Tidal control of equatorial vertical ExB drift under solar minimum conditions

Han-Li Liu[1] and Astrid Maute[2]

[1]National Center for Atmospheric Research, P. O. Box, 3000, Boulder, CO 80307-3000
[2]CIRES/ University of Colorado Boulder

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Abstract

Observations show that equatorial ionospheric vertical drifts during solar minimum differ from the climatology between late afternoon and midnight. By analyzing WACCM-X simulations, which reproduce this solar cycle dependence, we show that the interplay of the dominant migrating tides, their propagating and in-situ forced components, and their solar cycle dependence impact the F-region wind dynamo. In particular, the amplitude and phase of the propagating migrating semidiurnal tide (SW2) in the F-region plays a key role. Under solar minimum conditions, the SW2 tide propagate to and beyond the F-region in the winter hemisphere, and consequently its zonal wind amplitude in the F-region is much stronger than that under solar maximum conditions. Furthermore, its phase shift leads to a strong eastward wind perturbation near local midnight. This in turn drives a F-region dynamo with an equatorial upward drift between 18-1 hour local times.

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H.-L. Liu[1] and A. Maute[2]

[1]High Altitude Observatory, National Center for Atmospheric Research, Boulder, Colorado, USA
[2]CIRES, University of Colorado Boulder; NOAA Space Weather Prediction Center, Boulder, Colorado, USA

Key Points:

- Upward equatorial vertical ion drift near midnight under solar minimum conditions reproduced by WACCM-X
- Modulation of F-region dynamo by propagating semidiurnal tide is much stronger during solar minimum.
- Tidal phase change in equatorial F-region during solar minimum shifts upward drift toward midnight.

Corresponding author: Han-Li Liu, `liuh@ucar.edu`

Abstract

Observations show that equatorial ionospheric vertical drifts during solar minimum differ from the climatology between late afternoon and midnight. By analyzing WACCM-X simulations, which reproduce this solar cycle dependence, we show that the interplay of the dominant migrating tides, their propagating and in-situ forced components, and their solar cycle dependence impact the F-region wind dynamo. In particular, the amplitude and phase of the propagating migrating semidiurnal tide (SW2) in the F-region plays a key role. Under solar minimum conditions, the SW2 tide propagate to and beyond the F-region in the winter hemisphere, and consequently its zonal wind amplitude in the F-region is much stronger than that under solar maximum conditions. Furthermore, its phase shift leads to a strong eastward wind perturbation near local midnight. This in turn drives a F-region dynamo with an equatorial upward drift between 18-1 hour local times.

Plain Language Summary

The vertical ion motion in the equatorial ionosphere plays a key role in the space weather. Satellite observations found that such vertical motion during periods with low solar activity can be quite different from the known climatology, and the cause is not clear. Using a whole atmosphere general circulation model, WACCM-X, we are able to reproduce the pattern of the vertical ion motion similar to that observed during low activity solar cycle periods . By analyzing the model results, we find that the relative significance of the different atmosphere tidal wave components and its variation with solar activity contribute to the solar dependence of the vertical ion motion. The propagating altitudes of tide with 12-hour period, as well as where and when the tidal wind become large, are of particular importance.

1 Introduction

The ionospheric E×B drift is a key quantity in ionospheric electrodynamics. In particular, the vertical component of E×B drift at dusk and during night time can play a key role in the onset of F-region irregularities (Anderson et al., 2004; Fejer et al., 1999; Huang, 2018; Huang & Hairston, 2015; Kil et al., 2009). The vertical E×B drift climatology, based on radar and satellite measurements, shows a clear seasonal variation and solar activity dependence (Scherliess & Fejer, 1999). The most significant variability is found in the vertical drift around dusk: strong pre-reversal enhancement (PRE) of the vertical drift often occurs around equinox and under more active solar conditions. The E and F regions dynamo and the the alignment of the geomagnetic field lines and the evening terminator are thought to be responsible for the PRE and its seasonal and solar activity dependence (Farley et al., 1986; Tsunoda, 1985). Fesen et al. (2000) simulated PRE and its seasonal and solar activity dependence using the Thermosphere/Ionosphere/Electrodynamic General Circulation Model (TIEGCM), and found that the E-region migrating semi-diurnal tide (SW2) plays an important role. The seasonal and solar activity dependence of PRE is recently simulated by the Whole Atmosphere Community Climate Model with thermosphere/ionosphere extension (WACCM-X) (Liu et al., 2018). The analysis of WACCM-X simulation under solar maximum conditions found that the pattern of longitudinal-seasonal variation of PRE displays a remarkable similarity to the pattern of the equatorial plasma bubble (EPB) occurrence rate (Liu, 2020). Moreover, the simulated PRE shows large day-to-day variability, and it is strongly influenced by the variability of both migrating and non-migrating tides.

Vertical E×B drifts measured by the Coupled Ion Neutral Dynamics Investigation (CINDI) Ion Velocity Meter (IVM) instrument onboard the Communication/Navigation Outage Forecasting System (C/NOFS), on the other hand, have notable differences from the aforementioned climatology at solstices under solar minimum conditions (Stoneback et al., 2011): in contrast to the climatological behavior of upward drifts during the day and downward drifts at night (with weak or no of PRE in between), downward drifts in the afternoon and upward drifts near midnight are observed. The upward drifts at night correspond to regions with a high occurrence of post-midnight irregularities during the December 2008 and June 2009 solstices. The apparent semi-diurnal signal was postulated to be related to the semi-diurnal tides in the E-region. However, with semi-diurnal tides present at all seasons and under all solar conditions, it is unclear why this semi-diurnal signature only becomes apparent around solstice especially during Northern summer under solar minimum conditions.

In this study, we will investigate the possible mechanisms that cause upward drift near midnight, and the processes that controls the seasonal and solar cycle variation of the vertical E×B drifts using WACCM-X simulations, which reproduce salient features of the variation. Further, an ionospheric electric dynamo model is used to delineate the roles of E and F-region dynamo. A description of the models is given in Section 2. Analysis of model results is presented in Section 3, followed by Conclusions (Section 4).

2 Model Description

WACCM-X is one of the atmosphere components of the NCAR Community Earth System Model (CESM) (Hurrell et al., 2013) (also `http://www.cesm.ucar.edu/` for information on the most recent version, CESM version 2), with its top boundary set at the upper thermosphere. Detailed descriptions of the thermopheric and ionospheric physics used in the model can be found in Liu et al. (2010, 2018). The model configuration used in this study is the same as that described by Liu (2020), except that solar minimum condition is used here with the solar radio flux at 10.7 cm (F10.7 flux) set at 70 solar flux unit (sfu, 10^{-22} Wm^{-2} Hz^{-1}). It is a free running (FR) climate simulation over three model year.

The stand-alone ionospheric electrodynamo introduced by Maute and Richmond (2017) is employed. In the current study, we consider only forcing by the wind dynamo, which are provided by WACCM-X together with the ionospheric conductivities. Compared to the electrodynamo in WACCM-X, the stand-alone dynamo considers the flux tube geometry with the full 3D variation of apex quantities, however the effect on the electric potential solution is small and therefore the ExB drift from the stand-alone electrodynamo can be compared to the WACCM-X ExB drift.

3 Results

From WACCM-X simulations, it is seen that the equatorial vertical E×B drift ($(\mathrm{E}\times\mathrm{B})_z$, referred to as vertical drift hereafter) in June under solar minimum (referred to as Jmin hereafter) conditions display local time (LT)/longitudinal dependence that is different from those in June/solar maximum (Jmax) and December solar maximum (Dmax) and solar minimum (Dmin) (Figure 1). For the specific universal time shown here (UT 20 hour), the Jmin vertical drift becomes downward between LT 16–20 hours (with the largest downward drift of over 20 ms^{-1} between 18–19 hour LT/15–30°W), and upward between LT 20 and midnight (with peak value of 20 ms^{-1} at ∼22 hour LT/30°E) (Figure 1(a)). In contrast, the vertical drifts in all the other panels show the typical pre-reversal enhancement (PRE) at 20 hour LT or earlier, followed by a rapid reversal to downward afterward (before 23 hour LT). In the afternoon sector (14–16 hour LT/90–60°W) the equatorial vertical drift in Jmin is upward, switching quickly to downward afterwards. The afternoon equatorial vertical drifts in the other three cases, on the other hand, are weakly upward, straddling upward peaks before and after. Therefore, the equatorial vertical drift for Jmin displays a strong semidiurnal signature, with comparable peak values of ∼20 ms^{-1} at ∼10 and 22 hour LT (upward) and ∼1830 and 5 hour LT (downward). In the other cases, the upward peaks in the morning and around dusk (PRE) are both prominent, but the downward drift in the afternoon is either very weak or non-existing.

