Effect of Ion Drag on Thermospheric Neutral Dynamics During Wintertime in Southern Polar Cap

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Abstract

It is well known that the thermospheric neutral dynamics is mostly governed by neutral pressure gradient and ion drag forces. Unlike the neutral pressure gradient force, the ion drag force generally plays a different role depending on the geomagnetic latitudes. To the thermospheric constituents, the ionospheric plasma act as a load in the low and middle latitudes, whereas they can drive the motion of neutrals in the polar region as a drag force, resulting in sunward or anti-sunward motion in the auroral oval or polar cap region, respectively, in association with plasma convection which is induced by magnetospheric electric field. To investigate the effects of the ion drag force on the thermospheric neutral winds during wintertime, we analyzed the ion drift and thermospheric wind data obtained from the simultaneous thermospheric and ionospheric observations at Jang Bogo station (JBS), Antarctica. We found that the neutral winds are observed to be larger at around the MLT midnight than the MLT noon and it can probably be explained by the fact that the neutrals have been forced by ions longer at midnight than at noon. It is also found that the neutral winds more sensitively respond to the ion flows on the MLT dusk sector than on the MLT dawn sector, and the electron density measurement suggests that high ion density on the MLT dusk sector is responsible for this.

Purpose of this study

Figure 1. Location of JBS. Credit: Ministry of Oceans and Fisheries, Korea

- The geographic coordinates of JBS are 74.6 °S and 164.2 °E, and their corresponding AACGM coordinates are 79.9 °S and 53.6 °W on the ground, which corresponds to the southern polar cap.
- Since 2017, Korea Polar Research Institute (KOPRI) has performed simultaneous ionospheric and thermospheric observations at JBS.
- Considering relatively few ground-based observations in the southern polar cap, simultaneous ionospheric and thermospheric observations at JBS may contribute to improve our understanding of the ionosphere-thermosphere couplings in the southern polar cap.
- Using the simultaneous observation data, we studied polar cap ion-neutral couplings in a viewpoint of momentum transfer from ionosphere to thermosphere.

Data and methodology

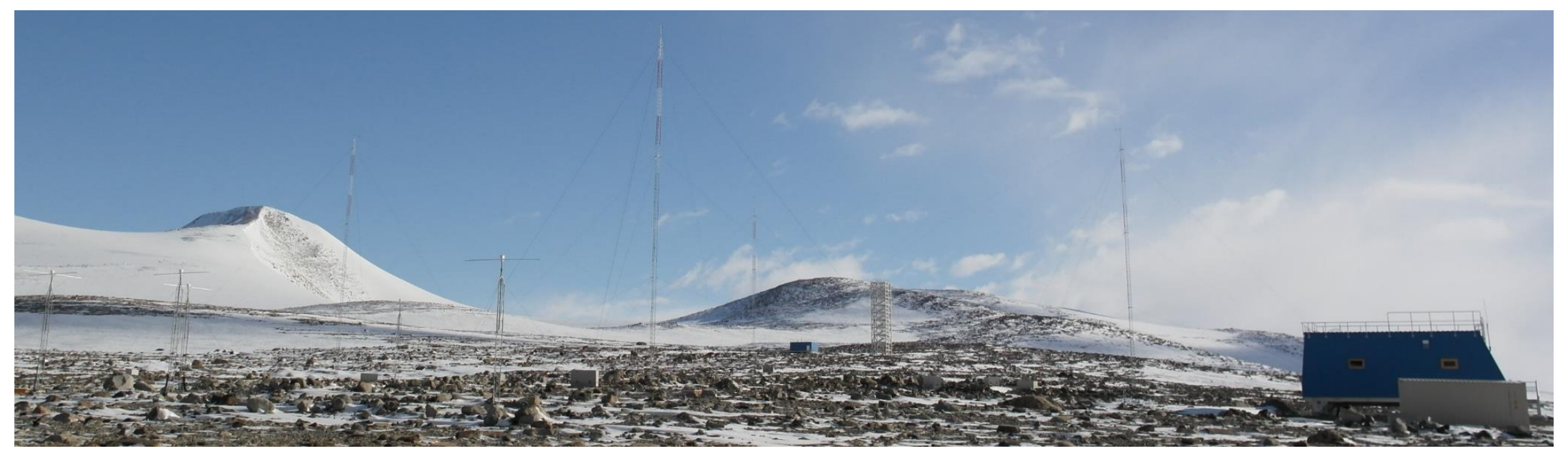

Figure 2. JBS - Vertical Incidence Pulsed Ionospheric radar – Dynasonde (JVD)

Fig 3. Fabry-Perot Interferometer (FPI)

- Two-year (2017-2018) data of JVD ion drifts and FPI neutral winds at 250 km were used.
- Since 24-hour FPI observation is only available during wintertime when the night is the longest, analysis was performed only for wintertime.

Sorting data by IMF conditions

- Because the plasma convection patterns dramatically change with the Interplanetary Magnetic field (IMF) condition, we performed data sorting by the IMF, and OMNI High Resolution (HRO) solar wind magnetic field data at Earth's Bow Shock Nose (BSN) were used.
- OMNI HRO at BSN data were time-shifted to the Cusp Ionosphere (CI) by considering the transit time from the BS to CI.

