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Magnetic meridional winds in the thermosphere obtained from Global Assimilation of Ionospheric Measurements (GAIM) model

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Abstract Thermospheric neutral winds play an important part in the dynamics of ionospheric plasma and represent one of the key inputs for ionospheric physics-based models. Yet wind measurements are scarce and generally lack global coverage and continuity. To help mitigate this shortcoming, a data assimilation model was used to estimate neutral winds in the low- and middle-latitude thermosphere. Seasonal global maps of \( N_m F_2 \) and \( h_m F_2 \) were generated from Constellation Observing System for Meteorology, Ionosphere, and Climate radio occultation measurements for geomagnetically quiet and low solar flux conditions. The maps were assimilated into the Utah State University Global Assimilation of Ionospheric Measurements–Full Physics (GAIM-FP) model. GAIM-FP, which uses the physics-based ionosphere-plasmasphere model (IPM) and employs an ensemble Kalman filter technique, significantly improved the agreement between the modeled and measured \( N_m F_2 \) and \( h_m F_2 \) globally compared to the IPM. Global quiet time magnetic meridional winds were derived for December and June solstices and March equinox. The morphology of the derived winds was analyzed and validated by comparing with ground-based measurements and with wind values from the empirical horizontal wind model. GAIM-FP-estimated winds were shown to be in good agreement with the wind observations. Furthermore, the sensitivity of the derived winds to uncertain parameters, including the O¹–O collision frequency, neutral composition, number of radio occultations, and data errors, was investigated. The uncertainties were found to have only small effects on the derived winds. The results of this work indicate that thermospheric wind estimation from GAIM-FP is a valuable tool for wind specification over regions where limited or no wind measurements exist.

1. Introduction

Thermospheric neutral winds play an important role in the dynamics of the low- and middle-latitude ionosphere [Rishbeth, 1972; Titheridge, 1995; Emmert et al., 2006; Makela et al., 2013]. At F region heights, where the ion gyrofrequency is much larger than the ion-to-neutral collision frequency, midlatitude neutral winds are effective in transporting ionospheric plasma along the tilted geomagnetic field lines. As a result, winds modify the field-aligned ionospheric plasma diffusion, which in turn changes the altitude of the maximum electron density \( (h_m F_2) \), where chemical loss and diffusion processes approximately balance each other. Furthermore, the different recombination and ionization rates at the new \( h_m F_2 \) lead to changes in the maximum electron density \( (N_m F_2) \) [Rishbeth, 1972; Titheridge, 1995]. At low latitudes, cross-equatorial winds [Meriwether et al., 2011] alter the ionization at the equatorial ionospheric anomaly crests and contribute to the global electron density asymmetry about the magnetic equator [Abub-Robb and Windle, 1969; Rishbeth, 1972; Anderson and Roble, 1981; Balan et al., 1995]. In addition, thermospheric winds influence the F region electron density distribution indirectly by generating dynamo electric fields [Rishbeth, 1971; Heelis, 2004].

Since thermospheric neutral winds have a critical effect on the temporal and spatial variations of ionospheric plasma, they constitute a very important input for stand-alone ionospheric models, and uncertainties in their representation affect the accuracy of ionospheric modeling and specification [Miller et al., 1989; Richards, 1991; Titheridge, 1995; Schunk et al., 2004a]. In addition, knowledge of neutral winds is important for a better understanding of the general circulation of the thermosphere itself [Roble et al., 1977; Fuller-Rowell, 1998].

The thermospheric neutral winds can be calculated from physics-based global circulation models, but their accuracy is affected by many uncertainties in the model [Meriwether et al., 2013]. With regard to empirical wind models, the most widely used ones are the Horizontal Wind Models, HWM93 [Hedin et al., 1991] and
HWM07 [Drob et al., 2008], which are based on many years of wind measurements by various ground- and satellite-based instruments. Even though the wind climatology obtained from these models is expected to be generally good over stations from where the wind data were incorporated into the model, studies show that they may fall short of reproducing the observed wind climatology over places where no or few observations were included [Titheridge, 1995; Makela et al., 2012]. Therefore, it is useful to develop new methods of global wind estimation, which, in turn, can help to improve the accuracy of ionospheric models.

Valuable information about the thermospheric neutral wind can be obtained through direct observations, but unfortunately, currently these observations are sparse both in space and in time. Ground-based thermospheric wind measurements that are based on interferometric methods (such as Fabry-Perot interferometer (FPI)) [Burnside et al., 1981; Meriwether et al., 2008] are mainly limited to nighttime and cloudless conditions and are restricted to a handful of locations [Hedin et al., 1991; Emmert et al., 2006; Drob et al., 2008]. Space-based wind measurements can be performed with interferometers and spectrometers onboard satellites, and cross-track wind estimations are also possible from satellite-based accelerometers [Hedin et al., 1988; Liu et al., 2006; Doornbos et al., 2010]. However, current space-based missions lack the ability of routine wind measurements over a given location for all local times.

Alternatively, ionospheric observations can be used to deduce neutral winds along the magnetic meridian for any local time. For example, the magnetic meridional wind can be derived from field-aligned plasma velocities obtained from incoherent scatter radar (ISR) measurements [Salah and Holt, 1974; Oliver and Salah, 1988; Oliver, 1990]. An analysis of combined FPI and ISR observations by Burnside et al. [1983] indicates that the agreement between ISR-derived and FPI-measured magnetic meridional winds is typically within 35 m/s for a midlatitude site. However, considering the overall statistical uncertainty of the wind derivation from the ISR together with uncertainties in neutral atmospheric parameters and the ion-neutral collision frequency used in the estimation, the overall wind accuracy during quiet and moderate geomagnetic conditions is thought to be up to 70 m/s [Oliver and Salah, 1988]. An obvious limitation of this method is that it is also restricted to the locations of current ISRs.