The model results, including the vertical drift, show large day-to-day variability (Liu, 2020), and the LT/UT and longitude dependence shown in Figures 1 may not be the same on different days. So we further examine the monthly climatology of the vertical drift under solar minimum conditions. Figure 2(a) is the monthly average of the vertical drift as a function of longitude and local time for June averaged over three model years. The semidiurnal structure is clearly seen in the plot at most longitudes, with local time dependence similar to that from Figure 1(a). Moreover, the longitudinal variation is evident in the monthly plot. The specific structure of the longitude variation agree with the C/NOFS results (June 2009) (Stoneback et al., 2011, Figure 7) in some longitude sectors, but not in others. The downward drift between LT 16–20 hour are rather strong between 30 and 130°E and 0-30°W and near 0 in the Pacific and American sectors (180–70°W). These are in general agreement with the C/NOFS results. It then turns upward at most longitudes except between 70–110°E (remaining downward) and 150–120°W (near 0 LT). By mid-night, the vertical drift becomes 0 or downward at most longitudes except between 30–65°E. This strong upward drift around mid-night is comparable to that in C/NOFS. The monthly average of the vertical drift at local mid-night is shown in Figure 2(b) for the whole simulation year under solar minimum conditions. It is seen that at midnight the average vertical drift is upward only during northern summer months (May–July) between 30–65°E. Three other local maxima are seen at 150°E, 150°W, and 65°W, with drift values of -3 ms^{-1}, 0 and 0, respectively. This four peak structure results from modulation of the dynamo by non-migrating tides diurnal eastward propagating wavenumber 3 (DE3), as determined from a spectral decomposition calculation. During northern winter, the monthly average of the vertical drift at midnight is weakly downward with longitudinal variation somewhat similar to that during northern summer. It is also noted that although on individual days the vertical drifts at midnight generally follow similar longitudinal patterns as the monthly averages, they can be upward at multiple longitude locations under solar minimum conditions for both June and December (Supporting Information, Figure S1).

The semidiurnal signature of the equatorial vertical drift during northern summer under solar minimum conditions has been identified by Stoneback et al. (2011) from C/NOFS observations. The simulation results discussed above for Jmin, including the local time variation with longitudes, compare quite well with the C/NOFS results. As suggested by Stoneback et al. (2011), this semidiurnal variation is probably related to semi-diurnal tides in the E-region. Since this feature is reproduced in WACCM-X simulations, we will examine the model results to understand the connection, especially regarding to the cause of the variation with season and solar activities.

We then examine the processes that are responsible for the differences between the vertical drifts under different solar conditions and at different season as seen above. Here we focus on the E to F-region dynamo, in particular the effects of the neutral winds. Specifically, electric field and E×B drifts are calculated using the standalone electrodynamo model with neutral winds and ionospheric conductivities input from WACCM-X, and UT 20 hour is chosen for detailed analysis. From Figure 3 it is seen that the vertical drifts (solid lines) are indeed the same as those from WACCM-X, with the equatorial upward drift for Jmin peaking at much later times than those in the Jmax and Dmin cases. In the control experiments, only neutral winds in one altitude region are used while winds at other altitudes are set to 0 in order to determine their respective contributions to the vertical drifts. Specifically, three altitude regions between 10^{-7} hPa, 1.2×10^{-6} hPa, 1.5×10^{-5} hPa and 8.5×10^{-5} hPa (approximately 250/175/125/105 km respectively for solar minimum, and 330/210/130/105 km respectively for solar maximum) are examined. These regions correspond to F-region, upper E-region where SW2 peaks in the winter hemisphere, and lower E-region where SW2 peaks in the summer hemisphere (Figure 4). It is noted that the drifts from these three regions do not add up to the total drift (solid lines in the figure), since contributions above 10^{-7} hPa or below 8.5×10^{-5} are not accounted for. This decomposition confirms that the dominant role of E-region dynamo during the day and F-region dynamo during the night. In all three cases, the vertical drifts by the lower E-region dynamo are qualitatively similar: they have an upward peak in the morning/noon sector, and become downward between ∼16 hour and midnight LT with the largest values between ∼18–20 hour LT. This variation is consistent with a previous analysis of WACCM-X drift results around dusk (Liu, 2020). Quantitatively, the largest change from the upward drift in the morning to the downward drift near dusk is found in Jmin. The upward drift in Jmin also peaks earlier (before 10 hour LT) than the other two cases.

The vertical drift by the F-region dynamo for Jmin, on the other hand, behaves differently from the other two cases: the upward drift peaks at ∼21:30 hour LT and remains upward till after local midnight, while in the other two cases the upward drifts peak at LT 19 hour, and become downward at 22-23 hour LT. Before dusk (LT 16-19 hour), the vertical drift from the F-region dynamo also shows difference between Jmin and the other two: it remains near zero in Jmin but is upward and becomes larger toward dusk in Jmax/Dmin. Since the downward drift peaks due to E-region dynamo are between 18–20 hour LT, the near zero vertical drift before dusk and upward drift peak at later local time in Jmin result in a prominent downward drift before 20 hour LT, followed by a large upward peak near 22 hour LT. In the other two cases, the peak downward and upward drifts occur at similar local times and thus offset each other. It is also seen that the upper E-region contributes to the dynamo similarly to the lower E-region before dusk and to the F-region after, though with smaller magnitudes. The total vertical drift in the Jmin case therefore shows an apparent semidiurnal feature, with two large upward peaks and two large downward peaks, similar to the observations as reported in Stoneback et al. (2011).

The seasonal variation and solar cycle dependence of the leading tidal modes, SW2 and DW1, are then examined. By comparing the zonal wind component of SW2 at F-region height (5.7×10^{-7} hPa) (Figure 4(a) and (b)), it is seen that SW2 attains maximum values (∼40 ms^{-1}) between June and August (JJA) under solar minimum conditions. The wave amplitude is the largest in the Southern Hemisphere (SH), but even in the Northern Hemisphere it is over 20 ms^{-1}. In contrast, the peak SW2 amplitude during JJA under solar maximum conditions is less than 20 ms^{-1}, and at equatorial latitudes the amplitude is less than 10 ms^{-1}. The SW2 phase (calculated at the equator) during JJA under solar minimum conditions approaches 12 hour LT, and the eastward wind perturbations are thus strongest approaching noon and midnight. The SW2 phase during JJA under solar maximum conditions, on the other hand, is between 6-7 hour and 18-19 hour LT–almost 180◦ out of phase with that under solar minimum condition. It would be at its strongest westward phase near midnight. It is noted that under solar minimum conditions the SW2 phase also approaches 12 hour LT during northern winter months, but the wave amplitude is weaker than during northern summer.

DW1 zonal wind component in the F-region also shows different seasonal features under different solar conditions (Figure 4(c) and (d)). Under solar minimum conditions, the DW1 wave amplitude (∼40 ms^{-1}) at equatorial latitudes is weak in comparison to mid-high latitudes in the summer hemisphere. This is the opposite under solar maximum conditions, when the DW1 amplitude is the largest at equatorial latitudes. The DW1 phase in the equatorial F-region is stable, with that under solar minimum conditions slightly later (22 hour LT) than that under solar maximum conditions (21 hour LT). Therefore, under solar minimum conditions the zonal wind perturbations of SW2 and DW1 are comparable at equatorial to mid-latitudes, and their superposition results in an enhanced eastward wind perturbation near local midnight in the F-region. This is directly responsible for driving the extended upward E×B drift seen in Figure 3(a) for Jmin. The SW2 tide does not significantly reinforce the eastward wind in the equatorial F-region in other season or under more active solar conditions, because its zonal wind perturbation is weaker and/or its phase is opposite (westward) near midnight.