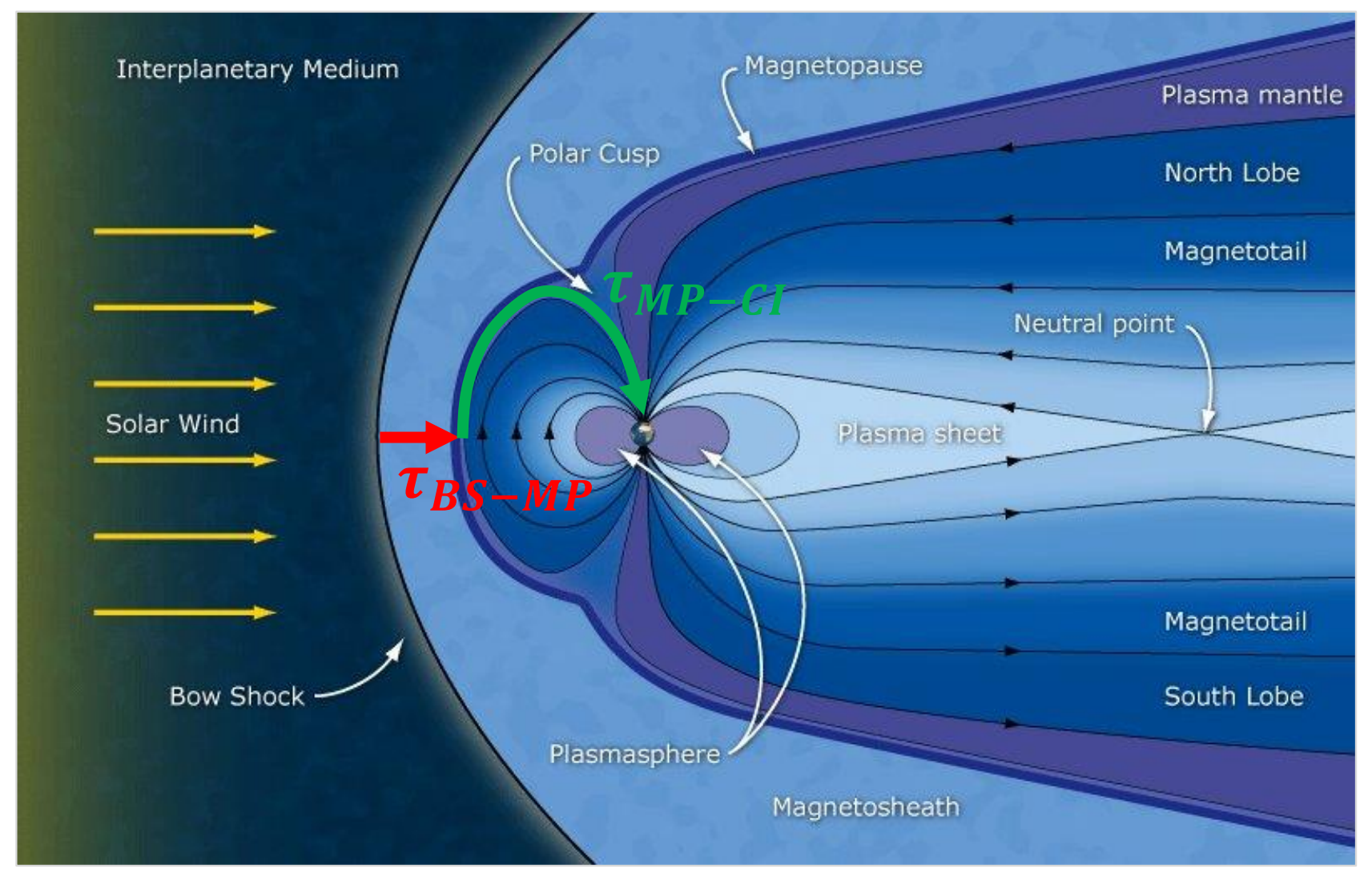

Figure 4. Structure of Earth's magnetosphere. Credit: ESA/C.T. Russell

$$\tau_{BS-MP} = \frac{1.66R_{MP}}{(V_{SW}-72)}\ln\left(\frac{V_{SW}}{72}\right),\ \tau_{MP-CI} \sim 2\ min.$$

Khan and Cowley [1999]