Another widely used technique to obtain neutral winds is the well-known “servo method” which uses the variations of the NmF2 and hmF2, measured, for example, by ionosondes [Rishbeth, 1967; Rishbeth et al., 1978; Buonsanto, 1986]. A closely related wind estimation method, using a physics-based model and measurements of hxF2, was proposed by Miller et al. [1986], assuming a linear relationship between the wind speed and the distance between mF2 and a so-called balance height. The results of this later method, however, were found to be essentially equivalent to the results from the servo method [Buonsanto et al., 1989]. The uncertainty in the wind estimation using the servo method is expected to be even larger than the uncertainties of ISR-derived winds [Buonsanto et al., 1997]. Furthermore, the servo method is generally valid only for midlatitudes, where neutral winds play an important role in the vertical dynamics of the plasma, and at times when electric field effects are small.

A recent study by Luan and Solomon [2008] demonstrated the value of observations from Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) to obtain information about thermospheric winds. They used variations of hmF2 retrieved from COSMIC radio occultation (RO) measurements with a servo model to estimate neutral winds for December solstice conditions and studied their longitudinal variations by taking advantage of the global coverage of the COSMIC data. However, due to the above-mentioned limitations of the servo model, their study was limited to midlatitudes.

Different from the above-mentioned approaches, several more recent studies used data assimilation techniques and showed that ionospheric data assimilation models have a promising potential of estimating thermospheric winds [Pi et al., 2004; Scherliess et al., 2011; Solomentsev et al., 2012]. In this paper we present a new method of deriving the climatology of thermospheric neutral wind based on the Utah State University Global Assimilation of Ionospheric Measurements–Full Physics (GAIM-FP) model. For this study, the model assimilated NmF2 and hmF2 values obtained from COSMIC radio occultation data to estimate the seasonal climatology of the magnetic meridional wind over the entire low- and middle-latitude regions. One of the main differences of this new technique to the servo method is that it can estimate the wind velocity over low and equatorial latitudes where uncertainties due to electric fields are overcome by a simultaneous wind and electric field estimation procedure. We show results of the quiet time global wind climatology for three different seasons (December and June solstices and March equinox) during the recent...
(2007–2009) solar minimum and compare our wind results with those measured by FPI at three different locations: Millstone Hill (42.6°N, 71.5°W), Arecibo (18.4°N, 66.8°W), and Arequipa (16.5°S, 71.5°W).

In addition to the magnetic meridional wind estimation, the data assimilation model significantly improves the accuracy of the climatological description of the global ionospheric electron density compared to the case when the HWM93 empirical wind and the “Scherliess-Fejer” equatorial vertical drifts [Scherliess and Fejer, 1999] are used in the stand-alone ionosphere-plasmasphere model (IPM). Our results show that the thermospheric wind estimation using our ionospheric data assimilation technique has promising potential for a reliable wind specification over the regions where traditionally wind observations are sparse.

To address the sensitivity of the proposed wind estimation technique to uncertain model parameters and to quantify it, we examined the effects of uncertainties in the O+–O collision cross section and neutral atmospheric density by performing wind estimation with different values of the collision frequency and exospheric temperature. In addition, we investigated the sensitivity to the number of radio occultation data and to the magnitudes of the errors in the data. It is found that the effect of these uncertainties on derived wind velocity is small, indicating the reliability and robustness of our method.

2. Data and Methodology

As noted above, the local time variations of \( N_mF_2 \) and \( h_mF_2 \) contain useful information about thermospheric winds. For this reason, we used \( N_mF_2 \) and \( h_mF_2 \) data obtained from COSMIC radio occultation measurements and assimilated them into the GAIM-FP model. The current number of daily occultations does not provide enough data to perform global (and local) wind estimations on a day-to-day basis. However, the validity of COSMIC data to study ionospheric \( F \) region climatology is well established [e.g., Liu et al., 2011; Burns et al., 2012]. As a compromise, seasonally averaged COSMIC data were employed and the derived winds are to be understood as climatological averages. The possibility of assimilating other ionospheric data types (such as total electron content (TEC)) with different spatial and temporal resolutions is a subject of a separate study and is not investigated in this paper. In the next two subsections we describe the steps which were performed to utilize the COSMIC data for assimilation into GAIM-FP and give some details about the ionospheric models used in this study.

2.1. COSMIC GPS Radio Occultation Data and \( F \) Region Climatological Maps

We use the GPS radio occultation measurements from the COSMIC/FORMOSAT-3. The constellation was launched in April 2006 consisting of six microsatellites in a circular orbit at about 800 km altitude with a 72° inclination and 30° separation in longitude. Electron density profiles are routinely retrieved from slant total electron content measurements using an Abel inversion technique [Hack and Romans, 1999; Schreiner et al., 1999]. COSMIC has been providing about 1000–2500 electron density profiles per day globally [Rocken et al., 2000; Anthes et al., 2008]. For the current study, the postprocessed electron density profiles were obtained from the COSMIC Data Analysis and Archive Center (http://www.cosmic.ucar.edu). The COSMIC RO-derived electron density profiles and \( F_2 \) region peak parameters have previously been validated by comparing them with measurements from ionosondes and ISRs [Lei et al., 2007; Kelley et al., 2009; Chuo et al., 2011; Krankowski et al., 2011] and are well suited to study the global climatology of the \( F_2 \) region ionosphere at low and middle latitudes.

In order to prepare the COSMIC data for the assimilation into GAIM-FP, a multistep process was employed. The values of \( N_mF_2 \) and \( h_mF_2 \) were extracted from individual electron density profiles, and an initial quality check of the data was performed in order to eliminate erroneous \( N_mF_2 \) and \( h_mF_2 \) values from the analysis. This was accomplished by verifying that the extracted \( h_mF_2 \) values were between ~180 and 590 km and the electron densities in a 10 km interval above and below \( h_mF_2 \) did not change by more than a factor of 2. This procedure removed apparent outliers which made up about 3% for December solstice, 2.4% for March equinox, and 5% for June solstice of the initial data (seasons are defined below). To describe the average global ionosphere during the recent solar minimum, the COSMIC data were combined from 2007 to 2009, during which the \( F_{10.7} \) solar radio index was nearly similar (yearly averages are about 73 for 2007, 69 for 2008, and 70 for 2009). The data were sorted into seasons consisting of December solstice (December 21 ± 27 days for the years 2007 and 2008), March equinox (March 20 ± 27 days for 2008 and 2009), and June solstice (June 21 ± 27 days for 2008 and 2009).
Data from the vernal and autumnal equinoxes were not combined because of the well-known ionospheric equinoctial asymmetry [Balan et al., 1998; Liu et al., 2010]. Note that the number of days in the selected intervals are multiples of the solar synodic rotation period of ~27 days, which is known to influence ionospheric parameters [e.g., Ma et al., 2012, and references therein], and thus, its effect on the average values is minimized. In addition, January 2009 data do not extend beyond day of year (DOY) 017 and therefore exclude the period of prominent sudden stratospheric warming (SSW), which is known to significantly affect ionospheric electron density [Lin et al., 2012]. This was done to eliminate possible influence of SSW on the regular seasonal values of $N_mF_2$ and $h_mF_2$. On the other hand, the selected periods provide a sufficient and almost uniform global coverage for our investigation. Since the current study focused on geomagnetically quiet conditions, observations were excluded for periods with a previous 24 h average $Ap \geq 16$ and/or corresponding $3h Ap \geq 16$, which eliminated between 5 and 13% of the remaining data.

