Using ROCSAT-1, DEMETER, and ICON Ion Velocities to Explore the Solar Activity Dependence of Daytime Ionospheric Four-peaked Structures

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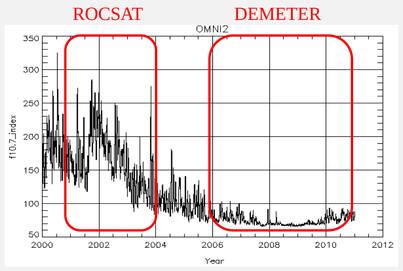
Abstract

The plasma density and temperature and ion velocities observed by the ROCSAT-1, DEMETER, and ICON satellites are used to examine the daytime four-peaked (wavenumber-4; WN4) feature in the equatorial ionosphere during various months and solar activity levels. The ROCSAT-1, DEMETER, and ICON ion density, ion temperature, and ion velocity generally yield prominent WN4 features over the center of Pacific Ocean, the west side of South America, the center of the Atlantic Ocean, and Southern India. The correlation coefficient between the ion density and upward ion drift is significant during high solar activity of 1999-2004. This confirms that the upward ion drift is essential during high solar activity, and the associated amplitude of dynamo eastward electric field is in the range of 0.10-0.14 mV/m, which is 15-19% of daily dynamo electric field. By contrast, the ion density and the northward field-aligned ion flow show a clear anti-correlation which yields a maximum coefficient in August during low solar activity. The amplitude of the ion flow is in the range of 10.44-13.91 m/s, which is 10-13% of the ambient ion flows. In addition, ICON meridional field-aligned ion flows also exhibit prominent WN4 feature in the low solar activity years of 2020-2021. The significant correlation of the DEMETER ion density versus ion flow and prominent WN4 features in the ICON ion flow demonstrate that the meridional field-aligned southward ion flow plays an important role during low solar activity.



ROCSAT-1
- Launch date: Jan 27, 1999 (end Jun 17, 2004)
- Solar activity: high
- Inclination: 35˚
- Observation range: Latitude ±40˚
- Altitude: 600 km
- Period: 96.7 minutes
- ROCSAT observations:

Ionosphere Plasma Electrodynamics Instrument (IPEI): ion density (Ni), ion temperature (Ti), and vertical ion velocity (Vz).

DEMETER
- Launch date: Jan. 2004 (end Dec. 2010)
- Solar activity: low
- Inclination: 98°, sun-synchronous (1030, 2230 LT)
- Observation range: Latitude ±65˚
- Altitude: 660~720 (initial) km
- Period: ~99 minutes (14 orbits per day; return in 16 days)
- DEMETER observations:
- - IAP (Instrument Analyseur Plasma): vertical ion velocity (Vz) and ion temperature (Ti).
- - ISL (Instrument Sonde de Langmuir): electron density (Ne), ion density (Ni), and electron temperature (Te).

1. Ionospheric Wavenumber-4 (WN4) features

- Following Bankov et al. (2009), to further recognize the WN4 signature, large scale variations are removed by applying the deviation data δA = smooth(A) – median(A), where smooth(A) is the smoothed constant LT map, and median(A) is 90˚ (i.e. ±45˚) longitudinal running median.

PO : the center of Pacific Ocean SA: the west side of South America AO: the center of the Atlantic Ocean SI: Southern India