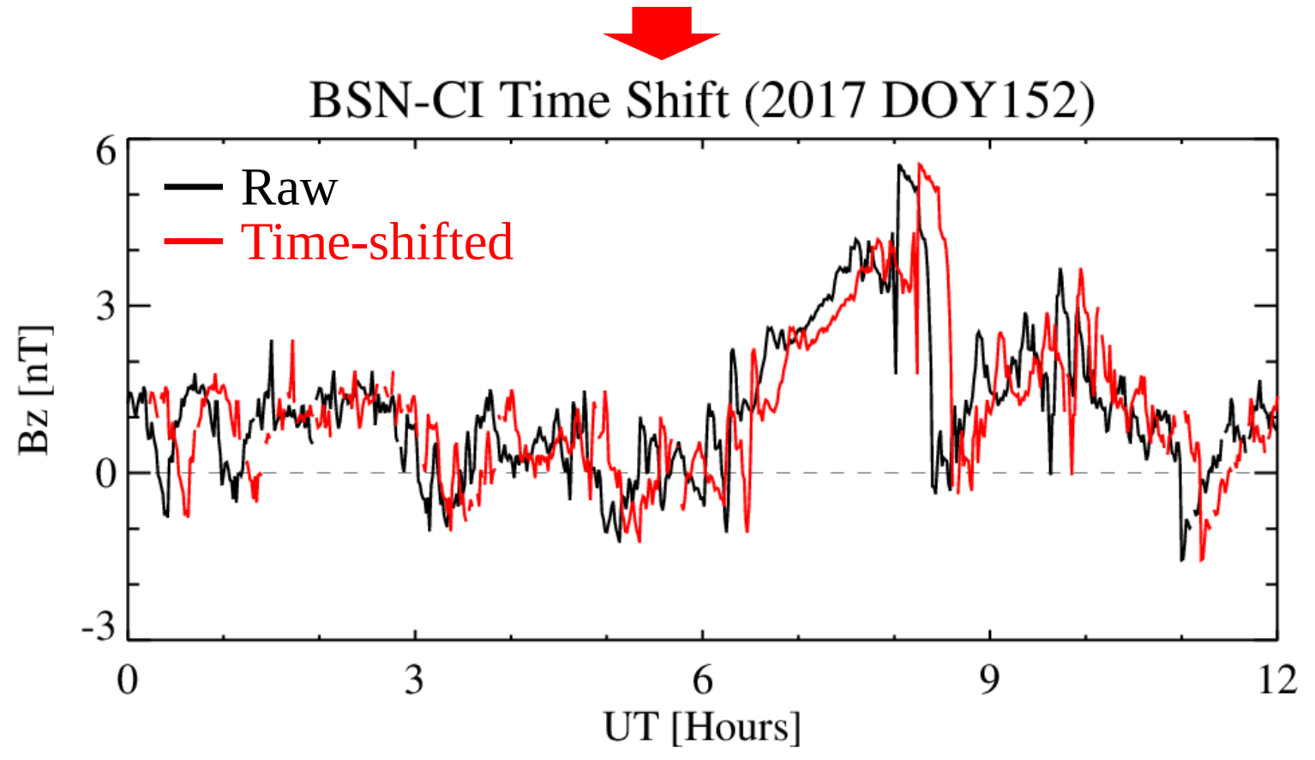

Figure 5. Example of time-shifted IMF data from BSN to CI

Wintertime averages of the ion drifts and neutral winds

- The time-shifted IMF data described above were averaged with non-overlapping 12-minute time windows, and time intervals showing the same IMF condition for at least 36 minutes were only selected (Pettigrew et al. [2010]).
- For four different IMF conditions (B_y+/-, B_z+/-), wintertime-average of the ion drifts and neutral winds were achieved.

