The Midlatitude Thermospheric Dynamics From an Interhemispheric Perspective

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Abstract Using Fabry-Perot interferometers at five midlatitude stations (Boulder, Palmer, Millstone Hill, Mount John, and Kelan) in both hemispheres, we examine the interhemispheric and seasonal variations of midlatitude thermospheric dynamics. We also use the National Center for Atmospheric Research Thermosphere Ionosphere Electrodynamics General Circulation Model (TIEGCM) to simulate the seasonal changes of winds and the effects from Sub-Auroral Polarization Streams. The observations and TIEGCM simulations show a clear seasonal variation with more westward and equatorward summer winds. The TIEGCM runs overestimate the westward zonal winds and underestimate the electron densities in the northern summer. We believe that the underestimated TIEGCM electron density leads to a weak ion drag effect in the model, and strong westward zonal winds. TIEGCM overestimates the Sub-Auroral Polarization Stream effects on neutral winds in most cases, probably because the empirical Sub-Auroral Polarization Stream model used by the TIEGCM applies an unrealistic persistent electric field for a long period of time (over 3 hr) due to the low temporal resolution of the Kp index.

1. Introduction

While the midlatitude thermosphere is the region most observed and investigated for insight into upper atmospheric dynamics (e.g., Hernandez et al., 1982; Hernandez & Roble, 1984a, 1984b, 1995; Huang et al., 2015; Wu et al., 2014; Wu et al., 2014), it remains least understood in many respects. Midlatitude thermospheric winds respond to lower thermospheric waves, geomagnetic activity, solar EUV conditions, and Sub-Auroral Polarization Streams (SAPS), and vary with latitude, longitude/UT, and season (e.g., Wang et al., 2011; Wang et al., 2012; Wang et al., 2012; Wang & Lühr, 2011; Wu, Noto, et al., 2014; Wu, Yuan, et al., 2014). It is hard to isolate and quantify the forcing that drives neutral winds and their variability in the midlatitude thermosphere. Moreover, the past mostly northern-hemisphere America-sector observations may bias our understanding of global dynamics in the thermosphere. It is rare to have simultaneous interhemispheric thermospheric wind observations in the midlatitudes (e.g., Wu, Noto, et al., 2014). That is due, in large part, to scarcity of southern hemisphere observations.

Interhemispheric difference is often associated with the seasonal difference, particularly during solstices, when the two hemispheres are in the opposite season. Most investigations of seasonal wind variation have been carried out using single stations (e.g., Emmert et al., 2006; Huang et al., 2015). However, simultaneous observations from opposite hemispheres advantageously provide a way to examine midlatitude thermospheric dynamics during different seasons, but under identical geomagnetic and solar activity conditions.

Wu, Noto, et al. (2014) used simultaneous Millstone Hill and Palmer Fabry-Perot interferometer (FPI) observations to examine interhemispheric wind differences. One major limitation to that study is that there were no austral summer observations at the Palmer station due to its relatively high geographic latitude (64°S). Hence, there was no comparison for the northern winter season. Recently, Harding et al. (2019) quantified the discrepancy between the Global Ionosphere and Thermosphere Model model and FPI observation with detailed analysis. On the other hand, there is no information on the whether the model overestimates or underestimates the winds.
In this investigation, we gather thermospheric wind data from five midlatitude FPIs in both hemispheres: Millstone Hill, Boulder, Kelan, Mount John, and Palmer during the year of 2013 to validate the National Center for Atmospheric Research Thermosphere Ionosphere Electrodynamics General Circulation Model (TIEGCM) simulation in the region. The locations of the stations and abbreviations are listed in Table 1. The subscript in the station abbreviations denotes the hemisphere of the station. It is very fortunate to have these instruments operating during the same year given the challenges to maintain their operation.

We will focus on interhemispheric comparisons of the thermospheric wind during different seasons. By combining data sets from different hemispheres, we are able to view each local observation in a global context. Because the TIEGCM is capable of including the SAPS inputs, we also use the model to simulate thermospheric winds at these locations, with and without SAPS inputs (Wang, Talaat, et al., 2012), and then examine the SAPS effects.