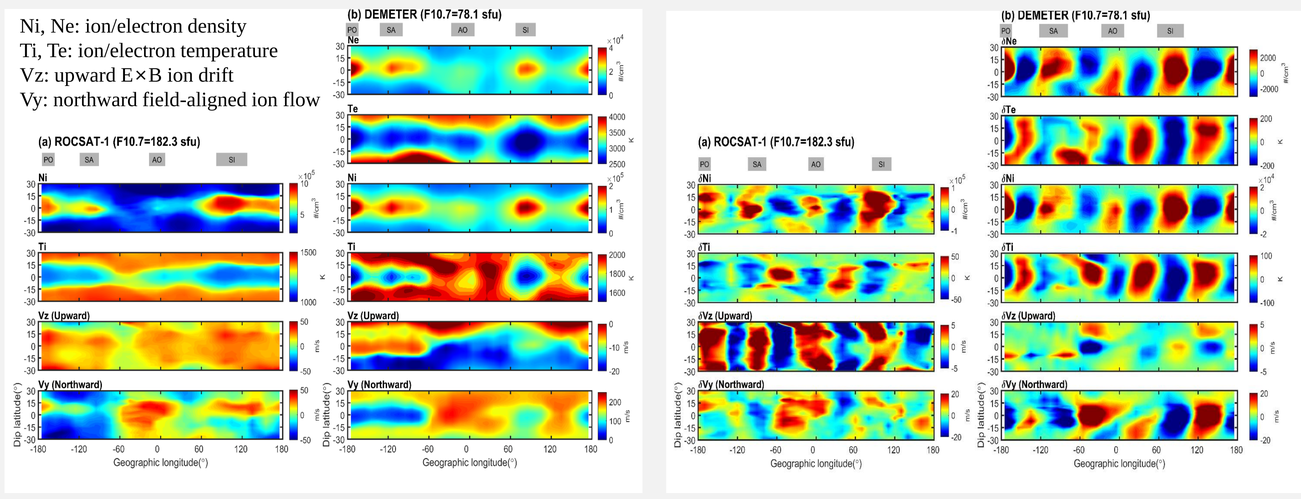


Figure 1. (left columns) Constant LT maps of plasma quantities probed by (a) ROCSAT-1 in 0900-1200LT in September 2000 and those by (b) DEMETER at 1030LT in September 2006. The spatial resolutions are 2˚ in dip latitude and 10˚ in geographic longitude. The monthly median of F10.7 in September 2000 and 2006 is denoted in the figure. (right columns) Deviation LT maps of the plasma quantities of (a) ROCSAT-1 in 0900-1200LT in September 2000 and those by (b) DEMETER at 1030LT in September 2006. The spatial resolutions are 2˚ in dip latitude and 10˚ in geographic longitude.

2. Monthly variations in WN4 signatures

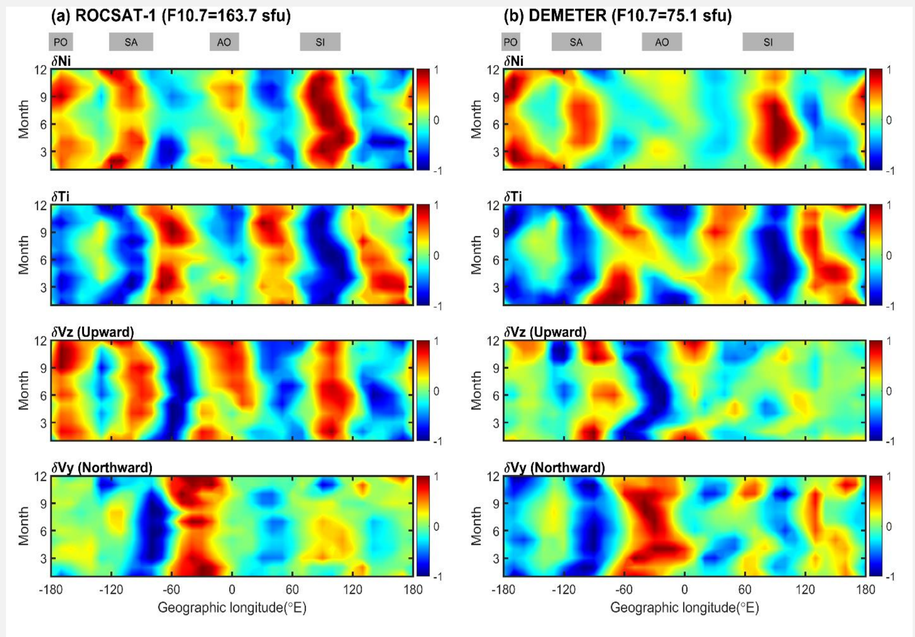


Figure 2. Monthly variations in WN4 signatures of the normalized plasma quantities within ±15° dip latitudes observed by ROCSAT-1 during (a) July 1999 – May 2004 and DEMETER during (b) July 2004 – December 2010. The plasma quantities in each longitude are divided by their associated longitudinal maximum, and therefore the quantities are unitless.

- ROCSAT-1 (high solar activity years of 1999-2004) δNi, δTi, and δVz, as well as DEMETER (low solar activity years of 2004-2010) δNi, δTi, and δVy show prominent WN4 features, and they follow similar monthly variations.
- C-shape longitudinal motion seen over PO (positive declination) and inverse C-shape over SA (negative declination) show that the meridional wind effect being significant on different orientations of the magnetic meridian.

3. Solar activity dependence

Extracting data used for Figure 2, Figure 3 exhibits the scatterplot of δNi vs δVz and δNi vs δVy for ROCSAT-1 (1999-2004) and DEMETER (2004-2010). ROCSAT-1 δNi vs δVz and DEMETER δNi vs δVy shows significant correlation and it meets statistical significance of 95%.