To better understand the solar activity dependence of the tidal waves, the latitude/height structure of the amplitudes and phases of SW2 and DW1 for Jmin and Jmax are examined in Figure 4(e-h). It is clear that these tides transition from propagating modes to in-situ forced/trapped modes with increasing altitudes. For the Jmin SW2, it shows phase propagation above $\sim$330 km ($\sim 10^{-8}$ hPa) over the Southern (winter) hemisphere and northern equatorial latitudes, while Jmax SW2 phase stagnates at $\sim$300 km (2×10^{-7} hPa). Consequently, the SW2 amplitude at the F-region altitudes is much larger in the case of Jmin as seen in Figure 4. The phase progression of DW1 in Jmin also extends to higher altitudes ($\sim$250 km, 10^{-7} hPa) than Jmax ($\sim$220 km, 10^{-6} hPa), but the F-region wind is generally dominated by the in-situ forced DW1 winds, especially under solar maximum conditions and at equatorial latitudes and summer high latitudes (also seen in Figure 4). It is therefore evident that SW2 can significantly modulate the ~~the~~ F-region wind under solar minimum conditions, but not so much under solar maximum conditions. This is also clearly seen from the total zonal wind at the equator (Supporting Information Figure S2).

4 Conclusions

Our analysis suggests that the E-region wind dynamo have similar contributions under different solar cycle conditions, and the interplay of the dominant migrating tides, DW1 and SW2, determines the F-region wind dynamo and the solar cycle variation of the equatorial E$\times$B drift. Under solar minimum conditions, the SW2 tide propagate to and beyond the F-region in the winter hemisphere, and consequently its zonal wind amplitude in the F-region is much stronger than that under solar maximum conditions. The zonal wind DW1 in the F-region, on the other hand, comes mostly from in-situ forcing under both solar maximum and minimum conditions, but with much larger amplitude at low latitudes for the former. Consequently, the SW2 tidal modulation of the F-region wind is more significant under solar minimum conditions. Moreover, the SW2 zonal wind phase at F-region height also shows a solar cycle dependence: $\sim$12 hour LT during solar minimum and $\sim$6 hour LT during solar maximum. The superposition of DW1 and SW2 results in a strong eastward wind perturbation near local midnight, and a westward (or weakly eastward) wind around dusk in the F-region under solar minimum conditions. This in turn drives a F-region dynamo with an equatorial upward drift between 18 and 01 hour local time, reaching its maximum near 22 hour LT. In contrast, the F-region wind is dominated by DW1 during solar maximum (eastward between 16 and 4 hour LT), and the SW2 modulation is rather insignificant. This drives an equatorial upward drift within the local time range 07 to 23 hour LT, with peak values near 19 hour. The total equatorial vertical E$\times$B drift during solar minimum is downward in the local afternoon and dusk, followed by an upward drift that extends toward midnight. Therefore, the apparent semi-diurnal variation during solar minimum is not a direct manifestation of SW2 in the E-region: The upward peaks in the local morning and pre-midnight are driven mainly by the E-region wind and the F-region wind respectively, and the downward peaks near the dusk peak and post midnight/early morning are by E-region and F-region winds respectively.

Longitudinal variation is apparent in both observations (Stoneback et al., 2011) and modeling results presented here. The 4-peak structure as seen in Figure 2 suggests the modulation by non-migrating tides, which is known to cause longitudinal variation (e.g. Fang et al., 2013). Modulation by the geometry and strength of geomagnetic field is another cause of longitudinal variation (e.g. Fang et al., 2012). The detailed mechanism responsible for the longitudinal variation of the nighttime vertical drift, including the upward drift at midnight at specific longitude sectors, needs to be further elucidated in future studies. Moreover, there is an apparent difference between the equatorial upward drift at June and December solstices under solar minimum conditions, with the semidiurnal feature and the upward drift around midnight more pronounced in the former case. In the model, this difference stems from the different semi-diurnal tidal winds at the F-region height, with the winter hemisphere wave amplitude much stronger around June solstice. The cause of this hemispheric difference in SW2 in the thermosphere should be further examined in future studies.

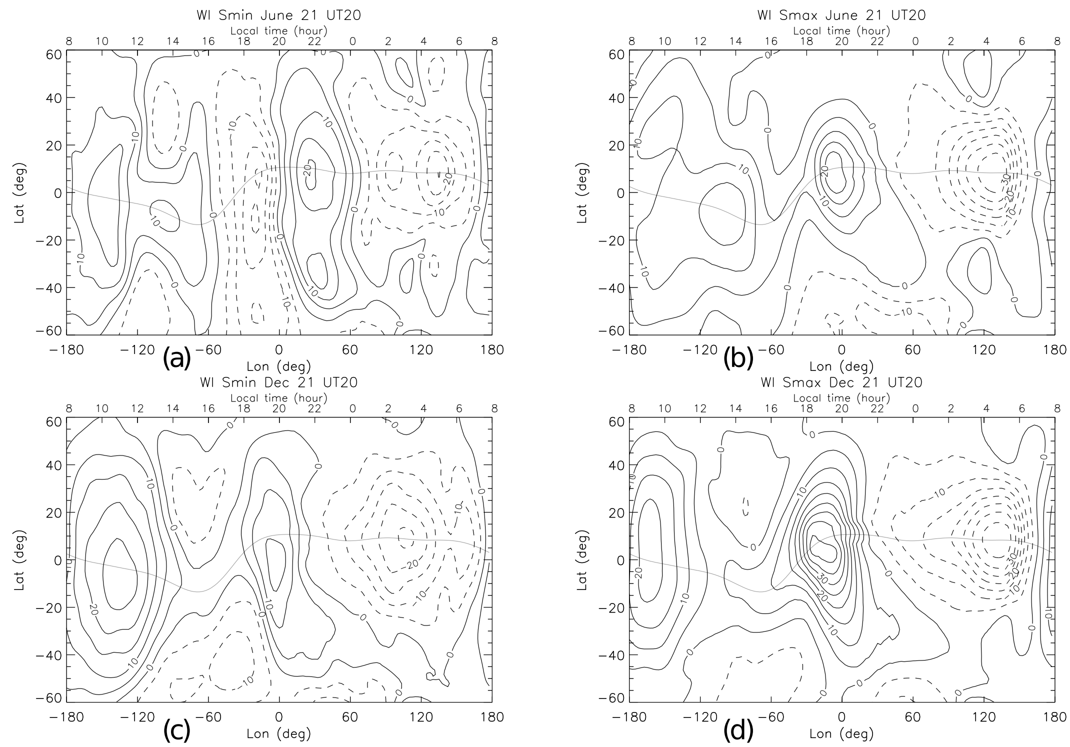

Figure 1: The vertical E×B drift (WI in figure) on June 21 (upper panel) and December 21 (lower panel) at 20 hour UT under solar minimum (left panel) and solar maximum (right panel) conditions. The local times are marked on the upper x axis. Contour interval: 5 ms^{-1} (solid: upward). Thin grey line: The magnetic equator.

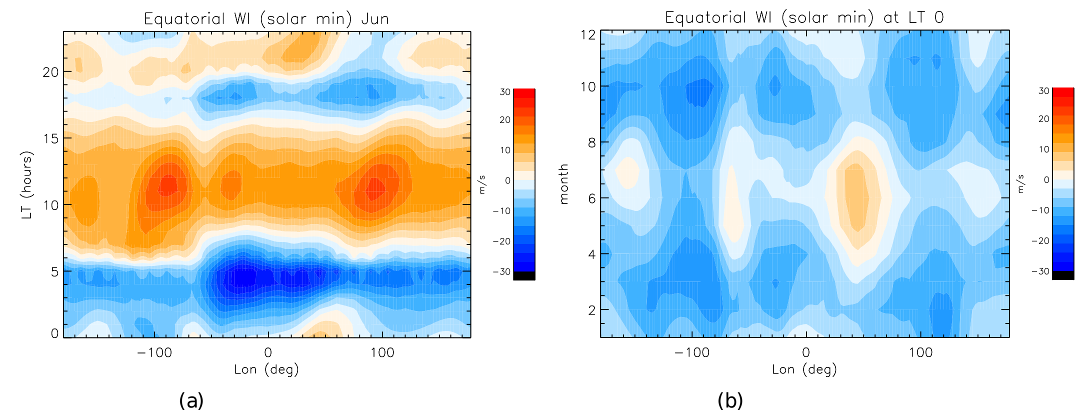

Figure 2: Monthly averaged vertical E×B drift (a) for June over all local times, and (b) for 0 hour local time over all year under solar minimum conditions.