The total number of final $N_mF_2$ and $h_mF_2$ pairs that passed the rejection criteria was ~161,600 for December; ~143,900 for March; and ~144,200 for June. The average solar and geophysical conditions for the selected periods were $F_{10.7} = 73$, $Ap = 5$ for December; $F_{10.7} = 70$, $Ap = 5$ for March; and $F_{10.7} = 67$, $Ap = 4$ for June. The days that best describe the climatological average conditions of the selected seasons are those for which solar declination angle is equal to the average angle during the selected 55 day interval. That results in the following representative days: DOY 006 for December solstice, DOY 079 for March equinox, and DOY 189 for June solstice.

To further reduce the COSMIC $N_mF_2$ and $h_mF_2$ data, we produced seasonally averaged global maps of $N_mF_2$ and $h_mF_2$ in 30 min intervals of universal time (UT). For the binning, a $7.5^\circ \times 2.5^\circ$ longitude/latitude grid was used with $15^\circ \times 5^\circ$ sliding window. To exclude additional outliers and other potentially erroneous data, the procedure was performed a second time and the data in a given grid point with a deviation from the mean value by more than $2\sigma$ were ignored (a similar approach to analyze TEC data was used by Shim et al. [2008]). This further reduced the data by about 4.3% for December solstice, 4.9% for March equinox, and 4.6% for June solstice, which changed, on the average, the values of $h_mF_2$ and $N_mF_2$ by about 1 km and 2%, respectively. Finally, we excluded data for which the averages were based on less than three observations for a given grid point.

Figure 1 shows the locations of all available quiet time COSMIC RO measurements during one of the selected 110 day periods and during a 30 min interval; these are the locations on the globe where quiet time $N_mF_2$ and $h_mF_2$ values were extracted. Note that the data distribution is nearly uniform with slightly more data points over the midlatitudes, which is due to the satellites’ orbits and consequent RO geometry. Figure 2 shows the global distributions of $N_mF_2$ and $h_mF_2$ together with corresponding standard deviations at each grid point, which were obtained from the COSMIC ROs shown in Figure 1 (note that the values in Figure 2
Figure 2. Global seasonal maps of (top) $N_m F_2$ and (bottom) $h_m F_2$ with their corresponding 1σ variations for December solstice conditions and UT = 12:00 h.

represent the final data distribution after all of the data reduction described above). The solid black line in the figure indicates the location of the magnetic equator. Prominent features of the $F$ region ionosphere, such as the equatorial ionization anomaly seen in $N_m F_2$, larger $h_m F_2$ on the summer side of the magnetic equator, and larger nighttime than daytime $h_m F_2$ at midlatitudes, are clearly visible in Figure 2. The $h_m F_2$ asymmetry is attributed to the thermospheric neutral winds that blow from the summer to the winter hemisphere, causing the lift of the ionization on the summer side and lowering on the winter side. The high nighttime values of $h_m F_2$ at midlatitudes are due to photochemical processes combined with the effect of neutral winds, which are equatorward at night and poleward during the day. The standard deviations in our case describe the variability of the corresponding parameters due to several factors, including geophysical variation on daily and monthly scales, and different accuracies in parameter retrieval due to different RO geometries. On average, based on global maps (including high latitudes) of sigma for the selected three seasons, the relative error in $N_m F_2$ is about 24% ($6.3 \times 10^4$ cm$^{-3}$ absolute) and the absolute error in $h_m F_2$ is around 17 km (7% relative).

An inspection of the underlying sample population furthermore revealed that the variability of the data around the mean closely resembled a normal distribution with median and mean values differing by less than 0.5 km and 1% for $h_m F_2$ and $N_m F_2$, respectively.

Finally, the obtained standard deviation maps of $h_m F_2$ and $N_m F_2$ were used to determine the measurement error covariances for $h_m F_2$ and $N_m F_2$, with the following adjustments: If $\sigma(h_m F_2)$ was found to be less than 10 km it was assumed to be 10 km, and for $\sigma(N_m F_2) < 0.1 \times N_m F_2$ cases the error was taken equal to 0.1 $\times N_m F_2$. This helps to avoid unrealistically small errors in these parameters, which in reality should include the errors related to the instruments, measurement techniques, and Abel inversion; however, these values are not available.

2.2. GAIM-FP Model

As part of the Global Assimilation of Ionospheric Measurements (GAIM) program [Schunk et al., 2004a, 2004b, 2005a, 2005b, 2011; Scherliess et al., 2004, 2006, 2009, 2011; Jee et al., 2007, 2008; Sojka et al., 2007; Thompson et al., 2006, 2009; Zhu et al., 2006] two physics-based data assimilation models for the Earth ionosphere have been developed at Utah State University. One of the models is the Full Physics-based Kalman filter model (GAIM-FP), and the second is a simpler Gauss-Markov Kalman filter model [Scherliess et al., 2006, 2009]. Some of the data that have previously been assimilated by these models include in situ electron density measurements from satellites, bottomside electron density profiles from ionosondes, slant TEC (sTEC) data from ground GPS stations, ultraviolet radiances from various space-based instruments, and sTEC from radio occultation data.
The GAIM-FP model uses an ensemble Kalman filter technique [Evensen, 2009], which is an approximation of the traditional Kalman filter and significantly reduces the computational requirements and eliminates the need to linearize nonlinear model and/or data dependencies [Evensen, 2009]. The plasma densities in the ionosphere and plasmasphere and their associated errors evolve in GAIM-FP using a physics-based ionosphere-plasmasphere model (IPM). The IPM was developed by Schunk et al. [2003], and its main characteristics are (1) it is based on a numerical solution of the plasma transport equations for six ion species and electron along geomagnetic field lines; (2) three coordinate transformations are introduced for numerical efficiency and stability; (3) includes a myriad of chemical and ionization processes; (4) allows for neutral wind, density, and temperature changes; (5) allows the plasma to drift across B field lines due to corotational and dynamo electric fields; (6) covers equatorial B field crossing altitudes from 90 to 30,000 km; (7) uses the International Geomagnetic Reference Field, which includes realistic inclination and declination angles [Finlay et al., 2010]; (8) the spatial and temporal resolutions are adjustable; (9) plasma bubble formation is not taken into account; and (10) it outputs plasma densities, drift velocities, and temperatures. Some initial IPM simulations are shown in Schunk et al. [2004a] and Scherliess et al. [2004].