In the next section, we will give a description of instruments and model simulations. Then we will show the observational data and comparison with model simulations. Discussion of the results follows. Finally, we summarize our findings.

2. Instruments

The BDn, KLn, and PA FPIs have the same specifications as the FPI in Resolute (Wu et al., 2004) and were built by National Center for Atmospheric Research. Each has a 10-cm clear aperture etalon with 2-cm gap, and uses a Princeton PIXIS 512B back-illuminated CCD camera. For the redline (O 630 nm) emission, a 5-min integration time is used. The instrument samples four cardinal directions with a 45-degree elevation angle. The wind measurement errors are intensity dependent and mostly about a few meters per second. Cloud detectors are installed at BDn and PA to monitor sky conditions. The KLn sky condition is judged based on the measurements of airglow intensity of O 630 nm, 557.7 nm, and OH 892 nm emissions. Under clear skies the emissions have clear intensity differences between the zenith direction and the four cardinal directions due to the Van Rhijn effect (e.g., Roach & Meinel, 1955). If all three emissions show Van Rhijn effects, we will use the data.

The MHn FPI has a 10.16-cm clear aperture etalon and a gap of 1.0525 cm. The instrument samples the four cardinal directions with a 45-degree elevation angle. The wind measurement errors are approximately 1 m/s, and intensity dependent. Sky conditions for the MHn FPI are determined by an infrared cloud monitor and by the Boston University all-sky imager. A data quality code is further assigned to these data, based primarily on the quality of nonlinear least squares spectral fitting.

The MJ FPI was built and deployed by the University of Washington (Hernandez & Mills, 1973). It is a 15.2-cm aperture scanning FPI with servo-control of the etalon spacing, 2.154-cm gap, and a photomultiplier tube detector. The elevation angle for cardinal direction measurements is 20°. The scan time for each direction is from 4 to 10 min. The scan time is emission dependent; when enough signal counts are accumulated to provide a signal-to-noise exceeding 5, the scan ends. The measurement cycle lasts from 30 to 60 min including four cardinal directions and the zenith. Wind measurement errors are typically between 10 and 20 m/s. The sky conditions are verified by the Boston University all-sky camera at MJ and the astronomical observatory weather log. Because the FPI measurements are affected by local weather conditions, in some cases, data from some stations are incomplete.

3. TIEGCM

The National Center for Atmospheric Research TIEGCM is a first-principle three-dimensional model of the coupled thermosphere and ionosphere system with self-consistent solution of the middle- and low-latitude dynamo (Richmond et al., 1992). The model uses the three-dimensional momentum, energy, and continuity equations for ion and neutral constituents and computes at 57 pressure surfaces with a typical time step of 120 s. The lower boundary of the model is ~97 km driven by the climatological tidal forcing from the Global Scale Wave Model (Hagan & Forbes, 2002, 2003). The upper boundary is at about 500-km altitude, which is solar EUV flux dependent. At high latitudes, the TIEGCM is driven by the Heelis or Weimer ion...
convection model (Heelis et al., 1982; Weimer, 2005). In this study, we used the Heelis model. A horizontal spatial resolution of 2.5° × 2.5° and ¼ scale height vertical grid is used. The SAPS-enabled TIEGCM has an empirical SAPS model based on the DMSP ion drift meter data, specifying SAPS statistical distribution in magnetic latitude and local time, with Kp index dependence. The SAPS genesis is placed just equatorward of the auroral boundary in the Heelis ion convection model, which is also specified using the Kp index (Wang, Talaat, et al., 2012). The TIEGCM simulation results are recorded hourly. The model grid points closest to the each of the stations are selected and compared with observations. We use 250-km altitude in selecting the modeled winds.