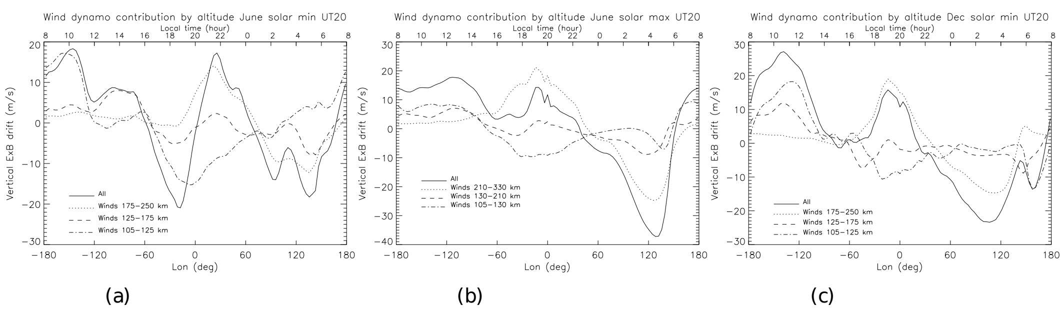

Figure 3: Contribution to total equatorial vertical E×B drift by different altitude regions for (a) June, solar minimum, (b) June, solar maximum and (c) December, solar minimum. 20 hour UT is shown, and the local times are marked by the upper x-axis.

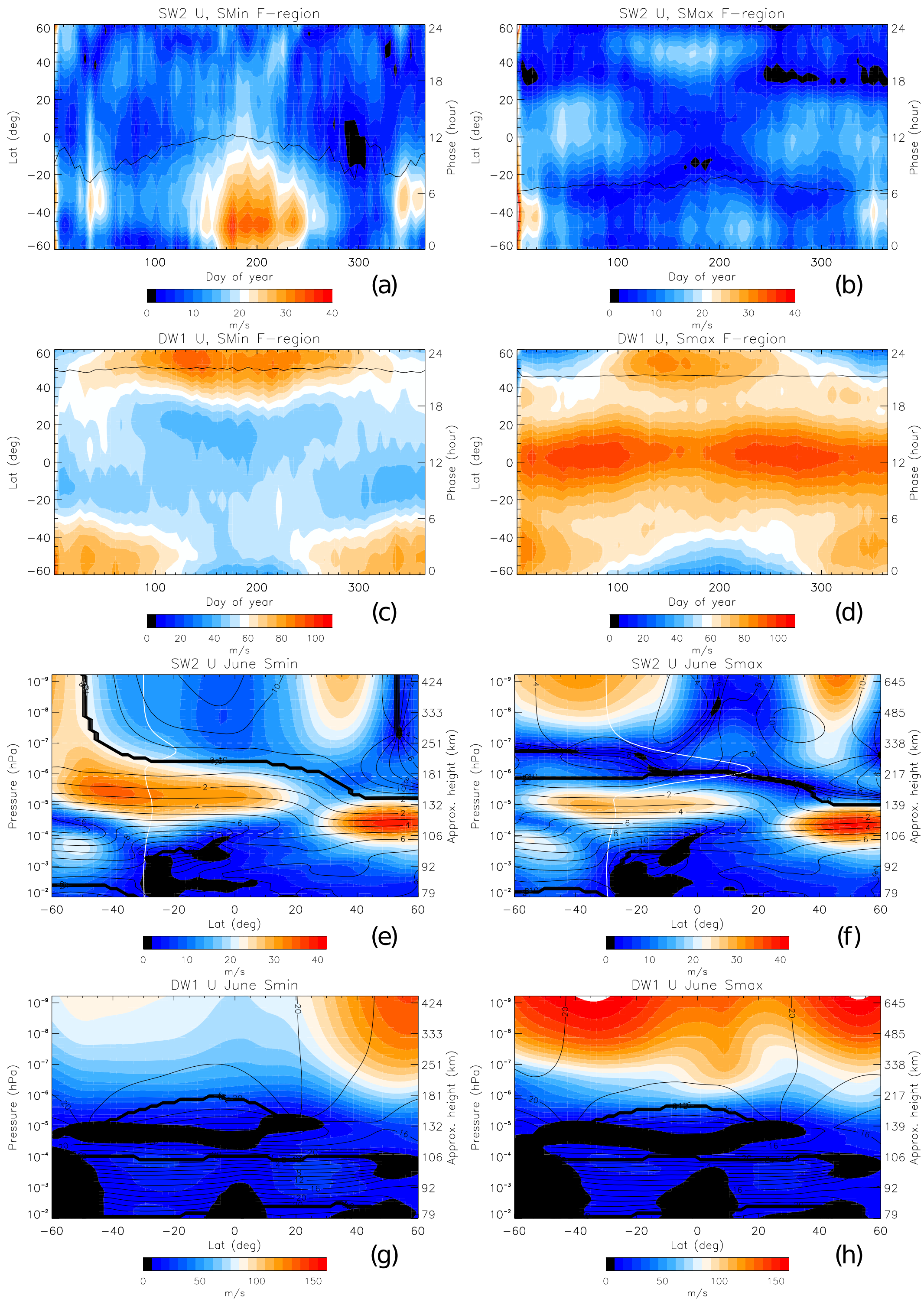

Figure 4: Seasonal variation of SW2 zonal wind amplitude (color contour) and phase (black line) in the F-region (5.7×10^{-7} hPa) for (a) solar minimum and (b) solar maximum. (c-d): Similar to (a-b) but for DW1. In (a-d) the phase values (marked by the y-axis on the right side) are in terms of local times for the respective tidal components at the equator. The latitude-height structure of the amplitude (color contour) and phase (line contour) of SW2 zonal wind for June under (e) solar minimum and (f) solar maximum conditions. (g-h): Similar to (e-f) but for DW1. The contour line interval is 1 hour in (e-f) and 2 hours in (g-h). The vertical profiles of Pedersen conductivity at 30°S are plotted in e (solar minimum) and f (solar maximum), with their zero values at 30°S and the conductivity values can be read from the x-axis (unit: 10^{-6} Sm^{-1}). The horizontal dashed lines are at 10^{-7} hPa, 1.2×10^{-6} hPa, 1.5×10^{-5} hPa and 8.5×10^{-5} hPa pressure levels.

Open Research

NCAR CESM/WACCM is an open-source community model, and is available at `https://doi.org/10.5065/D67H1H0V`. Model output used for this study is available through GLOBUS (shared end point: `https://tinyurl.com/mv2e6e2u`). Registration for a free Globus account is required to connect through the endpoint.

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Plain Language Summary

The vertical ion motion in the equatorial ionosphere plays a key role in the space weather. Satellite observations found that such vertical motion during periods with low solar activity can be quite different from the known climatology, and the cause is not clear. Using a whole atmosphere general circulation model, WACCM-X, we are able to reproduce the pattern of the vertical ion motion similar to that observed during low activity solar cycle periods . By analyzing the model results, we find that the relative significance of the different atmosphere tidal wave components and its variation with solar activity contribute to the solar dependence of the vertical ion motion. The propagating altitudes of tide with 12-hour period, as well as where and when the tidal wind become large, are of particular importance.