Results

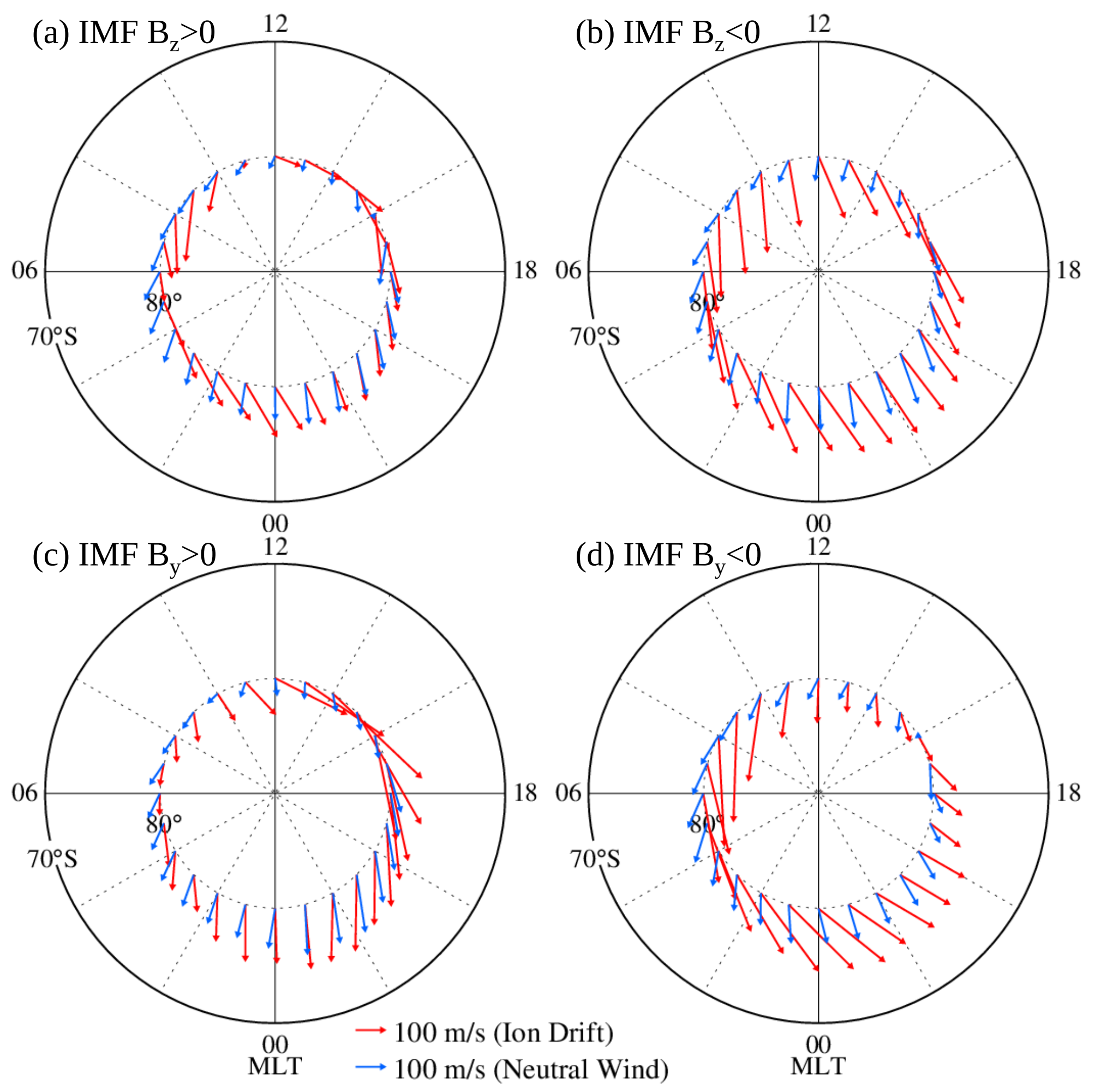

Figure 6. Wintertime average of ion drift and neutral winds sorted by different IMF conditions.

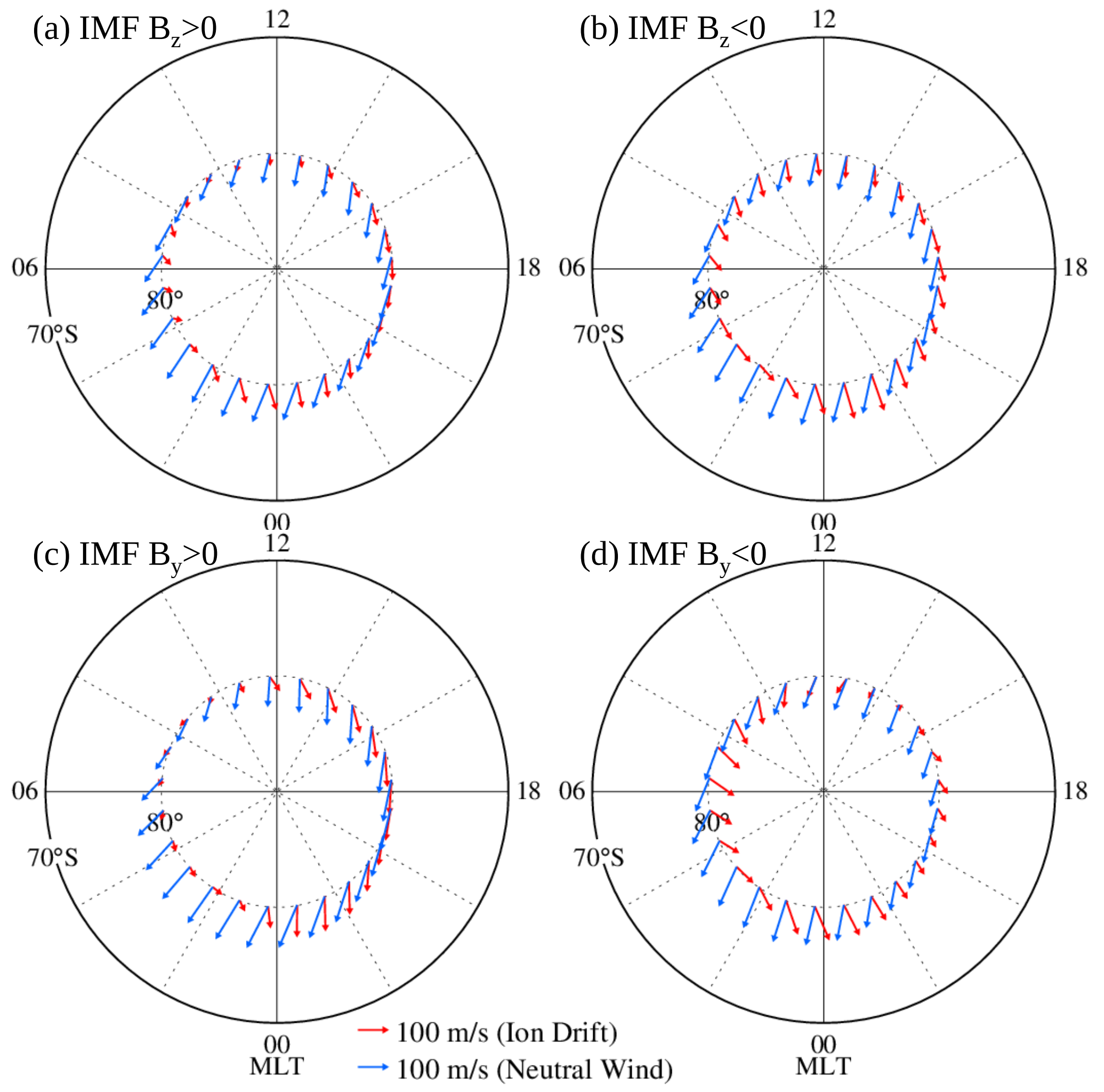

Figure 7. Same with figure 6, but from TIEGCM simulation (with Weimer model) results.

Observation - Ion drifts

- Ion drift data sorted by IMF conditions shows plasma convection patterns that can be expected within the polar cap.
  - Faster ion drifts for IMF B_z<0 than for IMF B_z>0.
  - Round-shaped dusk negative cell during IMF B_y<0 in the southern hemisphere is well pronounced.