The GAIM-FP model provides specifications of the three-dimensional electron and ion (NO, O₂, N₂, O⁺, H⁺, He⁺) density distributions from 90 km to near-geosynchronous altitude (~30,000 km). In addition, the model can provide the global distribution of the ionospheric drivers (electric field, neutral wind, and composition) that are consistent with the ionospheric observations. This is accomplished by using the internal sensitivities of the physics-based model to the various driving forces. In this process, the plasma densities and its drivers are adjusted to produce the optimal model-data combination of the ionosphere-plasmasphere system together with the consistent set of ionospheric drivers [Scherliess et al., 2009, 2011].

The GAIM-FP model was designed to specify ionospheric weather, but the model can also be run in a newly developed climatology mode. There are several distinct differences between the two modes that are important to point out. In its weather mode the model sequentially assimilates the various individual observations mentioned above using the actual time and geophysical conditions (e.g., 3 h Kp index and solar F₁₀.₇ cm flux) corresponding to the time of the observation. In contrast, in its climatology mode the model currently assimilates seasonal N₉mF₂ and h₉mF₂ maps using the geophysical conditions corresponding to the average conditions of the seasonal maps. The seasonal maps are furthermore iteratively assimilated, meaning that the seasonal maps are not only assimilated on 1 day, but instead, the same maps are again assimilated on the second day, on the third day, etc. Finally, GAIM-FP only solves for the ionospheric drivers in the current climate mode, and the corresponding 3-D plasma density distribution is generated by continuously feeding the obtained physical drivers back into the IPM model. It should be noted that throughout the simulations one can selectively keep, for example, the global neutral composition as specified by the Mass Spectrometer Incoherent Scatter Extended (MSISE-90) model and/or the low-latitude E x B drifts as specified by the Scherliess-Fejer model.

For the current study, the GAIM-FP state vector consists of the global magnetic meridional wind field together with the low-latitude vertical drifts, which are both simultaneously adjusted by GAIM-FP to match the modeled electron density parameters with the COSMIC N₉mF₂ and h₉mF₂ values. Initially, GAIM-FP starts from a zero wind field and from the empirical values of the low-latitude vertical drifts and adjusts both of them as needed. The wind component along the magnetic meridian is discretized in 15 min increments on a 2.5° x 7.5° latitude/longitude grid (3456 grid points) with an assumed correlation length of 30° in both latitude and longitude. The low-latitude vertical drifts are discretized in 15 min increments on a 7.5 longitude grid (48 grid points) with an assumed correlation length of 30° in longitude. Furthermore, it is assumed that the magnetic meridional wind is constant in altitude, which is a valid assumption during quiet times above the F region peak, where the altitude variations are smoothed out due to the increasing kinematic viscosity. At lower altitudes the wind is expected to have an altitude gradient, which potentially could affect the estimated wind velocity. However, it should be noted that the assimilated data sets, i.e., seasonal maps of N₉mF₂ and h₉mF₂, only contain very limited information about the bottomside wind profiles. Clearly, additional information/data are needed to specify the bottomside wind gradients.

The ensemble Kalman filter assimilation procedure was implemented as follows: 24 h before the representative day, the plasma distribution obtained from the IPM run was taken to be the initial distribution at the start
of the assimilation. At this point the initial ensemble of random wind and drift perturbations was generated using an initial uncertainty of 150 m/s and 15 m/s for the winds and drifts, respectively. Every 15 min, the global COSMIC $N_{m}F_2$ and $h_{m}F_2$ maps (section 2.1) were assimilated, the ensemble of ionosphere/plasmasphere model runs was integrated forward in time, and the model error covariance matrix was determined. Using the new data and the new error matrix, the ensemble Kalman filter reconstructed an updated estimate of the ionospheric drivers (winds and drifts). The new drivers were fed back into the IPM, and the assimilation was repeated at the next 15 min time mark. As time advanced, the ensemble Kalman filter produced a 3-D, time-dependent, plasma distribution for which $N_{m}F_2$ and $h_{m}F_2$ converged toward the COSMIC $N_{m}F_2$ and $h_{m}F_2$. Note that as mentioned above, when a simulation was advanced to the next day, the assimilated data remained the same.

2.2.1. Observational System Simulation Experiment

Before assimilating the actual COSMIC $N_{m}F_2$ and $h_{m}F_2$ seasonal maps, it is critical to first establish (i) the number of required ensemble members, (ii) the required number of days to iterate, and (iii) the fidelity of the model to globally specify the thermospheric neutral winds. These three steps are best performed in a controlled environment, and consequently, we have used an Observational System Simulation Experiment (OSSE) where the model assimilates synthetic (model-generated) $N_{m}F_2$ and $h_{m}F_2$ maps. The advantage of the OSSE is that in these controlled experiments the “true” global wind field is known and the convergence and fidelity of the model can be quantitatively assessed. In the OSSE, the simulated time-dependent $N_{m}F_2/h_{m}F_2$ maps were generated by using the IPM model, which was driven by climatological equatorial vertical drifts and horizontal neutral winds as provided by the Scherliess-Fejer vertical drift and the HWM93 neutral wind model, respectively. The IPM was run for the time period of 5–7 January 2009, using a constant $A_{p}$ index of 5 and a constant $F_{10.7}$ cm solar flux of 73. These geophysical conditions correspond to the average conditions of our December solstice case. The synthetic data were generated from the model output in 15 min increments, and $N_{m}F_2$ and $h_{m}F_2$ were obtained. In order to closely resemble the assimilation of the true COSMIC seasonal maps, the cadence and distribution of the synthetic maps were chosen to be identical to the actual COSMIC seasonal maps. Specifically, the $N_{m}F_2$ and $h_{m}F_2$ values were obtained from the IPM-generated, 3-D, time-dependent electron density distribution at the same locations where these values were present in the original COSMIC seasonal maps. In order to further ensure that the OSSE mimics the assimilation of the real COSMIC maps, the data error statistics was also chosen to follow those of the COSMIC maps. For this, the errors of $N_{m}F_2$ and $h_{m}F_2$ were taken from the corresponding data error covariances that were generated from the standard deviation maps (see Figure 2) and added as random noise to the synthetic data.