1 Introduction

The ionospheric E×B drift is a key quantity in ionospheric electrodynamics. In particular, the vertical component of E×B drift at dusk and during night time can play a key role in the onset of F-region irregularities (Anderson et al., 2004; Fejer et al., 1999; Huang, 2018; Huang & Hairston, 2015; Kil et al., 2009). The vertical E×B drift climatology, based on radar and satellite measurements, shows a clear seasonal variation and solar activity dependence (Scherliess & Fejer, 1999). The most significant variability is found in the vertical drift around dusk: strong pre-reversal enhancement (PRE) of the vertical drift often occurs around equinox and under more active solar conditions. The E and F regions dynamo and the the alignment of the geomagnetic field lines and the evening terminator are thought to be responsible for the PRE and its seasonal and solar activity dependence (Farley et al., 1986; Tsunoda, 1985). Fesen et al. (2000) simulated PRE and its seasonal and solar activity dependence using the Thermosphere/Ionosphere/Electrodynamic General Circulation Model (TIEGCM), and found that the E-region migrating semi-diurnal tide (SW2) plays an important role. The seasonal and solar activity dependence of PRE is recently simulated by the Whole Atmosphere Community Climate Model with thermosphere/ionosphere extension (WACCM-X) (Liu et al., 2018). The analysis of WACCM-X simulation under solar maximum conditions found that the pattern of longitudinal-seasonal variation of PRE displays a remarkable similarity to the pattern of the equatorial plasma bubble (EPB) occurrence rate (Liu, 2020). Moreover, the simulated PRE shows large day-to-day variability, and it is strongly influenced by the variability of both migrating and non-migrating tides.

Vertical E×B drifts measured by the Coupled Ion Neutral Dynamics Investigation (CINDI) Ion Velocity Meter (IVM) instrument onboard the Communication/Navigation Outage Forecasting System (C/NOFS), on the other hand, have notable differences from the aforementioned climatology at solstices under solar minimum conditions (Stoneback et al., 2011): in contrast to the climatological behavior of upward drifts during the day and downward drifts at night (with weak or no of PRE in between), downward drifts in the afternoon and upward drifts near midnight are observed. The upward drifts at night correspond to regions with a high occurrence of post-midnight irregularities during the December 2008 and June 2009 solstices. The apparent semi-diurnal signal was postulated to be related to the semi-diurnal tides in the E-region. However, with semi-diurnal tides present at all seasons and under all solar conditions, it is unclear why this semi-diurnal signature only becomes apparent around solstice especially during Northern summer under solar minimum conditions.

In this study, we will investigate the possible mechanisms that cause upward drift near midnight, and the processes that controls the seasonal and solar cycle variation of the vertical E×B drifts using WACCM-X simulations, which reproduce salient features of the variation. Further, an ionospheric electric dynamo model is used to delineate the roles of E and F-region dynamo. A description of the models is given in Section 2. Analysis of model results is presented in Section 3, followed by Conclusions (Section 4).

2 Model Description

WACCM-X is one of the atmosphere components of the NCAR Community Earth System Model (CESM) (Hurrell et al., 2013) (also `http://www.cesm.ucar.edu/` for information on the most recent version, CESM version 2), with its top boundary set at the upper thermosphere. Detailed descriptions of the thermopheric and ionospheric physics used in the model can be found in Liu et al. (2010, 2018). The model configuration used in this study is the same as that described by Liu (2020), except that solar minimum condition is used here with the solar radio flux at 10.7 cm (F10.7 flux) set at 70 solar flux unit (sfu, 10^{-22} Wm^{-2} Hz^{-1}). It is a free running (FR) climate simulation over three model year.

The stand-alone ionospheric electrodynamo introduced by Maute and Richmond (2017) is employed. In the current study, we consider only forcing by the wind dynamo, which are provided by WACCM-X together with the ionospheric conductivities. Compared to the electrodynamo in WACCM-X, the stand-alone dynamo considers the flux tube geometry with the full 3D variation of apex quantities, however the effect on the electric potential solution is small and therefore the ExB drift from the stand-alone electrodynamo can be compared to the WACCM-X ExB drift.

3 Results

From WACCM-X simulations, it is seen that the equatorial vertical E×B drift ($(\mathrm{E}\times\mathrm{B})_z$, referred to as vertical drift hereafter) in June under solar minimum (referred to as Jmin hereafter) conditions display local time (LT)/longitudinal dependence that is different from those in June/solar maximum (Jmax) and December solar maximum (Dmax) and solar minimum (Dmin) (Figure 1). For the specific universal time shown here (UT 20 hour), the Jmin vertical drift becomes downward between LT 16–20 hours (with the largest downward drift of over 20 ms^{-1} between 18–19 hour LT/15–30°W), and upward between LT 20 and midnight (with peak value of 20 ms^{-1} at ∼22 hour LT/30°E) (Figure 1(a)). In contrast, the vertical drifts in all the other panels show the typical pre-reversal enhancement (PRE) at 20 hour LT or earlier, followed by a rapid reversal to downward afterward (before 23 hour LT). In the afternoon sector (14–16 hour LT/90–60°W) the equatorial vertical drift in Jmin is upward, switching quickly to downward afterwards. The afternoon equatorial vertical drifts in the other three cases, on the other hand, are weakly upward, straddling upward peaks before and after. Therefore, the equatorial vertical drift for Jmin displays a strong semidiurnal signature, with comparable peak values of ∼20 ms^{-1} at ∼10 and 22 hour LT (upward) and ∼1830 and 5 hour LT (downward). In the other cases, the upward peaks in the morning and around dusk (PRE) are both prominent, but the downward drift in the afternoon is either very weak or non-existing.

The model results, including the vertical drift, show large day-to-day variability (Liu, 2020), and the LT/UT and longitude dependence shown in Figures 1 may not be the same on different days. So we further examine the monthly climatology of the vertical drift under solar minimum conditions. Figure 2(a) is the monthly average of the vertical drift as a function of longitude and local time for June averaged over three model years. The semidiurnal structure is clearly seen in the plot at most longitudes, with local time dependence similar to that from Figure 1(a). Moreover, the longitudinal variation is evident in the monthly plot. The specific structure of the longitude variation agree with the C/NOFS results (June 2009) (Stoneback et al., 2011, Figure 7) in some longitude sectors, but not in others. The downward drift between LT 16–20 hour are rather strong between 30 and 130°E and 0-30°W and near 0 in the Pacific and American sectors (180–70°W). These are in general agreement with the C/NOFS results. It then turns upward at most longitudes except between 70–110°E (remaining downward) and 150–120°W (near 0 LT). By mid-night, the vertical drift becomes 0 or downward at most longitudes except between 30–65°E. This strong upward drift around mid-night is comparable to that in C/NOFS. The monthly average of the vertical drift at local mid-night is shown in Figure 2(b) for the whole simulation year under solar minimum conditions. It is seen that at midnight the average vertical drift is upward only during northern summer months (May–July) between 30–65°E. Three other local maxima are seen at 150°E, 150°W, and 65°W, with drift values of -3 ms^{-1}, 0 and 0, respectively. This four peak structure results from modulation of the dynamo by non-migrating tides diurnal eastward propagating wavenumber 3 (DE3), as determined from a spectral decomposition calculation. During northern winter, the monthly average of the vertical drift at midnight is weakly downward with longitudinal variation somewhat similar to that during northern summer. It is also noted that although on individual days the vertical drifts at midnight generally follow similar longitudinal patterns as the monthly averages, they can be upward at multiple longitude locations under solar minimum conditions for both June and December (Supporting Information, Figure S1).

The semidiurnal signature of the equatorial vertical drift during northern summer under solar minimum conditions has been identified by Stoneback et al. (2011) from C/NOFS observations. The simulation results discussed above for Jmin, including the local time variation with longitudes, compare quite well with the C/NOFS results. As suggested by Stoneback et al. (2011), this semidiurnal variation is probably related to semi-diurnal tides in the E-region. Since this feature is reproduced in WACCM-X simulations, we will examine the model results to understand the connection, especially regarding to the cause of the variation with season and solar activities.