Observation - Neutral winds

- Result 1
  - Neutral winds are faster on the MLT midnight sector than on the MLT noon sector.
- Result 2
  - Neutral winds more sensitively responds to the ion drifts on the MLT dusk sector than on the MLT dawn sector.
- Result 3
  - On average, magnitudes of the neutral winds are smaller than those of ion drifts especially for negative B_z and B_y.

Comparison of observations with TIEGCM simulation results

- Result 4
  - TIEGCM significantly underestimates ion drifts.
  - TIEGCM slightly overestimates neutral winds.
  - It shows little dependence with IMF.

Discussions

Explanation for the result 1

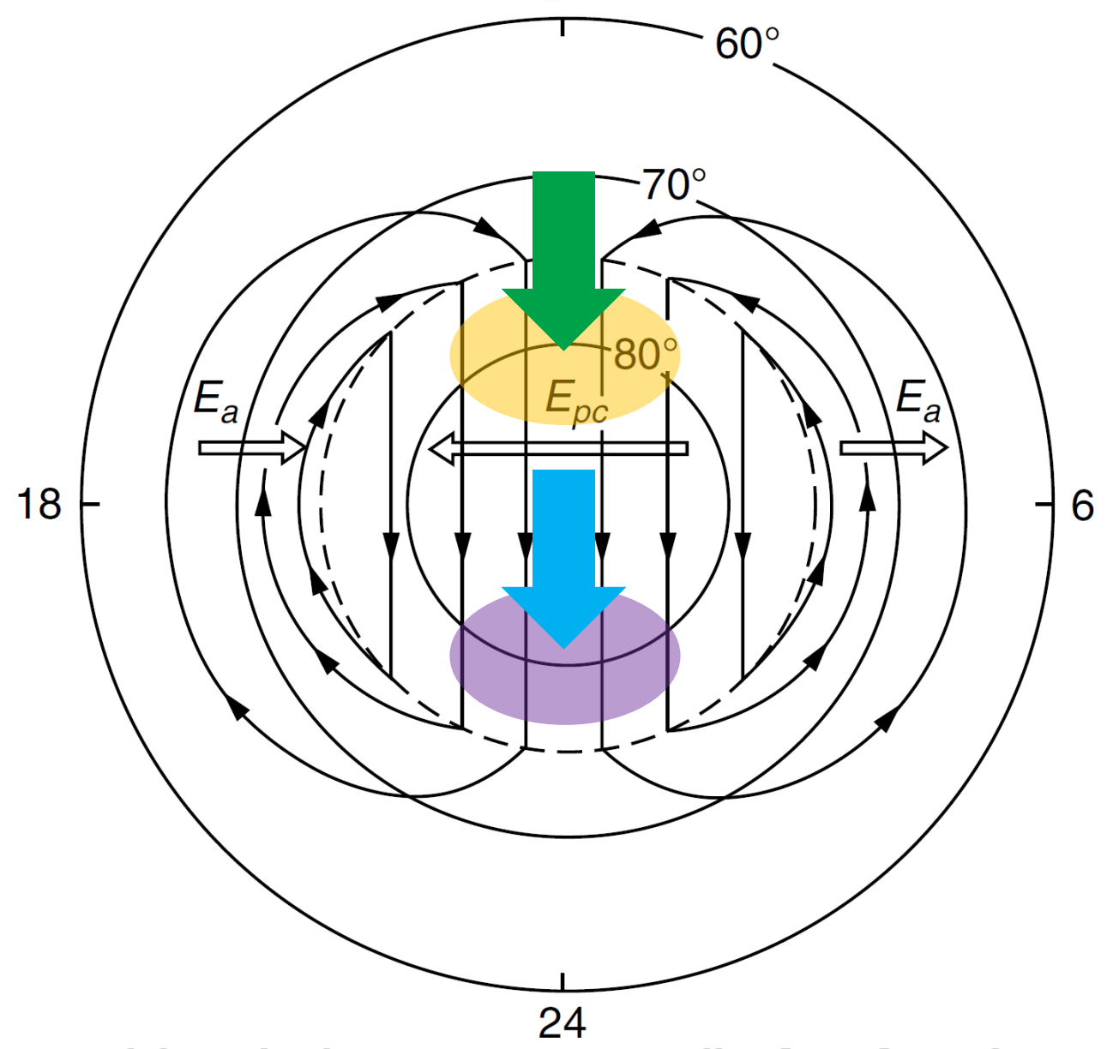

Figure 8. High latitude plasma convection. (Kelley [1989], Academic Press)

Neutral winds observed near MLT midnight

- Neutral fluids just entered the polar cap through the dayside entrance of the two-cell plasma convection pattern: they haven't been forced long enough to be accelerated by the ion drift.

Neutral winds observed near MLT noon

- Neutral fluids have been sufficiently affected by the antisunward ion flows across the polar cap

Considering the residence time of the neutral fluids in the polar cap, the neutral winds should be greater at around MLT midnight than noon.

Explanation for the result 2

- During southern winter solstice, the F-region ionosphere (~250 km) at the JBS location is still in the sunlit condition (figure 9), which stays for about 8 hours in the sunlit.
- Wintertime average of electron density observed by the JVD shows diurnal variation of being maximum near MLT dusk and minimum near MLT dawn (figure 10).