In our initial use of the OSSE we have inspected the global wind pattern obtained from GAIM-FP OSSE run and compared them with the “true”, i.e., the HWM93, wind field. Figure 3 shows a typical example of a global snapshot of the agreement between the low- and middle-latitude magnetic meridional winds at 250 km altitude as specified by HWM93 (Figure 3, left) and those obtained from the GAIM-FP OSSE for the case of 15 ensemble members and for the second day of the simulation (Figure 3, middle). The difference between the HWM93 and the GAIM-FP map is shown in Figure 3 (right). Figure 3 indicates that GAIM-FP successfully
specified the global-scale wind pattern as provided by HWM93 with errors that are generally on the order of 10–20 m/s.

Next, we have used the OSSE to estimate the effect of the number of ensemble members on the estimated wind field. For this, we have run GAIM-FP with 15, 25, and 60 ensemble members. Figure 4 shows the distribution of the GAIM-FP errors, i.e., the differences between the magnetic meridional winds obtained from HWM93 and those specified by GAIM-FP in the OSSE, for an entire 24 h day (96 individual 15 min intervals). For reference, Figure 4 also shows a normal distribution with zero mean and 15 m/s standard deviation (red curve). The error distribution for the second day of the simulation and for 15 and 60 ensemble members is shown in the middle and right plots, respectively. Results indicate that the error distribution only marginally changes from 15 to 60 ensemble members with a change in the mean from $-2.2$ m/s to $-1.1$ m/s and a change in the standard deviation from 14.6 m/s to 13.8 m/s. Given the errors introduced by additional uncertainties in the model when assimilating real data, as outlined in section 3.3, we have chosen for the reminder of the study a use 15 ensemble members. Note that the difference between the 15 and 25 ensemble member runs (not shown) was found to be even smaller than those between the 15- and 60-member runs.

Finally, we have used the OSSE to investigate the required number of iteration days by running the model for three consecutive days. The histogram of the model errors for the first day and the second day are shown in the left and middle plots of Figure 4. Similar to our investigation on the number of ensemble members, we found that the mean and standard deviation only slightly improved from first day to second day, with values for the mean of $-3.5$ m/s and $-2.2$ m/s and standard deviations of 15.5 m/s and 14.6 m/s for the first and second days, respectively. The changes in the values from second day to third day were found to be even smaller than those between first day and second day. Based on these results, we have chosen for the reminder of the study to present results corresponding to the second day of the simulation. In summary, as a result of our OSSE tests, all following results correspond to the second day of the simulation and 15 ensemble members.

Figure 4. Distribution of differences between HWM93 and GAIM-FP OSSE magnetic meridional winds for December solstice conditions. (left) The first simulation day and 15 ensemble members, (middle) the second simulation day and 15 ensemble members, and (right) the second simulation day and 60 ensemble members, respectively. A normal distribution with zero mean and 15 m/s standard deviation (red curve) is also shown. Note that the sigma values are calculated by considering only data with $|\Delta V_{\text{mag}}| \leq 40$ m/s.
members. The OSSE furthermore indicates that the GAIM-FP model successfully specified the global-scale wind pattern as provided by HWM93 with errors that are unbiased and on the order of 15 m/s.

Our above-mentioned OSSE studies clearly show that the model is well-suited to determine the global magnetic meridional wind field. However, when assimilating real observations, additional uncertainties and caveats need to be considered. In particular, at low latitudes, the vertical motion of plasma due to $E \times B$ drifts plays a very important role in ionospheric variations. Their effects are separated from the wind effects during the estimation process by considering that the $E \times B$ drift moves plasma across the geomagnetic field lines, while the wind is effective in moving $F$ region ionospheric plasma along the field lines. At the midlatitudes, however, the effective vertical motion due to $E \times B$ drifts is not separated from the motion due to the winds by the model. Therefore, the derived magnetic meridional wind at midlatitudes could contain a contribution from the ion drift, and, for this reason, it is usually denoted as an effective or equivalent wind. It should be noted, however, that the ion drift effect during quiet times is typically small, and indeed, an estimate based on the Scherliess-Fejer midlatitude drift model [Scherliess et al., 2001] for the Millstone Hill station shows that the effect is about 15 m/s.

Finally, there are several uncertain model parameters in the ionospheric models that could lead to large uncertainties in the ionospheric model results [Jee et al., 2005; Schunk et al., 2012]. One is the $O^-\text{O}$ collision frequency, which is only known within a factor of 2 [e.g., Nicolls et al., 2006, and references therein]. This parameter is considered to be one of the major sources of the errors, along with the neutral density, in various thermospheric wind estimation methods [Buonsanto et al., 1989; Miller et al., 1989; Oliver, 1990; Richards, 1991; Buonsanto and Witasse, 1999]. Similarly, it is also expected that the wind values from GAIM-FP are sensitive to the $O^-\text{O}$ collision frequency and to the specified neutral composition (currently MSISE-90). A discussion on these uncertainties is given in section 3.3.
3. GAIM-FP Climatology

In this section, first, a comparison of the ionospheric \( N_mF_2 \) and \( h_mF_2 \) from COSMIC to corresponding results from GAIM-FP and IPM is presented. Next, the derived neutral winds are shown and compared with corresponding measurements from FPI instruments and with values from the HWM93 model. Finally, the sensitivity of the derived wind to uncertain model parameters is analyzed. An investigation of the derived electromagnetic drifts, including their sensitivity analysis and validation, is out of the scope of this paper and will be considered in future studies.