We then examine the processes that are responsible for the differences between the vertical drifts under different solar conditions and at different season as seen above. Here we focus on the E to F-region dynamo, in particular the effects of the neutral winds. Specifically, electric field and E×B drifts are calculated using the standalone electrodynamo model with neutral winds and ionospheric conductivities input from WACCM-X, and UT 20 hour is chosen for detailed analysis. From Figure 3 it is seen that the vertical drifts (solid lines) are indeed the same as those from WACCM-X, with the equatorial upward drift for Jmin peaking at much later times than those in the Jmax and Dmin cases. In the control experiments, only neutral winds in one altitude region are used while winds at other altitudes are set to 0 in order to determine their respective contributions to the vertical drifts. Specifically, three altitude regions between 10^{-7} hPa, 1.2×10^{-6} hPa, 1.5×10^{-5} hPa and 8.5×10^{-5} hPa (approximately 250/175/125/105 km respectively for solar minimum, and 330/210/130/105 km respectively for solar maximum) are examined. These regions correspond to F-region, upper E-region where SW2 peaks in the winter hemisphere, and lower E-region where SW2 peaks in the summer hemisphere (Figure 4). It is noted that the drifts from these three regions do not add up to the total drift (solid lines in the figure), since contributions above 10^{-7} hPa or below 8.5×10^{-5} are not accounted for. This decomposition confirms that the dominant role of E-region dynamo during the day and F-region dynamo during the night. In all three cases, the vertical drifts by the lower E-region dynamo are qualitatively similar: they have an upward peak in the morning/noon sector, and become downward between ∼16 hour and midnight LT with the largest values between ∼18–20 hour LT. This variation is consistent with a previous analysis of WACCM-X drift results around dusk (Liu, 2020). Quantitatively, the largest change from the upward drift in the morning to the downward drift near dusk is found in Jmin. The upward drift in Jmin also peaks earlier (before 10 hour LT) than the other two cases.

The vertical drift by the F-region dynamo for Jmin, on the other hand, behaves differently from the other two cases: the upward drift peaks at ∼21:30 hour LT and remains upward till after local midnight, while in the other two cases the upward drifts peak at LT 19 hour, and become downward at 22-23 hour LT. Before dusk (LT 16-19 hour), the vertical drift from the F-region dynamo also shows difference between Jmin and the other two: it remains near zero in Jmin but is upward and becomes larger toward dusk in Jmax/Dmin. Since the downward drift peaks due to E-region dynamo are between 18–20 hour LT, the near zero vertical drift before dusk and upward drift peak at later local time in Jmin result in a prominent downward drift before 20 hour LT, followed by a large upward peak near 22 hour LT. In the other two cases, the peak downward and upward drifts occur at similar local times and thus offset each other. It is also seen that the upper E-region contributes to the dynamo similarly to the lower E-region before dusk and to the F-region after, though with smaller magnitudes. The total vertical drift in the Jmin case therefore shows an apparent semidiurnal feature, with two large upward peaks and two large downward peaks, similar to the observations as reported in Stoneback et al. (2011).

The seasonal variation and solar cycle dependence of the leading tidal modes, SW2 and DW1, are then examined. By comparing the zonal wind component of SW2 at F-region height (5.7×10^{-7} hPa) (Figure 4(a) and (b)), it is seen that SW2 attains maximum values (∼40 ms^{-1}) between June and August (JJA) under solar minimum conditions. The wave amplitude is the largest in the Southern Hemisphere (SH), but even in the Northern Hemisphere it is over 20 ms^{-1}. In contrast, the peak SW2 amplitude during JJA under solar maximum conditions is less than 20 ms^{-1}, and at equatorial latitudes the amplitude is less than 10 ms^{-1}. The SW2 phase (calculated at the equator) during JJA under solar minimum conditions approaches 12 hour LT, and the eastward wind perturbations are thus strongest approaching noon and midnight. The SW2 phase during JJA under solar maximum conditions, on the other hand, is between 6-7 hour and 18-19 hour LT–almost 180$\circ$ out of phase with that under solar minimum condition. It would be at its strongest westward phase near midnight. It is noted that under solar minimum conditions the SW2 phase also approaches 12 hour LT during northern winter months, but the wave amplitude is weaker than during northern summer.

DW1 zonal wind component in the F-region also shows different seasonal features under different solar conditions (Figure 4(c) and (d)). Under solar minimum conditions, the DW1 wave amplitude (∼40 ms^{-1}) at equatorial latitudes is weak in comparison to mid-high latitudes in the summer hemisphere. This is the opposite under solar maximum conditions, when the DW1 amplitude is the largest at equatorial latitudes. The DW1 phase in the equatorial F-region is stable, with that under solar minimum conditions slightly later (22 hour LT) than that under solar maximum conditions (21 hour LT). Therefore, under solar minimum conditions the zonal wind perturbations of SW2 and DW1 are comparable at equatorial to mid-latitudes, and their superposition results in an enhanced eastward wind perturbation near local midnight in the F-region. This is directly responsible for driving the extended upward E×B drift seen in Figure 3(a) for Jmin. The SW2 tide does not significantly reinforce the eastward wind in the equatorial F-region in other season or under more active solar conditions, because its zonal wind perturbation is weaker and/or its phase is opposite (westward) near midnight.

To better understand the solar activity dependence of the tidal waves, the latitude/height structure of the amplitudes and phases of SW2 and DW1 for Jmin and Jmax are examined in Figure 4(e-h). It is clear that these tides transition from propagating modes to in-situ forced/trapped modes with increasing altitudes. For the Jmin SW2, it shows phase propagation above ~330 km (~10^{-8} hPa) over the Southern (winter) hemisphere and northern equatorial latitudes, while Jmax SW2 phase stagnates at ~300 km (2×10^{-7} hPa). Consequently, the SW2 amplitude at the F-region altitudes is much larger in the case of Jmin as seen in Figure 4. The phase progression of DW1 in Jmin also extends to higher altitudes (~250 km, 10^{-7} hPa) than Jmax (~220 km, 10^{-6} hPa), but the F-region wind is generally dominated by the in-situ forced DW1 winds, especially under solar maximum conditions and at equatorial latitudes and summer high latitudes (also seen in Figure 4). It is therefore evident that SW2 can significantly modulate the ~~the~~ F-region wind under solar minimum conditions, but not so much under solar maximum conditions. This is also clearly seen from the total zonal wind at the equator (Supporting Information Figure S2).

4 Conclusions

Our analysis suggests that the E-region wind dynamo have similar contributions under different solar cycle conditions, and the interplay of the dominant migrating tides, DW1 and SW2, determines the F-region wind dynamo and the solar cycle variation of the equatorial E×B drift. Under solar minimum conditions, the SW2 tide propagate to and beyond the F-region in the winter hemisphere, and consequently its zonal wind amplitude in the F-region is much stronger than that under solar maximum conditions. The zonal wind DW1 in the F-region, on the other hand, comes mostly from in-situ forcing under both solar maximum and minimum conditions, but with much larger amplitude at low latitudes for the former. Consequently, the SW2 tidal modulation of the F-region wind is more significant under solar minimum conditions. Moreover, the SW2 zonal wind phase at F-region height also shows a solar cycle dependence: ~12 hour LT during solar minimum and ~6 hour LT during solar maximum. The superposition of DW1 and SW2 results in a strong eastward wind perturbation near local midnight, and a westward (or weakly eastward) wind around dusk in the F-region under solar minimum conditions. This in turn drives a F-region dynamo with an equatorial upward drift between 18 and 01 hour local time, reaching its maximum near 22 hour LT. In contrast, the F-region wind is dominated by DW1 during solar maximum (eastward between 16 and 4 hour LT), and the SW2 modulation is rather insignificant. This drives an equatorial upward drift within the local time range 07 to 23 hour LT, with peak values near 19 hour. The total equatorial vertical E×B drift during solar minimum is downward in the local afternoon and dusk, followed by an upward drift that extends toward midnight. Therefore, the apparent semi-diurnal variation during solar minimum is not a direct manifestation of SW2 in the E-region: The upward peaks in the local morning and pre-midnight are driven mainly by the E-region wind and the F-region wind respectively, and the downward peaks near the dusk peak and post midnight/early morning are by E-region and F-region winds respectively.

Longitudinal variation is apparent in both observations (Stoneback et al., 2011) and modeling results presented here. The 4-peak structure as seen in Figure 2 suggests the modulation by non-migrating tides, which is known to cause longitudinal variation (e.g. Fang et al., 2013). Modulation by the geometry and strength of geomagnetic field is another cause of longitudinal variation (e.g. Fang et al., 2012). The detailed mechanism responsible for the longitudinal variation of the nighttime vertical drift, including the upward drift at midnight at specific longitude sectors, needs to be further elucidated in future studies. Moreover, there is an apparent difference between the equatorial upward drift at June and December solstices under solar minimum conditions, with the semidiurnal feature and the upward drift around midnight more pronounced in the former case. In the model, this difference stems from the different semi-diurnal tidal winds at the F-region height, with the winter hemisphere wave amplitude much stronger around June solstice. The cause of this hemispheric difference in SW2 in the thermosphere should be further examined in future studies.