4. Observations and Simulations

We selected six cases from different seasons under geomagnetically quiet conditions (mostly Kp ≤ 2) when the observations from the two hemispheres are available simultaneously for interhemispheric comparison. Data for these six cases are shown in Figures 1–6. The results are summarized in Table 2. It is very rare to have data from all five stations on the same day, as the data availability is weather dependent. Cases from different seasons show the gradual seasonal change in thermospheric winds under relatively quiet conditions. Then we show five cases (Figures 7–11), when the TIEGCM simulations show significant SAPS effects under moderate conditions (mostly Kp ≥ 2) to investigate these SAPS effects on thermospheric winds. The main features of these five cases are also listed in Table 2. All the observations and simulations are shifted to local times in the figures.

5. Discussion

5.1. Longitudinal Variations (Geomagnetic Latitudinal Dependence)

Since the data come from different longitudinal regions (American and Asian sectors), it may introduce longitudinal variations in the data set. Wu, Yuan, et al. (2014) investigated longitudinal variations in the midlatitude thermospheric winds and found that longitudinal variations are mostly due to geomagnetic latitude difference, in other words, due to the geomagnetic dipole tilt angle. Hence, in our discussion of seasonal variations in difference hemispheres, we will also examine longitudinal and magnetic latitude difference as well if the interhemispheric comparison is between different longitudinal sectors. Most of our interhemispheric comparisons are made within the same longitudinal sector.

5.2. Seasonal Variations Under Relatively Quiet Conditions (Kp ≤ 2)

The cases from different seasons under relatively quiet conditions show a clear seasonal variation from the two hemispheres. In the local summer season (regardless in which hemisphere) the meridional winds are more equatorward and zonal winds are more westward than those in other seasons. That is consistent with the notion that the meridional winds have a tendency to flow from the summer hemisphere (equatorward) to the winter hemisphere (poleward) due to the stronger heating in the summer hemisphere. Consequently, the mostly equatorward nighttime meridional winds driven by daily variation of pressure gradient are stronger in the summer and weaker in the winter. The stronger summer equatorward winds can lead to a strong forcing in the westward direction due to the Coriolis force. As a result, we have stronger westward zonal winds in the summer hemisphere. The seasonal wind differences in the zonal winds tend to be larger than those in the meridional winds. We should note that the daily variation of pressure gradient still is the dominant forcing for both the meridional and zonal winds. The TIEGCM simulations with and without SAPS show almost no differences under magnetically quiet conditions, because under such conditions, the SAPS in the model are very weak as they are specified using the Kp index. The TIEGCM simulations agree with observations remarkably well in most cases for quiet conditions.

Only during the June solstice, the northern (summer) hemisphere zonal winds at BDn and MHn have significant differences between the model and observations. The TIEGCM simulated winds tend to be more westward than the observations. The difference is larger at MHn (Figure 2) than at BDn (Figure 1). The difference at KLn is very small (Figure 1). That could be due to the magnetic latitude difference among the three stations (see Table 1). The TIEGCM versus observation discrepancy during the northern summer season has been noted by others (e.g., Jiang et al., 2018). It is interesting and new from this study that during the austral summer, the MJn data do not show the same zonal wind discrepancy against the model as its northern counterparts do (Figures 5 and 6), even though the magnetic latitude of MJn is similar to that
Figure 1. Observations and simulations for 13 May 2013, day of year (DOY) 133. The (top) meridional winds and (bottom) zonal winds from MJ, (maroon), BD, (pink), and KL, (dark blue) FPIs (symbols) and TIEGCM with SAPS (dashed lines) and without SAPS (dotted lines) for the respective stations in the same color coding. Data from some stations are not always available due to instrument and weather conditions. The data are plotted in local times of each station. The positive meridional winds are equatorward. Zonal winds are positive eastward. MJ data separated for viewing directions because the FPI used relatively low-elevation angle. The triangular symbols are for northward and eastward viewing directions (meridional) and the square for southward and westward (zonal). KL and MH data are averaged between the opposite viewing directions with triangular symbols, which are also used for all viewing directions for BD and PA data.

