

Storm-Time Strip-Like Plasma Density Bulges at Middle Latitudes Shaped by Meridional Wind Gradients

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1. Introduction

During geomagnetic storms, a type of plasma density fine structure with narrow meridional extension can be observed in the middle latitude ionosphere, namely strip-like bulges. These bulges emerge during geomagnetic storms, exhibiting a broad longitudinal span of over 150° and a narrow latitudinal extent of 1°–5°. The neutral wind is found turning equatorward by the time of the bulges' initiation, coincident with the presence of equatorward ion drifts. It is then proposed that the enhanced equatorward neutral wind could shrink/compress the much milder mid-latitude plasma density enhancement. However, this hypothesis as well as the evolution details had not been properly validated, and previous studies also lack research on how neutral winds shape such fine-scale structures. The combination of the observational data and the physics-based model has been proven a powerful method to help us understand the effect of neutral winds on ionospheric structures.

2. Data and Model

The Defense Meteorological Satellite Program (DMSP) F16, F17, and F18 provided the in-situ ion density and ion drift velocity data. The Ionospheric Connection Explorer (ICON) satellite provided horizontal neutral wind vectors, in-situ measurements of the ion density and ion drift velocity.

SAMI2 is a two-dimensional model which simulates the dynamic plasma and chemical evolution of ions along dipole magnetic field. The input parameters of the model are set as follows: Year = 2021, day of year (DOY) = 308 (4 November), geographic longitude (GLON) = 260°, Ap = 179, F10.7 = 92.3, and F10.7A = 85.5. This study focuses only on the effects of neutral winds, and a scale factor n is applied to modify the meridional wind velocities in different latitude ranges.

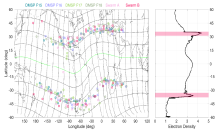


Figure 1. The strip-like bulge observed by multi-satellites. Each bulge sample is marked as a dot on the map.

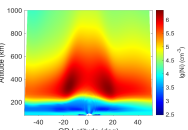


Figure 2. The altitude-QD latitude maps of ion density simulated by SAMI2 model.

3. Observations

The gradients of ion drifts and meridional neutral winds are stronger on the poleward side and weaker (or reversed sign) on the equatorward side in reference to the bulge location .

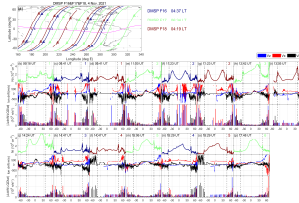


Figure 3. Ion density, ram ion drift, vertical cross-track ion drift, horizontal cross-track ion drift and absolute gradient of these drift components versus the QD latitude observed by DMSP satellites near 260°E longitude on 4 November 2021. The average absolute gradient was calculated within 5° bins.

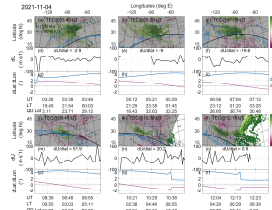


Figure 4. The total electron content (TEC) maps along with the plasma and neutral measurements made by ICON. (a–c, j–l) The dark blue and light arrows denote the horizontal neutral wind and ion drift vector, respectively. (d–f, m–o) The epoch difference of meridional wind (dU). (g–i, p–r) The epoch difference of latitude and longitude. The average $dU/dLat$ is marked in panels (d–f), (m–o); positive values indicate weaker equatorward (or stronger poleward) wind as latitude decreases.

4. Simulations

SAMI2 reproduces bulges at $\pm 30^\circ$ QD latitude when the wind gradient reaches ~ 37 m/s/°, since the vertical component of field-aligned drift is maximum at $I = 45^\circ$ (near $\pm 30^\circ$ QD).

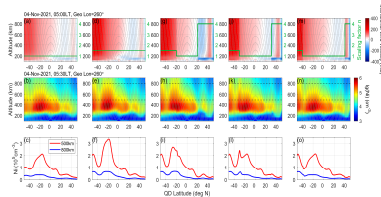


Figure 5. Altitude-QD latitude maps of meridional wind (positive northward, first row) with scaling factor n applied, total ion density (second row), and ion density at 500 and 800 km (third row). The ion density lags the wind by 30 minutes.

At the bulge location, the equatorward wind gradient weakens or reverses the equatorward drift with decreasing latitude, causing ion input from higher latitudes to exceed output at lower latitudes and leading to ion accumulation.

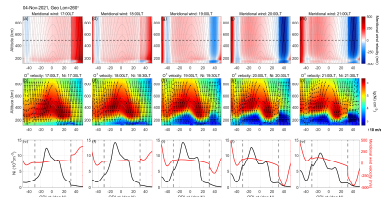


Figure 6. Temporal evolution of meridional wind (first row), ion density (second row) and ion drift (third row) during bulge formation.

5. Conclusion

Based on the in-situ observation data provided by satellites, we have observed the significant gradients of ion drift and neutral wind at bulge locations. To investigate this feature, the SAMI2 model is used to simulate the latitudinally narrow characteristics of strip-like bulges by amplifying default meridional wind velocities across middle latitudes. The results indicate that storm-induced strong meridional wind gradients drive asymmetric field-aligned ion transport between the poleward and equatorward sides of flux tubes, leading to ion accumulation and bulge formation via a pile-up mechanism, analogous to wind-shaped desert dunes. This process is most efficient near $\pm 30^\circ$ quasi-dipole latitude with a 45° magnetic inclination where the meridional wind most effectively promotes vertical ion transport.