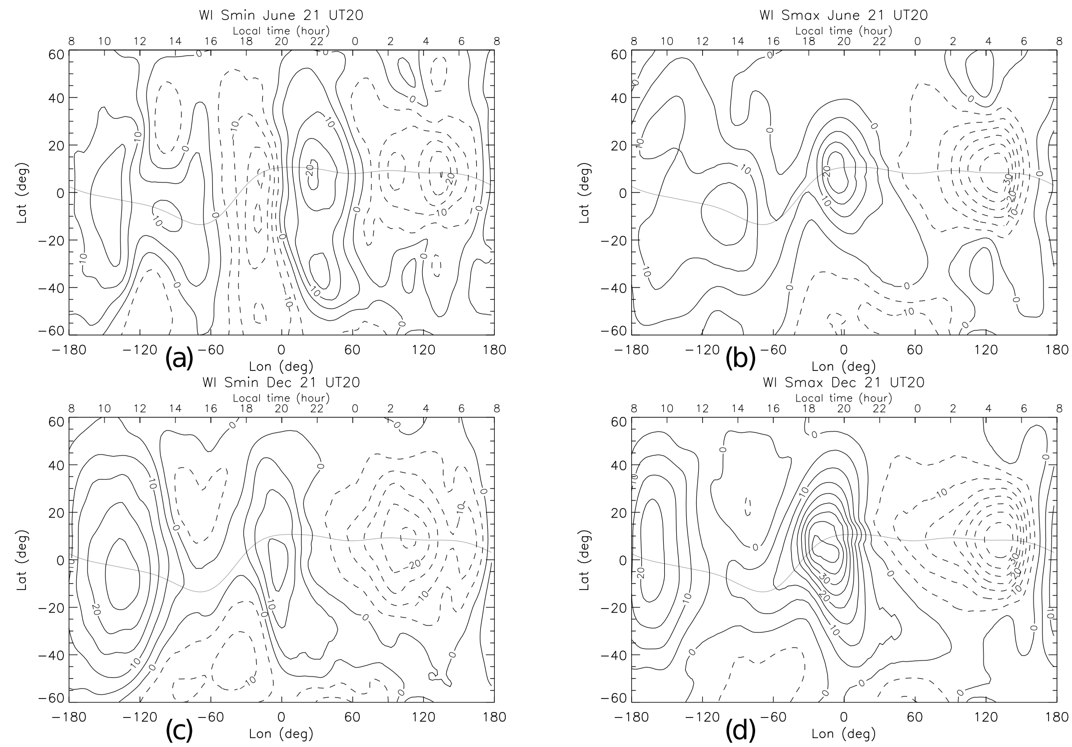

Figure 1: The vertical E×B drift (WI in figure) on June 21 (upper panel) and December 21 (lower panel) at 20 hour UT under solar minimum (left panel) and solar maximum (right panel) conditions. The local times are marked on the upper x axis. Contour interval: 5 ms^{-1} (solid: upward). Thin grey line: The magnetic equator.

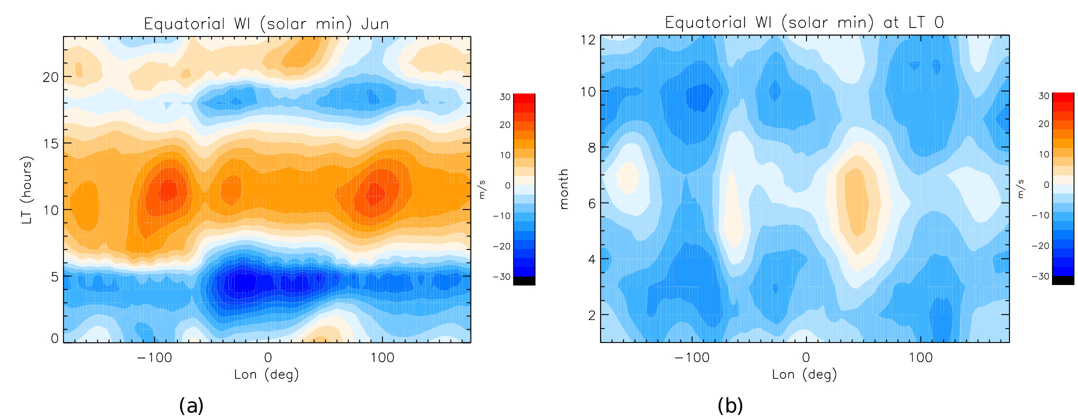

Figure 2: Monthly averaged vertical E×B drift (a) for June over all local times, and (b) for 0 hour local time over all year under solar minimum conditions.

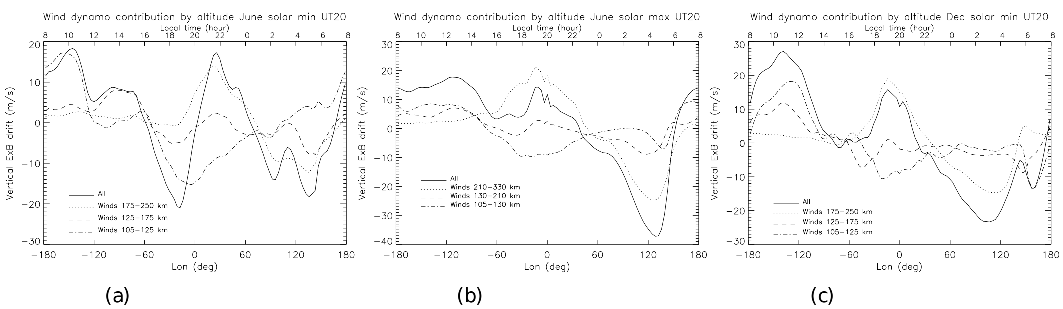

Figure 3: Contribution to total equatorial vertical E×B drift by different altitude regions for (a) June, solar minimum, (b) June, solar maximum and (c) December, solar minimum. 20 hour UT is shown, and the local times are marked by the upper x-axis.