3.1. Comparison of COSMIC, GAIM-FP, and IPM \( N_mF_2 \) and \( h_mF_2 \)

The GAIM-FP model assimilates the COSMIC data and estimates the low- and middle-latitude thermospheric winds and the poleward/upward component of low-latitude \( \mathbf{E} \times \mathbf{B} \) drift. On the other hand, stand-alone IPM uses the HWM93 empirical wind model for the neutral winds and the Scherliess-Fejer model for the low-latitude plasma drifts. In both cases, the neutral atmosphere was obtained from the MSISE-90 empirical model, and all other input parameters (except winds and drifts) were the same. For the selected seasons, the outputs of empirical models were generated using the average geophysical conditions corresponding to the COSMIC maps. The left plots of Figure 5 show the COSMIC maps of \( N_mF_2 \) for three seasons (December solstice, March equinox, and June solstice) at UT = 12 h. The corresponding differences between the COSMIC maps and the GAIM-FP and IPM results are shown in the middle and right plots, respectively. Here the values are normalized to the observations and thus show relative differences. Values of less than 0.2 are set to 0 because they are close to the average standard deviations of the COSMIC data. The COSMIC data are only shown for low and middle latitudes with the same latitudinal extent as the model simulations. Figure 6 shows results for \( h_mF_2 \) and this time for absolute differences with values less than 15 km set to zero.

![Figure 5](image1.png)

![Figure 6](image2.png)

Figure 6. Same as Figure 5 but for \( h_mF_2 \) and absolute differences in \( h_mF_2 \). Here differences less than 15 km are set to zero.
assimilation model was able to obtain more accurate values for both $F_2$ layer peak parameters by simultaneously adjusting thermospheric neutral winds and $E \times B$ drifts. The derived winds and drifts push the ionospheric model parameters closer to the observed values than those obtained from the empirical models, and this is the case for daytime and nighttime, for all three seasons, and for low or middle latitude. It should be noted that, in general, the improved performance of GAIM-FP compared to IPM was expected. However, what is important to note is that the adjustment of the winds and drifts improve both $N_{mF_2}$ and $h_{mF_2}$ simultaneously. From Figures 5 and 6 it can be noticed that, on average, the IPM model overestimates both $N_{mF_2}$ and $h_{mF_2}$. The results from GAIM-FP are closer to the observations, albeit certain systematic differences are still present. For example, $N_{mF_2}$ is generally underestimated, while $h_{mF_2}$ remains higher than the observed values. Given the current constraints, the GAIM-FP found the optimal agreement between the data and the model results. It is expected that the agreement will be further improved if the neutral composition also becomes part of the estimation process. The inclusion of neutral composition as a state variable is also expected to affect the estimated winds but is beyond the scope of this study. However, the sensitivity of GAIM-FP winds on neutral composition is discussed in section 3.3.

In order to further quantify the improvements in the description of the $F_2$ layer parameters by the data assimilation model for all UTs, the root-mean-square error was used as an indicator of the model accuracy and was evaluated for $h_{mF_2}$ and $N_{mF_2}$ for all three seasons. Relative $N_{mF_2}$ was chosen to accommodate for the order of magnitude difference between daytime and nighttime $N_{mF_2}$ values. The results are shown in Figures 7 and 8, which again indicate that data assimilation significantly improves the agreement between the model and data for all seasons. Note that the large differences seen in IPM $N_{mF_2}$ and $h_{mF_2}$ over the South Atlantic and South Pacific are considerably reduced in the GAIM-FP results. Significant improvements are also seen over eastern Asia. However, there are certain places where the IPM model performed relatively well (for example, over the southern part of North America and Australia), and no major differences in the two modeling results are visible.

A region of relatively large differences between the modeled and observed densities can be seen near the poleward edge of the midlatitudes during local winter and to a lesser degree during equinox (Figures 7 and 8). These discrepancies can most likely be attributed to high-latitude ionospheric processes and features like the well-known midlatitude trough [Rodger et al., 1992; Schunk and Nagy, 2009; He et al., 2011], which were not included in our GAIM-FP simulation. Other, albeit smaller, differences can be seen at equatorial and low latitudes where the model needs to separate the plasma motion across the Earth’s magnetic field.

Figure 7. Global distributions of the mean square error of relative $N_{mF_2}$ for (left) December solstice, (middle) March equinox, and (right) June solstice and for (top) GAIM-FP and (bottom) IPM.
due to \( \mathbf{E} \times \mathbf{B} \) drifts from the field-aligned plasma motion due to the neutral winds. This added complexity might be responsible for some of the observed differences. It is, however, also important to point out that the accuracy of the Abel inversion, which is used to obtain the values of \( N_mF_2 \) and \( h_mF_2 \), is known to be less reliable at these latitudes [Yue et al., 2010]. They noted that \( N_mF_2 \) at low latitudes could possibly be biased due to the large horizontal gradients at these latitudes. This, in turn, could lead to an inconsistency between \( N_mF_2 \) and \( h_mF_2 \) in the physics-based data assimilation process.

Figures 9–11 show detailed comparison of the local time variation of the modeled and measured values of \( N_mF_2 \) and \( h_mF_2 \) for stations where ground-based wind measurements are available. These variations are shown for three seasons (December solstice, March equinox, and June solstice) for Millstone Hill, Arecibo, and Arequipa. The COSMIC data and their corresponding error bars are the same as those used in the data assimilation. For the comparison, the model and the COSMIC data were both taken at the grid point that was closest to the corresponding ground station: for Millstone Hill at 43.0°N, 71.25°W; for Arecibo at 19.0°N, 63.75°W; and for Arequipa at 17.0°S, 71.25°W. In Figures 9–11, the GAIM-FP results for Millstone Hill during all three seasons are significantly closer to the COSMIC values than their corresponding IPM values. For Arecibo and Arequipa, both the GAIM-FP and IPM results closely describe the observed local time variations of \( N_mF_2 \) and \( h_mF_2 \). The results show that the data assimilation and driver estimation procedure produce reliable agreement between the assimilated and modeled parameters.

