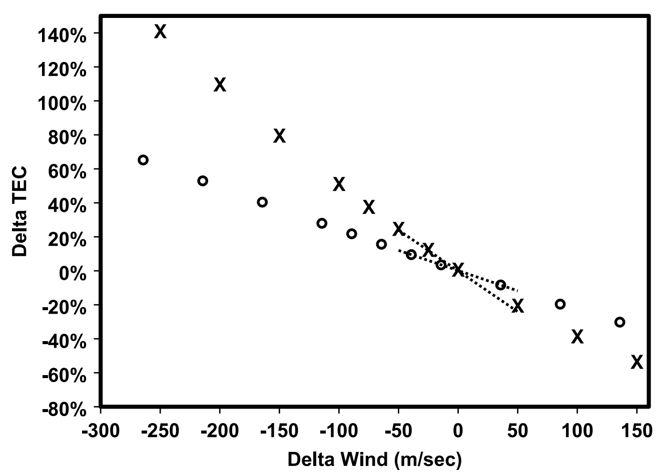

Figure 9. Uncertainty in modeled TEC versus uncertainty in the meridional wind, at the polar cap location a, for the 0500 UT case (circles), and the 1700 UT case (crosses). Equinox and solar medium conditions. ΔTEC and ΔWind are defined in section 4 and illustrated in Figure 4.

7. Discussion and Summary

The neutral wind can be a major driver of *F* region ionospheric densities by redistributing plasma in altitude, changing the rate at which ions are lost to recombination. We have addressed the question of how sensitive the ionosphere is to this wind and, in particular, how sensitive an ionospheric model is to uncertainties in its neutral wind input and how this may limit our ability to model or forecast the ionosphere. The climatological wind model used here is the HWM14 [*Drob et al.*, 2015], and the ionospheric model is Utah State University's TDIM.

Table 4. Uncertainties in Modeled Polar Cap TEC Values

	Equinox	Summer	Winter	
Universal Time				
0500	6%	5%	10%	Location a
1700	10%	9%	19%	
0500	5%	7%	8%	Location b
1700	12%	13%	12%	
0500	8%	8%	10%	Location c
1700	5%	3%	7%	

The degree of uncertainty in the HWM14 wind model has been taken to be ± 40 m/s, rounded up from the ± 37 m/s given by *Drob et al.* [2015]. This uncertainty in the wind model may be attributed to three sources: scarcity of measurements, uncertainty in measurements, and thermospheric weather. If the latter is a significant contributor, it raises the question as to what time scales may be appropriate for neutral wind weather. We have assumed that it is sensible to hold a wind to a fixed value for a 3 h period. We have looked at the ionospheric model's sensitivity to uncertainties in the wind in three distinct regions: the midlatitude dayside, the midlatitude nightside, and the polar cap.

The most significant finding of the study is this: the degree of uncertainty that currently exists in climatologically averaged models of the neutral wind is responsible for limiting *F* region ionospheric modeling in midlatitude regions to be no more accurate than within ±20 to 30%. In modeling there are of course additional factors involved, each having their own uncertainties, which contribute to making the ionospheric modeling even worse; but we find that the uncertainty in the wind alone is sufficient to account for a 20–30% uncertainty in the ionospheric model's output.

In the polar regions, uncertainty in the neutral wind has a less severe effect; this is because the neutral wind is less geoeffective at high latitudes, owing to the near-verticality of the magnetic field lines. We found that the ionospheric model's uncertainty due to the wind at high latitudes is about ± 5 to 10%.

We found a linear relationship between uncertainty in the neutral wind expressed in m/s and the resulting uncertainty in modeled TEC values expressed as a percentage over the range of meridional wind uncertainties relevant to this study. This means that improvements gained in the understanding of and measurement of thermospheric winds will benefit ionospheric modeling or forecasting in a corresponding degree. Thus, if the uncertainty in the wind's specification were only ± 20 m/s, instead of 40 m/s, this would improve ionospheric modeling to the degree that the uncertainty due to the wind would be just 10–15%.

This study has been carried out using a single ionospheric model (the TDIM), but we believe our conclusion proceeds from basic ionospheric physics and does not depend upon particular features of this model and should also be applicable in the case of other physics-based ionospheric models that rely on empirical neutral wind models for their input. We are at present working with the TDIM model to discover its sensitivity to other factors, including a high-resolution solar irradiance spectrum, topside fluxes of heat or particles, reaction rate parameterization, and the density and composition of the neutral atmosphere.