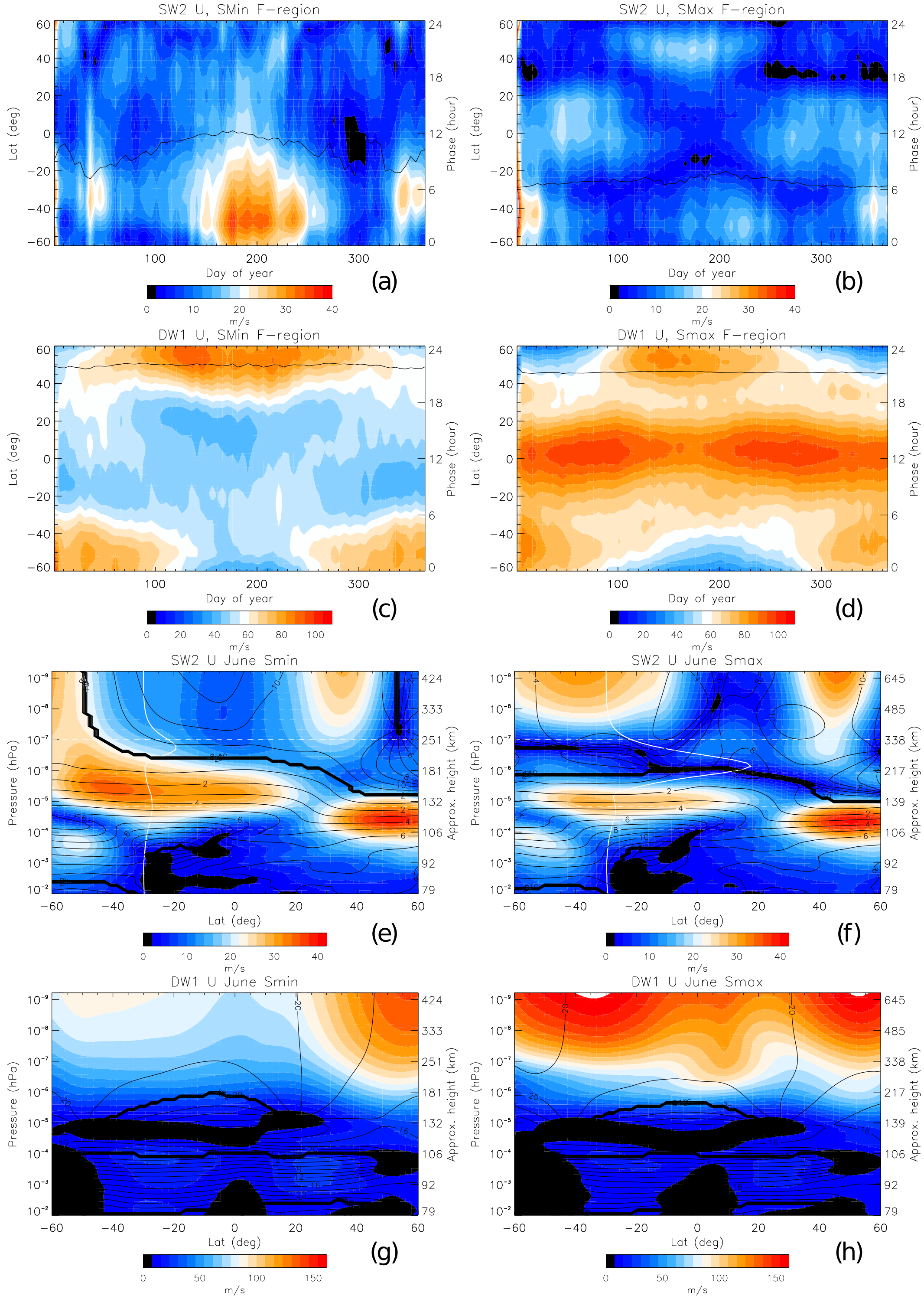

Figure 4: Seasonal variation of SW2 zonal wind amplitude (color contour) and phase (black line) in the F-region (5.7×10^{-7} hPa) for (a) solar minimum and (b) solar maximum. (c-d): Similar to (a-b) but for DW1. In (a-d) the phase values (marked by the y-axis on the right side) are in terms of local times for the respective tidal components at the equator. The latitude-height structure of the amplitude (color contour) and phase (line contour) of SW2 zonal wind for June under (e) solar minimum and (f) solar maximum conditions. (g-h): Similar to (e-f) but for DW1. The contour line interval is 1 hour in (e-f) and 2 hours in (g-h). The vertical profiles of Pedersen conductivity at 30°S are plotted in e (solar minimum) and f (solar maximum), with their zero values at 30°S and the conductivity values can be read from the x-axis (unit: 10^{-6} $\mathrm{Sm^{-1}}$). The horizontal dashed lines are at 10^{-7} hPa, 1.2×10^{-6} hPa, 1.5×10^{-5} hPa and 8.5×10^{-5} hPa pressure levels.

Open Research

NCAR CESM/WACCM is an open-source community model, and is available at `https://doi.org/10.5065/D67H1H0V`. Model output used for this study is available through GLOBUS (shared end point: `https://tinyurl.com/mv2e6e2u`). Registration for a free Globus account is required to connect through the endpoint.

Acknowledgments

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Supporting Information for "Tidal control of equatorial vertical E×B drift under solar minimum conditions"

H.-L. Liu,[1*] and A. Maute,[2]
Email: liuh@ucar.edu

1. High Altitude Observatory, National Center for Atmospheric Research, Boulder, CO, USA,

2. NOAA SWPC, Boulder, CO, USA.
(*) Corresponding author

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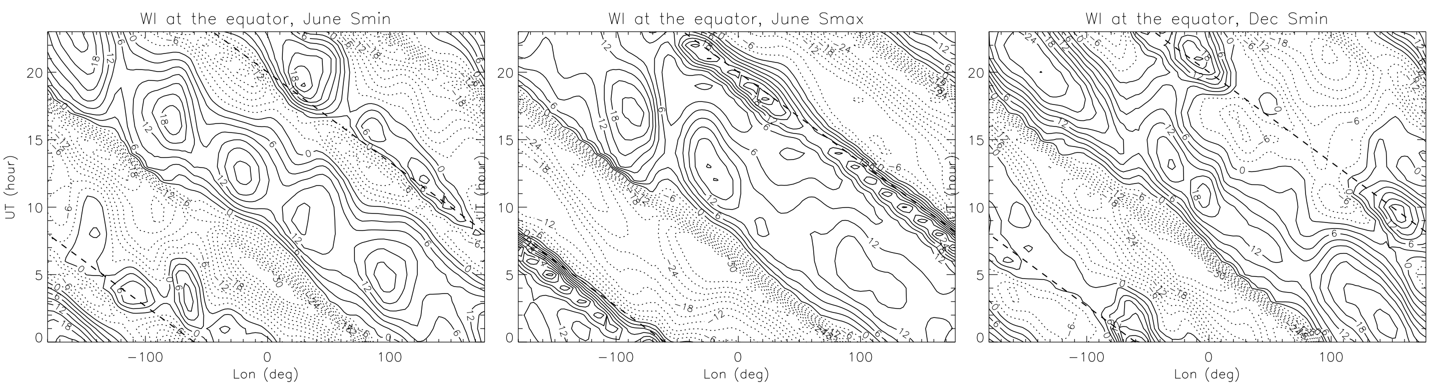
1. Figure S1

2. Figure S2

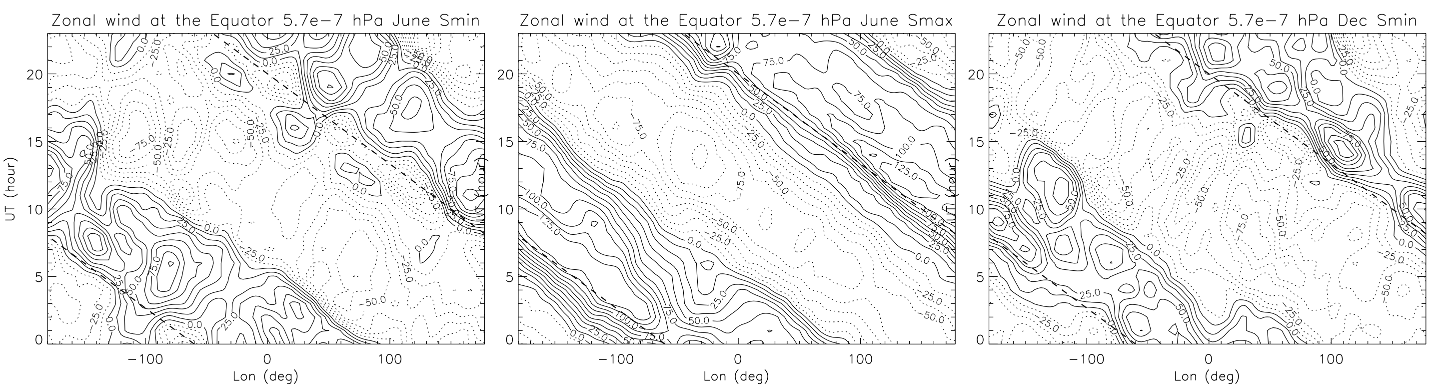
Introduction This Supporting Information includes two figures (Figure S1 and Figure S2).

Figure S1. WACCM-X vertical E×B drift at the equator over one day in (a) June under solar minium conditions, (b) June under solar maximum conditions, and (c) December under solar minimum conditions. Contour interval: 3 ms^{-1} (solid: upward). **Figure S2.** WACCM-X zonal wind at the equator in the F-region over one day in (a) June under solar minium conditions, (b) June under solar maximum conditions, and (c) December under solar minimum conditions. Contour interval: 12.5 ms^{-1} (solid: eastward).



(a) (b) (c)

Figure S1: WACCM-X vertical E×B drift at the equator over one day in (a) June under solar minium conditions, (b) June under solar maximum conditions, and (c) December under solar minimum conditions. Contour interval: 3 ms^{-1} (solid: upward).



(a) (b) (c)

Figure S2: WACCM-X zonal wind at the equator in the F-region over one day in (a) June under solar minium conditions, (b) June under solar maximum conditions, and (c) December under solar minimum conditions. Contour interval: 12.5 ms^{-1} (solid: eastward).