### 3.2. Derived Neutral Winds

Figure 12 shows the derived magnetic meridional winds for different seasons and UTs at 250 km altitude, with positive values indicating the northward winds. The derived wind pattern agrees with the well-established characteristics. Namely, the wind is equatorward during the night and poleward during the day, the magnitude of wind is up to ~150 m/s, and the wind is predominantly from the summer to winter hemisphere during solstices and is more symmetric about the geographic equator during equinox. Longitudinal variations in the wind can also be seen in Figure 12 by comparing different UTs for a given season. The results indicate that the estimated low- and middle-latitude winds represent the thermospheric dynamics very well.

For validation, the GAIM-FP magnetic meridional wind climatology was compared with direct wind observations obtained from the Millstone Hill, Arecibo, and Arequipa FPI stations. The FPI instruments obtain geographic zonal and meridional components of the neutral wind, corresponding to an altitude of about 250 km, by measuring the line-of-sight Doppler shift of 630.0 nm nightglow emission at different azimuth angles. The three stations have provided extensive nighttime wind data over several decades [e.g., Emmert et al., 2003, 2006, and references therein]. In addition, upgraded instruments at these stations...
Noto et al., 2006, 2011; Meriwether et al., 2008] currently provide valuable wind measurements with higher accuracy. The newer data for Arecibo and Arequipa are available for certain months in 2008 and 2009 and overlap with the period for which the COSMIC data were averaged for this study. Unfortunately, there is an observational gap in Millstone Hill data during the recent solar minimum, and new wind data are only available starting from the end of 2009.

Figure 9. Local time variations of (left) $N_mF_2$ and corresponding (right) $h_mF_2$ as observed from COSMIC (black circles) and modeled by IPM (magenta) and GAIM-FP (blue) for (top) Millstone Hill, (middle) Arecibo, and (bottom) Arequipa for December solstice conditions. Error bars indicate $1\sigma$ variations in the COSMIC data.

Figure 10. Same as Figure 9 except for March equinox.
To create the seasonal climatology of magnetic meridional winds from the FPI observations, first, all available zonal and meridional wind data for each station were obtained from the Madrigal database (http://www.openmadrigal.org/). The total number of data points for the meridional (zonal) wind were over 83,100 (78,100) for Millstone Hill (years spanned: 1989–2002 and 2009–2013); over 27,300 (27,200) for Arecibo (years spanned: 1980–1994, 1996–2005, 2008–2009, and 2012–2013); and over 22,800 (27,200) for Arequipa (years spanned: 1983–1984, 1986, 1988–1990, 1996–1999, 2005, 2007–2010, and 2012–2013). Note that the seasonal distribution of the data is not uniform, and the time resolution varies from station to station and from year to year, ranging from more than 30 min to less than 5 min. Also note that the FPI wind data for the three stations have previously been used in a variety of different studies [e.g., Fejer, 1993; Fejer et al., 2002; Biondi et al., 1999; Emmert et al., 2006; Brum et al., 2012].

The FPI data were sorted by season in the same way as the COSMIC data, and only measurements with $F_{10.7} < 100, 3\ h\ Ap < 16$, and $12\ h\ average\ Ap < 16$ were considered. The mean zonal and meridional winds were computed for every 15 min bin together with their corresponding standard deviations ($\sigma$). Again, following our analysis of COSMIC data, the mean and sigma were used to remove data that deviated from the mean by more than $2\sigma$, and the remaining data were used to recalculate the mean and the standard deviation. In the final step, only averages based on more than 10 data points were considered. Note that the average wind for a given time bin contains contribution from different solar cycles. Furthermore, different time bins may combine a different number of data points, and zonal and meridional wind averages may also be based on a slightly different number of measurements. The median numbers of distinct nights that contributed to the final wind climatology are 47, 27, and 81 for Millstone Hill during December, March, and June, respectively; 27, 10.5, and 26 for Arecibo; and 0, 23, and 75 for Arequipa. Finally, to obtain the magnetic meridional wind (assuming no vertical wind) the two horizontal components of the wind were combined by $v_{mag} = u \cdot \sin D + v \cdot \cos D$, where $u$ and $v$ denote the geographic eastward and northward components of the wind, respectively and $D$ is the magnetic declination angle. To calculate the corresponding sigma, the appropriate error propagation expression, $\sigma_{v_{mag}} = \sqrt{\sigma_{u}^2 \sin^2 D + \sigma_{v}^2 \cos^2 D}$, was employed. Here the declination angles of the closest grid points to the corresponding ground stations were used with values of $D = -14.4^\circ$ for Millstone Hill, $D = -13.3^\circ$ for Arecibo, and $D = -3.4^\circ$ for Arequipa.

Figure 11. Same as Figure 9 except for June solstice.
Figure 13 compares the estimated magnetic meridional winds at 250 km altitude to the corresponding night-time FPI values and also to the corresponding values from the empirical HWM93 model (a positive value here indicates an equatorward wind). The error bars on the FPI winds in Figure 13 correspond to one standard deviation and characterize the geophysical variations of the quiet time winds, day-to-day weather variability, and instrument errors. Figure 13 shows that the GAIM-FP winds are in very good agreement with the observations during the night (nearly always within the 1σ range of the observed data) and also are reasonably close to HWM93 winds throughout the day for all stations and seasons. The presented comparisons demonstrate that the GAIM-FP-estimated wind climatology is reliable over the low and middle latitudes during all seasons. Note that the largest difference between the GAIM-FP and the FPI winds is during June solstice. Interestingly, a climatology of ISR-derived winds over Millstone Hill shows similar differences in June as the GAIM-FP wind [Buonsanto and Witasse, 1999; Emmert et al., 2003]. Finally, note that the HWM93 model, when constructed, included ground-based wind data from either ISR or FPI (or from both) over the selected three stations in Figure 13 [Hedin et al., 1991].