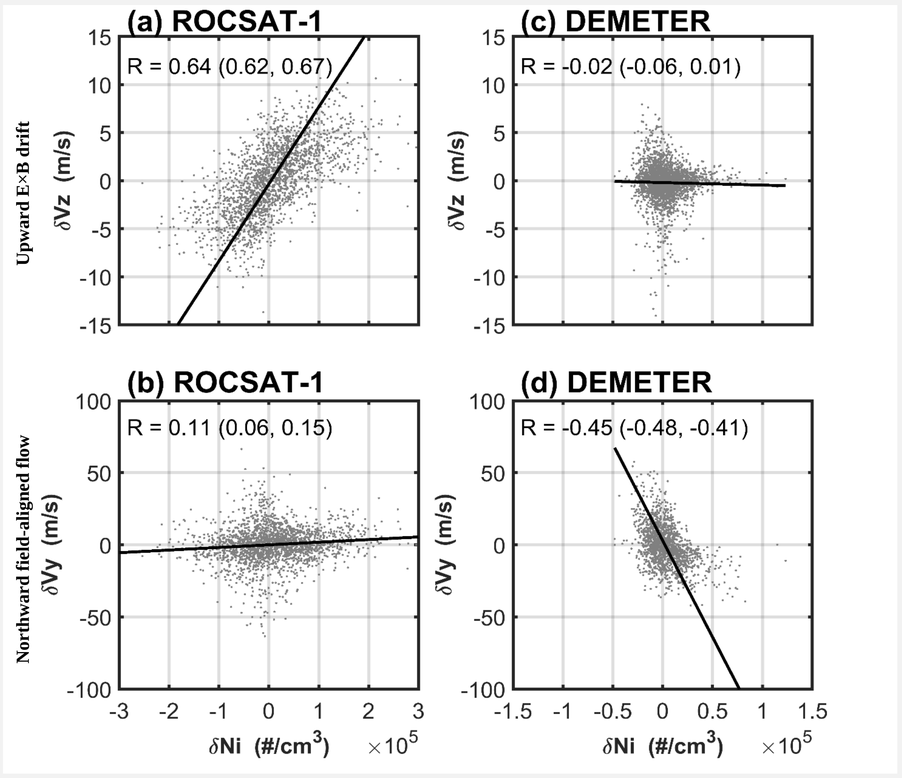


Figure 3. Scatterplots of δNi vs δVz and δNi vs δVy observed by (a)-(b) ROCSAT-1 and (c)-(d) DEMETER. The black lines are the linear regression lines. The numbers in the parentheses stand for the associated 95% confidence interval for the correlation coefficient.

- There is strong evidence that the WN4 feature is associated with diurnal eastward wavenumber 3 (DE3) nonmigrating tides since the tidal winds contribute to the E-region electric fields which in turn map to the F-region and modulates vertical E×B plasma drifts that finally control the EIA structure.
- However, nonlinear wave interactions of the tides responsible to meridional winds, the offset of the magnetic equator, and the DE3 nonmigrating tide will give modifications of the WN4 structure in the plasma density in different tidal modes.