Figure 2. Same as Figure 1 but for the 16 June 2013 (DOY 167) case. MH (light blue) and PA (green) data are available during this day.
of BD\textsubscript{n}. The TIEGCM simulation and FPI observations at MJ\textsubscript{s} agree very well during the austral summer, and that is contrary to the northern stations of MH\textsubscript{n} and BD\textsubscript{n}. TIEGCM performs better in the southern hemisphere during December than in the northern hemisphere during June.

To examine the hemispheric difference in the model versus observation discrepancy, we plot the two nights from MH\textsubscript{n} and MJ\textsubscript{s} during each of the summer seasons for a comparison (Figure 12). The FPI data from MH\textsubscript{n} and MJ\textsubscript{s} show no consistent hemispheric differences, except for the case of 10 June, which was for a moderately disturbed condition. The geomagnetic condition may cause the stronger westward zonal winds. Nevertheless, the TIEGCM simulation at MH\textsubscript{n} seems to show a persistent difference (between 50 and 100 m/s more westward) from the MH\textsubscript{n} FPI observations. This is true for the 16 June case as well. The TIEGCM simulations are much closer to the observations at MJ\textsubscript{s}. This raises the question about the cause for the model versus observation discrepancy. We need to know if this occurs only in the northern hemisphere and June. In addition to the neutral wind data, we also plotted the ion drift data from the simulations. The ion drifts from the simulation are not inconsistent with the climatology from the Millstone incoherent scatter radar observations during the June solstice season (Buonsanto et al., 1993; Buonsanto & Witasse, 1999). Hence, ion drifts in the TIEGCM are not the primary source for the model and observation discrepancy in the zonal winds.

To see whether the June discrepancy also occurs in the southern hemisphere or not, we compare the MJ\textsubscript{s} data and model simulations (Figure 13). The data have relatively wider scattering due to large measurement errors. Overall the simulations do show a slightly westward bias. On occasion, the simulations can be more westward (e.g., 10 June). But the differences between model and data are mostly less than 50 m/s.

Figure 3. Same as Figure 1 but for the September equinox season (26 September 2013, DOY 269). PA\textsubscript{n}, MJ\textsubscript{s}, KL\textsubscript{n}, and some MH\textsubscript{n} data are available in this case.

Figure 4. Same as Figure 1 but for the 28 October 2013 (DOY 301) case. Data from MH\textsubscript{n}, KL\textsubscript{n}, and MJ\textsubscript{s} are available.
The next question is whether such discrepancy is unique for the June solstice. To answer this question, we selected a few cases in December at MHn for a similar comparison (Figure 14). The comparison at MHn is more complicated than that of MJs. The FPI data show much larger local time variations than the model does. The simulated zonal winds are more westward before 04 LT and more eastward after.

Overall, the simulations have a tendency to be more westward than the measurements in December and June in both hemispheres. However, during June in the northern hemisphere the differences are much larger and
seem to be persistent. The observed June solstice northern hemisphere zonal winds did not show any significant difference from their counterparts in the southern hemisphere December solstice. The TIEGCM produces zonal winds that are significantly more westward than the observations in June at MHn. The zonal winds have a seasonal variation (more westward in summer), which the TIEGCM captures. This indicates that the model probably has the correct thermospheric dynamics (pressure gradient). A key factor for calculating winds is ion drag, which is determined by ion drifts and the drag coefficient (proportional to the electron density). Given that the ion drifts in the model do not show any stronger westward tendency during the June solstice (Figure 12), they are unlikely to be the source of the stronger simulated westward winds. Hence, ionospheric electron density might be an issue during the solstices to cause large westward winds.