3.3. Sensitivity of Derived Wind to Uncertain Model Parameters

It is well known that ionosphere models are sensitive to a variety of uncertain atmosphere and ionosphere parameters [Lee et al., 2005; Jenniges, 2011; Schunk et al., 2012]. Also, there are uncertainties associated with the data used in assimilation models. We conducted several studies in order to determine how some of the most important uncertainties can influence the estimated wind values. In particular, we focused on the O\(^+\)-O
collision frequency, the neutral composition, the effect of the number of radio occultations assimilated, and the effect of the assumed errors associated with the assimilated data on the derived winds. A comprehensive description of our sensitivity studies, with corresponding figures, is given in Lomidze [2015]. Here we merely summarize the results.

The O⁺–O collision frequency affects the O\(^{+}\) field-aligned diffusion velocity and, in turn, the neutral wind estimation. In various model studies, the theoretical value given by Banks [1966] has been multiplied by factors from 0.75 to 2.0 [Nicolls et al., 2006], and this factor has been called the Burnside Factor (F) [e.g., Salah, 1993]. In the IPM and GAIM-FP models, F = 1.0, and therefore, all model results presented so far are based on this value. To see the effect of F on the ionospheric parameters and estimated winds, the GAIM-FP model was rerun with F = 1.4 for all cases. The N\(_m\)F\(_2\) and h\(_m\)F\(_2\) values were virtually unaffected by this change, indicating that the model was able to match the data with the same degree of accuracy as before. However, the obtained neutral wind was modified. The average nighttime wind differences at midlatitudes (30°N–60°N, 30°S–60°S) were between 19 and 25 m/s, but during the day they were only 5–7 m/s. At low latitudes (±25°), the wind difference did not change much during the course of the day and the daily average of the wind difference was 3–5 m/s.

The neutral composition and temperature play a critical role in the wind determination, and both IPM and GAIM-FP models are based on the MSISE-90 empirical atmosphere model, which has estimated errors of 15–20% [Hedin et al., 1991]. To determine the effect of this uncertainty on the wind estimation, we globally reduced the neutral exosphere temperature (T\(_{ex}\)) in MSISE-90 by 60 K for each season and repeated the GAIM-FP runs. This reduced T\(_{ex}\) resulted in a reduction of the global average mass density of 14% at 250 km and 31% at 400 km. The reduction of T\(_{ex}\) was motivated by the smaller than expected neutral densities during the recent solar minimum [Emmert et al., 2010]. Similar to the Burnside Factor study, the N\(_m\)F\(_2\) and h\(_m\)F\(_2\) values were only slightly modified by the T\(_{ex}\) change. The average difference in the estimated winds at midlatitudes and at night was 28 m/s for winter, 25 m/s for equinox, and 15 m/s for summer. For daytime

![Figure 13. Local time variations of seasonal magnetic meridional winds at 250 km altitude for (left) Millstone Hill, (middle) Arecibo, and (right) Arequipa and during (top) December solstice, (middle) March equinox, and (bottom) June solstice conditions. The circles indicate the seasonally averaged FPI observations in 15 min intervals with their corresponding 1σ variability. The estimated winds from GAIM-FP (blue) and HWM93 (magenta) are also shown. Positive values indicate equatorward winds.](image)
midlatitudes, the wind differences were 8 m/s for all seasons. At low latitudes, the daily average of the wind differences was 5 m/s.

For our uncertainty study concerning the data, we focused on the December solstice period. We first randomly excluded one third of the original quiet time COSMIC radio occultations during that period and then performed the data processing and binning as described in section 2.1. The new data maps generated for \( N_mF_2 \) and \( h_mF_2 \) were assimilated into GAIM-FP, and the global meridional wind was determined. The comparison of this wind field with the original wind field showed that the root-mean-square difference was typically 7 m/s, with some places where it reached 10–15 m/s. Next, we studied the sensitivity of our wind determination to the assigned COSMIC data errors. This was accomplished by increasing all \( N_mF_2 \) and \( h_mF_2 \) data errors by 30% in the default COSMIC maps and then again performed the GAIM-FP data assimilation for December solstice. The comparison of the new and original wind fields differed by about 4 m/s.

The individual wind uncertainties due to uncertain model parameters listed above are relatively small compared to typical magnetic meridional wind values (100–200 m/s). However, note that when they are in action at the same time, the combined uncertainties might be different.

4. Summary

The ability to reliably estimate the thermospheric wind is important for accurate modeling of the ionosphere, to better elucidate ionospheric and thermospheric phenomena related to the neutral winds, and for an improved understanding of thermospheric dynamics. The climatology of the magnetic meridional wind for low and middle latitudes was deduced using the GAIM-FP data assimilation model for solar minimum and low geomagnetic activity conditions. For this study, GAIM-FP assimilated quiet time, global, seasonally averaged maps of \( N_mF_2 \) and \( h_mF_2 \) obtained from COSMIC GPS radio occultation measurements. The GAIM-FP model provided the 3-D climatology of the ionosphere, the meridional wind, and the low-latitude \( \mathbf{E} \times \mathbf{B} \) drift. In general, the \( N_mF_2 \) and \( h_mF_2 \) values obtained from the GAIM-FP model were significantly closer to the corresponding COSMIC data than those obtained from the background physics-based ionosphere-plasmasphere model (IPM), which was driven by the empirical horizontal wind model (HWM93) and the low-latitude vertical drift model (Scherliess-Fejer). The deduced meridional winds were shown to display the expected global and seasonal patterns. In addition, there was very good agreement between the deduced meridional winds and FPI measurements made at Millstone Hill, Arecibo, and Arequipa for the three seasons considered (December and June solstices and March equinox).

We also studied the sensitivity of the deduced meridional winds to the uncertainties associated with the \( \text{O}^+ \)-ion collision frequency, the neutral composition, the effect of the number of radio occultations assimilated, and the effect of the assumed errors connected with the assimilated data. The uncertainties in the deduced meridional winds were found to be relatively small compared to typical meridional winds (100–200 m/s), and hence, our data assimilation approach can be a useful tool to estimate neutral winds in regions where wind data are scarce. For example, the GAIM-FP model is currently being used to understand the causes of the Weddell Sea Anomaly [Lomidze and Scherliess, 2010] and to elucidate the role of the neutral wind in the formulation of the midlatitude ionospheric evening anomalies [Lomidze and Scherliess, 2011]. Work is also currently underway to use the estimated global magnetic meridional wind, along with other model parameters, to obtain the geographic zonal and meridional components of the neutral wind [Lomidze and Scherliess, 2013].

References


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