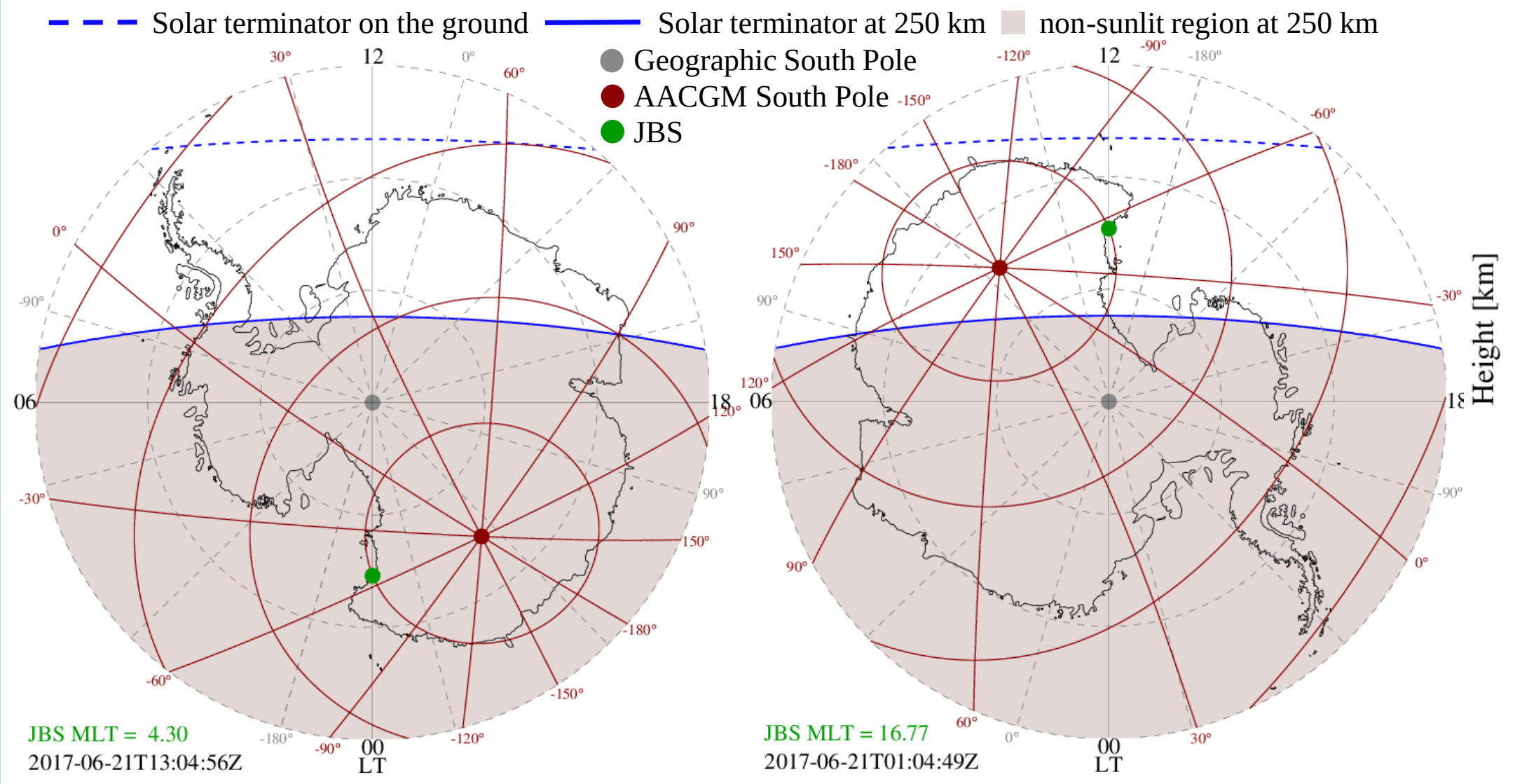

Figure 9. Solar terminator on the southern hemisphere at 250km height during southern winter solstice, when the JBS is at LT midnight (Left), and at LT noon (Right).