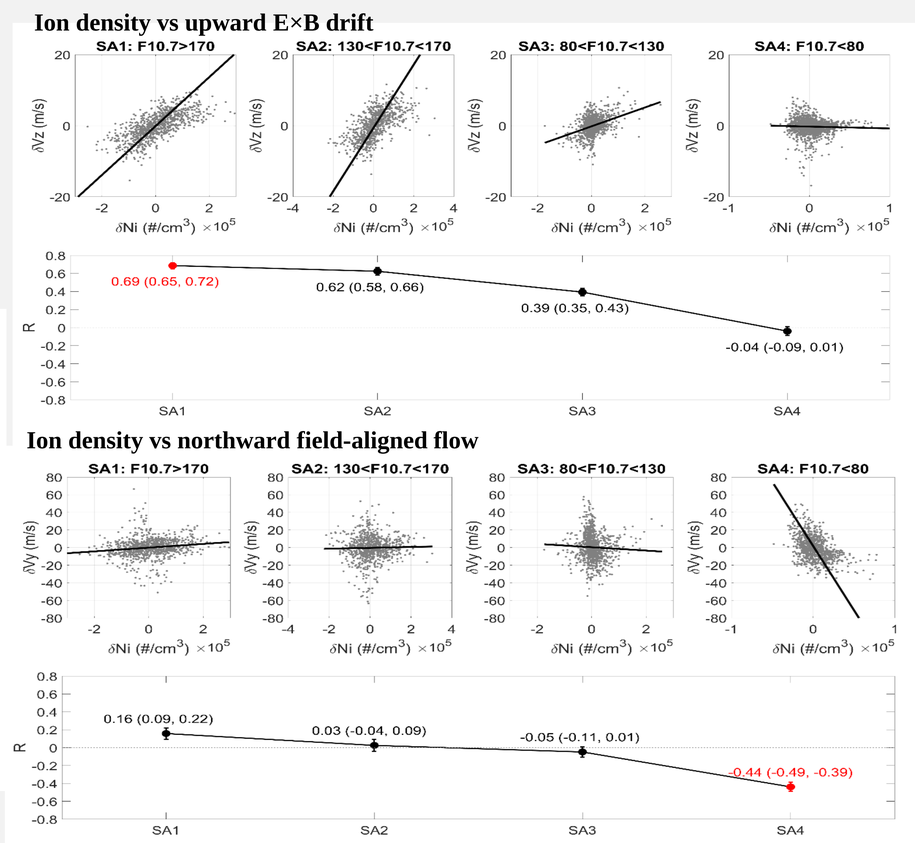


Figure 4. Solar activity variation of R(δNi vs δVz). The red dot in the lower panel denotes the largest absolute value of R. Black solid lines in upper panels are linear regression lines. Error bars in the lower panel stand for the upper and lower bounds for a 95% confidence interval for each coefficient.

- Correlation coefficients (R) between δNi and δVz are significant in SA1-SA3, while R is insignificant in SA4 due to the 95% confidence interval including 0. This indicates the deviation of the vertical ion drift to the WN4 peaks of δNi plays an important role during the high solar activity.
- R between δNi and δVy are weakly correlated or insignificant in SA1-SA3, while R is significant in SA4. This shows that the deviation of southward ion flow is related to that of the ion density during the low solar activity.

4. ICON WN4 signatures

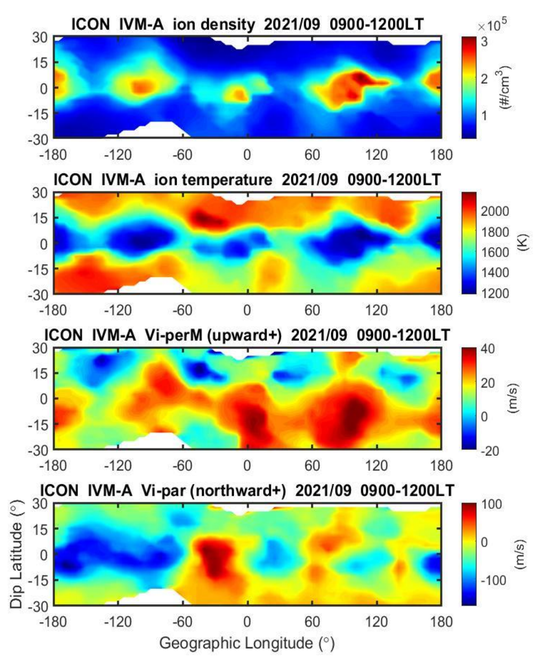
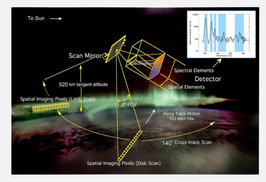


Figure 5. Constant LT maps of plasma quantities probed by ICON IVM-A in 0900-1200LT in September 2021. The spatial resolution is the same as Figure 1. The monthly median of F10.7 is 88.4 sfu.

Since DEMETER flew at sun-synchronized orbit of 98 degrees and ROCSAT-1 flew at 35 degrees inclination, there might be effects of the orbit inclinations embedded in the ion velocity data. Thus, ion parameters measured by ICON/IVM, flying at a satellite inclination of 27 degrees and in low solar activity years of 2019-2022, are used to cross-compare with our results. Prominent WN4 features in ICON ion density, temperature, and velocities can be also observed, which agrees with DEMETER results (Figure 1b). These similarities show that the WN4 longitudinal pattern in the ion parameters can be clearly detected regardless satellite inclinations



ICON
- Launch: October 11, 2019
- Inclination: 27˚
- Period: 97 miniutes
- Altitude: ~580 km
- Observation range: ±30˚ latitude
- Instruments:

- IVM: speed of the charged particle motions. Ion densities, temperatures, and velocities.
- MIGHTI: temperature and speed of the neutral atmosphere
- EUV: O+ density profile (Daytime)
- FUV: O/N2 ratio (Daytime), O+ density profile (Nighttime)

Summary

- Upward E×B drifts modulated by the dynamo electric fields is the major driver in forming WN4 features during high solar activity.
- Agreement between DEMETER and ICON δV_y shows that meridional winds can heavily modify the WN4 feature in the low solar activity.
- The WN4 longitudinal feature during the daytim is prominent regardless satellite inclination.

This paper has been submitted and is soon to be published