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References

Anderson, D. N., et al. (1998), Intercomparison of physical models and observations of the ionosphere, *J. Geophys. Res.*, *103*(A2), 2179–2192, doi:10.1029/97JA02872.

David, M., J. J. Sojka, and R. W. Schunk (2014), Sources of uncertainty in ionospheric modeling: The neutral wind, *J. Geophys. Res. Space Physics*, *119*, 6792–6805, doi:10.1002/2014JA020117.

Drob, D. P., et al. (2008), An empirical model of the Earth's horizontal wind fields: HWM07, *J. Geophys. Res.*, *113*, A12304, doi:10.1029/2008JA013668.

Drob, D. P., et al. (2015), An update to the Horizontal Wind Model (HWM): The quiet time thermosphere, *Earth Space Sci.*, *2*, 301–319, doi:10.1002/2014EA000089.

Emmert, J. T., D. P. Drob, G. G. Shepherd, G. Hernandez, M. J. Jarvis, J. W. Meriwether, R. J. Niciejewski, D. P. Sipler, and C. A. Tepley (2008), DWM07 global empirical model of upper thermospheric storm-induced disturbance winds, *J. Geophys. Res.*, *113*, A11319, doi:10.1029/2008JA013541.

Hardy, D. A., M. S. Gussenhoven, R. Raistrick, and W. J. McNeil (1987), Statistical and functional representations of the pattern of auroral energy flux, number flux, and conductivity, *J. Geophys. Res.*, *92*, 12,275–12,294, doi:10.1029/JA092iA11p12275.

Hedin, A. E., N. W. Spencer, and T. L. Killeen (1988), Empirical global model of upper thermosphere winds based on Atmosphere and Dynamics Explorer satellite data, *J. Geophys. Res.*, *93*, 9959–9978, doi:10.1029/JA093iA09p09959.

Heppner, J. P., and N. C. Maynard (1987), Empirical high-latitude electric field models, *J. Geophys. Res.*, *92*, 4467–4489, doi:10.1029/JA092iA05p04467.

Murphy, J. A., G. J. Bailey, and R. J. Moffett (1976), Calculated daily variations of O+ and H+ at mid latitudes—I. Protonospheric replenishment and *F*-region behaviour at sunspot minimum, *J. Atmos. Sol. Terr. Phys.*, *38*, 351–364.

Picone, J. M., A. E. Hedin, D. P. Drob, and A. C. Aikin (2002), NRLMSISE-00 empirical model of the atmosphere: Statistical comparisons and scientific issues, *J. Geophys. Res.*, *107*, 1468, doi:10.1029/2002JA009430.

Schunk, R. and A. Nagy (2009), *Ionospheres*, 2nd ed., Cambridge Univ. Press, Cambridge, Cambridge Books Online. Web. 12 May 2015, doi:10.1017/CBO9780511635342.

Schunk, R. W. (1988), A mathematical model of the middle and high-latitude ionosphere, *Pure. Appl. Geophys.*, *127*, 255–303.

Schunk, R. W., J. J. Sojka, and M. D. Bowline (1986), Theoretical study of the electron temperature in the high-latitude ionosphere for solar maximum and winter conditions, *J. Geophys. Res.*, *91*, 12,041–12,054, doi:10.1029/JA091iA11p12041.

Soicher, H., and F. J. Gorman (1985), Seasonal and day-to-day variability of total electron content at mid-latitudes near solar maximum, *Radio Sci.*, *20*(3), 383–387, doi:10.1029/RS020i003p00383.

Sojka, J. J. (1989), Global scale, physical models of the *F*-region ionosphere, *Rev. Geophys.*, *27*, 371–403, doi:10.1029/RG027i003p00371.

Sojka, J. J., J. Jensen, M. David, R. W. Schunk, T. Woods, and F. Eparvier (2013), Modeling the ionospheric *E* and *F1* regions: Using SDO-EVE observations as the solar irradiance driver, *J. Geophys. Res. Space Physics*, *118*, 5379–5391, doi:10.1002/jgra.50480.