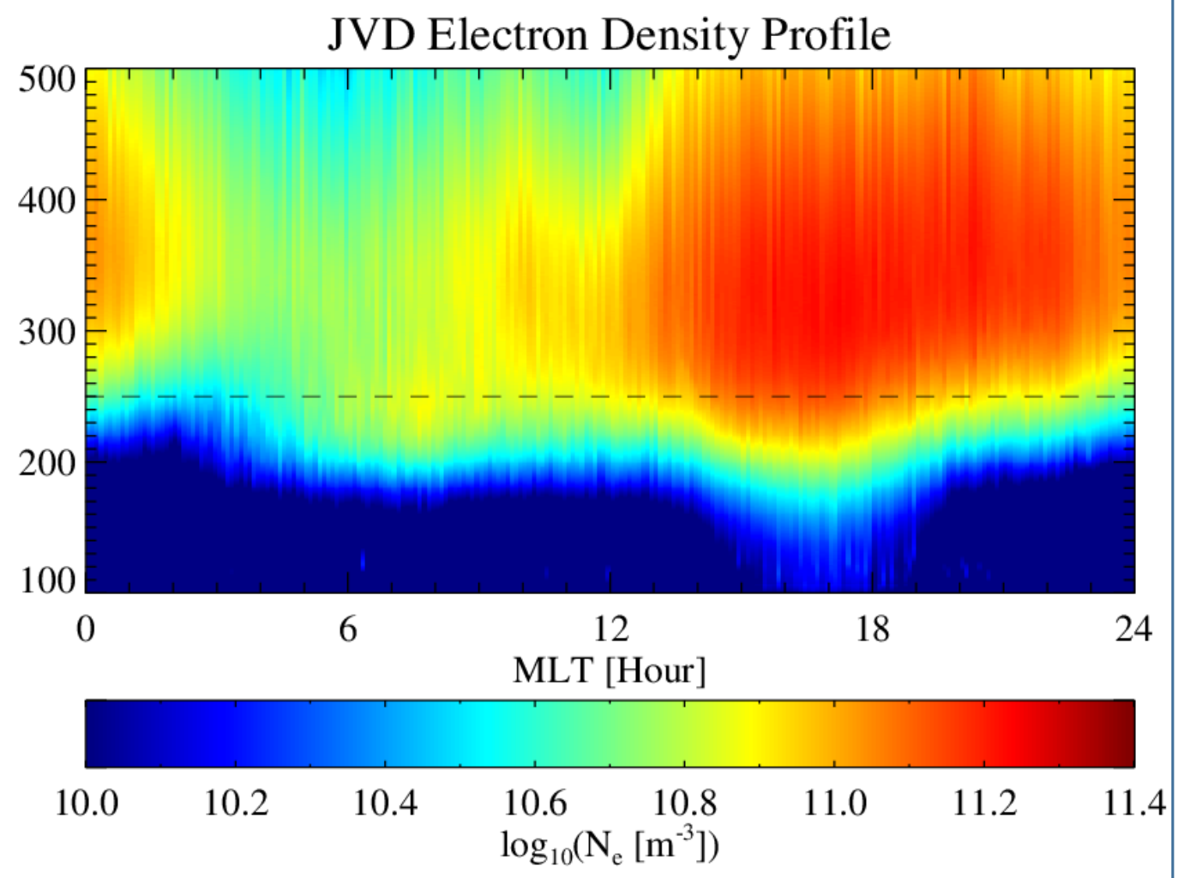

Figure 10. Wintertime average of electron density observed by the JVD

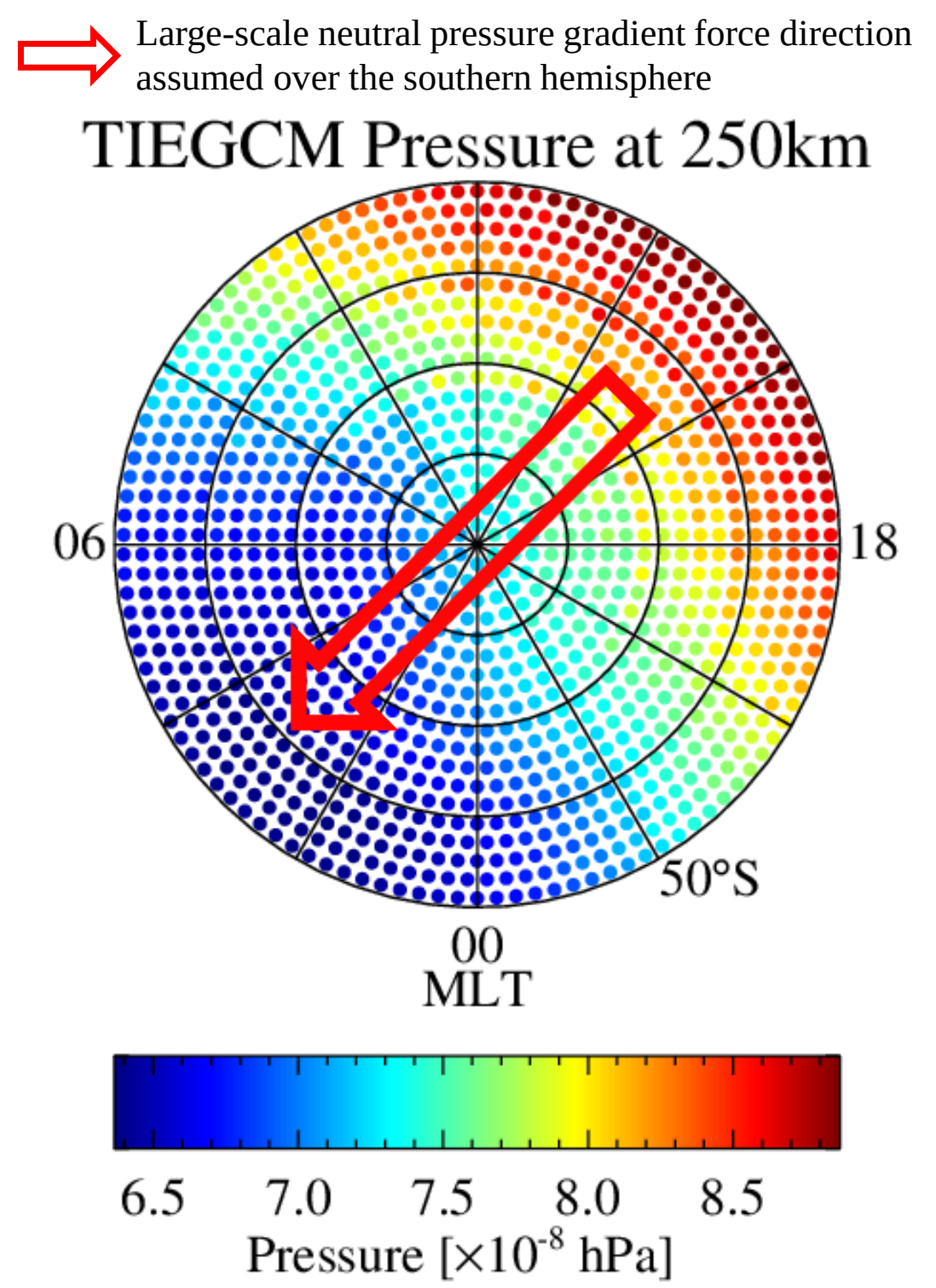

Figure 11. Wintertime average of TIEGCM neutral pressure at 250 km height

Momentum equation of neutrals in Earth-fixed frame

$$\rho\frac{d\vec{u}}{dt} = -\vec{\nabla}p + \rho\vec{g}^* + \eta\nabla^2\vec{u} - \vec{\nabla}\cdot\pi_w - 2\rho\left(\vec{\Omega}\times\vec{u}\right) + \rho\nu_{n,i}^*(\vec{v}-\vec{u})$$

ρ: neutral mass density , $\vec{u}$: Neutral winds, p: neutral pressure, $\vec{g}^*$: effective gravitational field, η: dynamic viscosity coefficient, π_w: momentum flux density tensor due to waves, $\vec{\Omega}$: Earth's angular velocity, $\nu_{n,i}^*$: neutral-ion momentum transfer collision frequency, $\vec{v}$: ion drift

Assumption

- Ion flows are solely driven by the solar-wind/magnetospheric forcings (Momentum equation of the ion is not considered).
- Dominant forces governing the neutral dynamics are pressure gradient and ion drag forces.
- Collisions between oxygen atoms and oxygen ions (dominant neutral and ion species in the F-region height) are only considered.

Momentum equation of neutrals assumed : $\boldsymbol{\rho\frac{d\vec{u}}{dt} = -\vec{\nabla}p + \rho\nu_{O,O^+}^*(\vec{v}-\vec{u})}$

Solution : $\vec{u}(t) = \left[\vec{u}_0 - \vec{v} + \frac{1}{\rho\nu_{O,O^+}^*}\vec{\nabla}p\right]e^{-\nu_{O,O^+}^* t} + \underbrace{\vec{v} - \frac{1}{\rho\nu_{O,O^+}^*}\vec{\nabla}p}_{\text{Steady-state solution}}$

- From the momentum equation of neutrals, it is found that neutral-ion momentum transfer collision frequency determines how effectively the neutral winds respond to the ion drifts.
  - The neutral-ion momentum transfer collision frequency is proportional to ion density.
- Figure 10 suggests that neutral-ion momentum transfer collision frequency becomes maximum near MLT dusk at JBS location, thus yielding higher sensitivity of neutral winds near MLT dusk than dawn.
- Modulation of the level of the ion-neutral coupling by the momentum transfer collision frequency is well pronounced in the observation (figure 6). Considering figure 11, it is found that directions of the neutral winds deviate further from the direction of the pressure gradient force near MLT dusk than dawn.