Taking advantage of the availability of the MHn incoherent scatter radar (ISR) data during June of 2013, we perform a comparison between the TIEGCM simulated ionospheric density and the MHn ISR observations (Figure 15). The data from ISR are from 21 UT 11 June to 01 UT 12 June, so they do not cover a whole day. The ISR observation is one day after the 10 June event discussed earlier. We notice that the ISR observed ionospheric densities are higher than those of the TIEGCM simulations at MHn. We also plot the TIEGCM simulated zonal neutral winds and ion drifts. The neutral winds are mostly westward, particularly during the daytime. The electron density comparison here is consistent with Lei et al.’s (2007) comparison between the MHn ISR and TIEGCM. They showed that in summer the TIEGCM electron density in the afternoon is

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only half of what is observed by the ISR. Consequently, the ion drag in the model is smaller. The dynamics of the thermosphere during the summer season gives an overall westward zonal wind. With less ion drag in the model, the modeled westward zonal winds are stronger. Hence, the source of the stronger simulated westward wind is likely to be the lower simulated electron densities. At the moment, we do not have daytime thermospheric wind observations to verify the simulation results, which is a big hurdle to be tackled in the future, perhaps, with the balloon-borne FPI instrument HIWIND (Wu et al., 2012).

Figure 7. The 12 April 2013 (DOY 102) case in the same format as Figure 1.

Figure 8. For the case of 10 June 2013 (DOY 161) in the same format as Figure 1.
Lei et al. (2007) also showed that the TIEGCM overestimates the electron density at MHn by a factor of 2 in the winter. Hence, we have the opposite situation during December at MHn for the model, when the simulated ion drag is overestimated leading to smaller thermospheric winds. In the winter, we have mostly eastward winds, and the underestimated eastward TIEGCM winds are consistent with the comparisons with December FPI observations at MHn shown in Figure 14.

These discrepancies do have a strong implication for the TIEGCM simulation of the seasonal variations of the ionosphere in the low and middle latitudes. While we suspect that the ionospheric density is the cause

Figure 9. For the case of 20 June 2013 (DOY 171) in the same format as Figure 1.

Figure 10. For the 28 August 2013 (DOY 240) case in the same format as Figure 1.
of the wind discrepancies, the wind discrepancies can also lead to ionospheric discrepancy in the model as the thermosphere and ionosphere are a nonlinearly coupled system. As to the source of the low simulated ionospheric density in June, it could be due to the plasmasphere and ionosphere interaction, which is not in the TIEGCM model. While we discuss the possible cause of the wind discrepancy from the underestimated electron density, we cannot totally rule out the discrepancy in the modeled pressure gradient as a cause. Since the winds are mostly consistent in all other seasons besides June solstice, we should expect that the solar UV heating, which produces the pressure gradient in the model, is most correct. That makes the pressure gradient an unlikely source. Given that we do not have observations of the pressure gradient, it is unknown at this point.

5.3. SAPS Effects Under Relatively Active Conditions ($Kp \geq 2$)

We have selected a few cases when the $Kp$ index is moderately higher (2–3). The TIEGCM simulations with the SAPS show a significant impact on the zonal winds even with this modest level of geomagnetic activity. Moreover, the simulated SAPS effect seems to linger even when the $Kp$ index drops to ~1 (Figure 7 at MJ$_n$). The observations, however, do not consistently show the same kind of effects in the zonal winds as those seen in the model simulations. In this case, the observations at BD$_n$ and MJ$_n$ are very similar. Even though they are in different longitudinal sectors, their magnetic latitudes are similar.

Large SAPS effects on the zonal winds (~200 m/s) are shown by the TIEGCM at MH$_n$ and BD$_n$ during northern summer (Figures 8 and 9); the observations do not show the same effects. It is possible that the predicted SAPS location is misplaced by the SAPS empirical model in the TIEGCM. When the SAPS are added during moderate geomagnetic conditions, the SAPS appeared at MH$_n$ and BD$_n$ stations overhead. That indicates that the auroral boundary in the TIEGCM is lower than the observations suggest. Given there is not much reaction to the SAPS effect in the observed zonal winds,
MHn and BDn stations are probably farther away from the real auroral boundary than the modeled auroral boundary.

Another possibility is that the TIEGCM SAPS empirical model applies more persistent and consistent westward ion drag to the neutrals. In reality, during moderate geomagnetic conditions, the SAPS may not be constant. Since the TIEGCM SAPS empirical model is driven by the $K_p$ index, any disturbance induced by SAPS will persist at least 3 hr in the model. The real SAPS are very dynamic and may not last that long. Consequently, the SAPS effects may be overestimated in the model. There is one case when the TIEGCM-simulated SAPS effects are consistent with the observations at MJn (Figure 11). During the December solstice, we already have a good agreement between the observations and simulations without SAPS to begin with. In this case, the interhemispheric differences are mostly due to time difference between the two stations, because they are at different longitudes. The TIEGCM model captures that longitudinal difference (time difference) very well and shows no SAPS effect at MHn.

5.4. Other Model/Observation Discrepancies

There are model versus observation discrepancies in the meridional as well. We focused most of our attention to the summer zonal wind discrepancy, which we believe that we have found the source for it. Other

**Figure 13.** MJn winter (June) zonal wind observations and model comparison. The $K_p$ index for 4 June (DOY 155), 1-2; 5 June (DOY 156), 0-1; 9 June (DOY 160), 2-3; 10 June (DOY 161), 2-3; 11 June (DOY 162), 2-3.

**Figure 14.** MHn winter (December) zonal wind observations and model comparison. The $K_p$ index for 2 January (DOY 002), 0-1; 3 January (DOY 003), 1-2; 8 January (DOY 008), 0-1; 11 December (DOY 345), 0-1; 12 December (DOY 346), 0-0.
discrepancies are not persistent. During the more active periods (Figures 6, 8, 9, and 11), there are more discrepancies, when the model performance degraded. There could be many reasons, we focused on the SAPS, which helped only in some cases. It shows the challenges we are facing to understand the midlatitude thermosphere and ionosphere.

6. Summary

By using midlatitude FPI observations from both hemispheres in combination with the TIEGCM simulations with and without the SAPS, we found the following:

1. A clear seasonal and hemispheric variation is shown by the observations and TIEGCM simulations in the midlatitude thermospheric wind: summer zonal (meridional) winds are more westward (equatorward). The seasonal changes in the zonal winds are larger than those in the meridional winds.
2. The TIEGCM-simulated zonal winds are persistently more westward in the northern midlatitudes during the June solstice than the measured winds.
3. There is no similar model/observation discrepancy in zonal winds of similar size in the December solstice in the southern hemisphere. Overall the TIEGCM has a tendency to give slightly more westward zonal winds than the measurements.
4. TIEGCM underestimates ionospheric densities compared to the Millstone Hill ISR observations during the June solstice, which leads to smaller ion drag and stronger modeled westward zonal winds.
5. The SAPS-enabled TIEGCM overestimates the SAPS effects in most cases, probably because the empirical SAPS model applies an unrealistically persistent electric field (over 3 hr) due to the low temporal resolution of the $Kp$ index.

Figure 15. Comparison of (top panel) Millstone Hill ISR observed ionospheric density and (middle panel) the TIEGCM simulation without SAPS. The density is in the unit of log10 m$^{-3}$. The dashed lines mark the $h_mf_2$. The zonal winds (solid line) and ion drifts (dashed line) from the TIEGCM simulation without SAPS are plotted in the bottom panel. The local noon and midnight are indicated by the vertical dashed lines in all panels. The dotted line in the bottom panel is the zero wind line. The date and UT hours for TIEGCM electron density (middle panel), neutral wind, and ion drift (bottom panel) are the same as the Millstone Hill ISR.
Because we have only one-year simultaneous multisatellite observations in the two hemispheres, there are many uncertainties related to the discussed topics in this study. It is unfortunate that the MJ FPI observations have ceased and we had only one year of data in recent years, while other stations are operational. We also do not have an ISR or ionosonde in New Zealand at the moment to do a comparison with the model simulations for the December solstice, so it is not possible to examine the consistency between the model and observation in the southern hemisphere. Given the many uncertainties related to the midlatitude thermosphere, the southern hemisphere observations are urgently needed. Continuous observations in the northern hemisphere are needed as well. Moreover, we also need daytime thermospheric winds to have a more complete view of midlatitude thermospheric dynamics.

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