Parallel to $-\vec{\nabla}p$: $u_{\parallel}(t) = \left[u_{0\parallel} - v_{\parallel} + \frac{1}{\rho\nu_{O,O^+}^*}\frac{\partial p}{\partial x_{\parallel}}\right]e^{-\nu_{O,O^+}^* t} + v_{\parallel} - \frac{1}{\rho\nu_{n,i}^*}\frac{\partial p}{\partial x_{\parallel}}$ **Perpendicular to $-\vec{\nabla}p$** : $u_{\perp}(t) = [u_{0\perp} - v_{\perp}]e^{-\nu_{O,O^+}^* t} + v_{\perp}$

- For the completely different ion drift patterns during B_y positive and negative conditions, their different effects on the neutral winds are well represented on MLT dusk sector. Ion drifts during B_y<0 condition are almost perpendicular to the pressure gradient force ($\vec{v}\sim\vec{v}_{\perp}$, $\vec{v}_{\parallel}\sim 0$). As a consequence, neutral winds parallel to $-\vec{\nabla}p$ decrease, whereas those perpendicular to $-\vec{\nabla}p$ increase. It makes the deviation of the neutral winds from the direction of pressure gradient force most noticeable near dusk.

Explanation for the result 3

- Angles of ion drift vectors from the pressure gradient force hardly exceed 90 °. The steady-state solution suggest that the balanced winds should be greater than the ion drift in this situation. Our observations, however, show that ion drifts are faster than neutral winds on average, and it may indicate that it is not easy for neutral winds to reach a steady-state.

Explanation for the result 4

- It is expected that the underestimated TIEGCM ion drifts will result in the underestimation of neutral winds, which is not the case. One possible explanation is that pressure gradient force may be too large compared with the ion drag force in the TIEGCM.

Conclusion

- Neutral winds are faster near MLT midnight than noon, and it may be explained by the differences of the residence time of neutrals at noon and midnight in the polar cap.
- In winter polar cap, the effect of the ion drag maximizes in the sunlit region (where the ion density is maximized near the MLT dusk at JBS location) due to increased neutral-ion momentum transfer collision frequency.
- On average, neutral winds are slower than the neutral winds. It may indicate that balanced winds are hardly reached in the winter polar cap.
- TIEGCM simulation largely underestimates ion drifts, but slightly overestimated neutral winds. It seems that the pressure gradient force is too large compared with the ion drag force in the TIEGCM, but further analysis is required to confirm this.