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Vertical structure of longitudinal differences in electron densities at mid-latitudes

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Abstract By using Constellation Observing System for Meteorology, Ionosphere, and Climate satellite observations, and Global Ionosphere and Thermosphere Model simulations, the altitudinal dependences of the longitudinal differences in electron densities *Ne* were studied at mid-latitudes for the first time. Distinct altitudinal dependences were revealed: (1) In the northern (southern) hemisphere, there were wave-1 variations mainly in the daytime in the altitudes below 180 km, but wave-2 (wave-1) variations over a whole day above 220 km; (2) a transition (or separation) layer occurred mainly in the daytime within 180 and 220 km, showing reversed longitudinal variation from that at lower altitudes. Solar illumination was one of the plausible mechanisms for the zonal difference of *Ne* at lower altitudes. At higher altitudes, both neutral winds and solar illumination played important roles. The neutral winds effects accounted for the longitudinal differences in *Ne* in the European–Asian sector. Neutral composition changes and neutral wind effects both contributed to the formation of the transition layer.

Keywords Electron density · Neutral wind · Atmospheric composition · Solar illumination

The ionospheric electron density (*Ne*) at mid-latitudes exhibited prominent longitudinal (or zonal) variation, which was reported by Zhang et al. [1] from GPS ground-based receivers in North America. They reported that the total electron content (TEC) within 20°–60° geographical latitude (GLat) was larger in the Western geographical longitudes (110°W–130°W, GLon) than in the Eastern (60°W–80°W, GLon) in the pre-noon time, while smaller in the afternoon. Zhang et al. [2] further reported a good correlation during the nighttime between Fabry–Perot interferometer (FPI) wind observations and West–East (92°W–51°W GLon) differences in electron densities measured by the incoherent scatter radar located at Millstone Hill (47° ± 6° GLat). A zonal wind-magnetic declination mechanism was proposed for explanation of the longitudinal differences in electron densities. Due to non-zero magnetic declination, neutral winds can transport the plasma along the magnetic field. As the plasma are pushed up (down) to higher (lower) altitudes where the recombination rates are lower (higher), electron densities are enhanced (decreased). Since the magnetic declination angles have longitudinal variations, the vertical velocities of the plasma driven by the zonal winds have longitudinal differences. As a consequence, the electron densities exhibit longitudinal differences. By applying an empirical orthogonal function (EOF) decomposition procedure to a 12-year ground-based GPS TEC data set (20°–60° GLat, 135°W–50°W GLon) over America, Zhang et al. [3] found a good correlation between spatial variations in the second EOF mode and the vertical plasma drift driven by the zonal wind, further supporting the zonal wind-magnetic declination mechanism.

Similar longitudinal structures were reported over other regions based on ground and satellite observations. Zhao et al. [4] found that the morning peak electron density (NmF2) in the Far Eastern regions (40°–45° GLat) was larger on the Western side (82° ± 6° E GLon) than on the

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Eastern side (129° ± 13° E GLon), although smaller in the evening. Xu et al. [5] compared the West–East differences of TEC over North America (35° ± 7° GLat, 120°W vs. 70°W GLon), South America (−40° ± 7° GLat, 80°W vs. 50°W GLon), and South Ocean (−30° ± 7° GLat, 110°E vs. 180°E GLon). Luan and Dou [6] studied longitudinal differences in electron densities at southern mid-latitudes during the night time (18–24 h magnetic local time, MLT), based on Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) satellite observations. The results were theoretically consistent with the zonal wind-magnetic declination effects. Meanwhile, they had proposed that the meridional wind effect should be taken into account in the southern hemisphere, which had been assumed negligible by Zhang et al. [2] over North America. Recently Wang et al. [7] quantitatively investigated various physical processes that could modulate the longitudinal differences in the electron density at 400 km altitudes from both CHAMP satellite observation and global ionosphere–thermosphere model simulation. This revealed that in addition to the zonal wind, the meridional wind, solar illumination, migrating tides, and high-latitude activity could affect the longitudinal structure of F-region *Ne* at mid-latitudes.

Although the global pattern of the longitudinal electron densities at mid-latitudes has been studied extensively, the vertical (altitudinal) structure of the longitudinal electron densities have not previously been reported in the literature. Previous work studied the vertical structure of the longitudinal electron density pattern at equatorial regions [8]. The mid-latitudinal night time anomaly (MSNA) or diurnal anomaly has been investigated by a lot of researchers [9–12]. The formation of sporadic E-layers was investigated in associated with AGWs over a moderate mid-latitude station [13]. The COSMIC satellite observations under solar minimum conditions, in combination with the Global Ionosphere–Thermosphere Model (GITM) simulations were used for investigation in the present work. The aim is to understand the physical mechanism that is responsible for the vertical variations. The present work mainly concentrates on physical processes occurring in the ionosphere and thermosphere. The tidal effects on the longitudinal variation of *Ne* are not so significant at mid-latitudes, as compared to the equatorial regions. As our previous work indicated [7, 14], the non-migrating tidal effects improved the model results with respect to observations over the North America sector, while not over the European–Asian sector and in the southern hemisphere. The wave-2 and wave-1 structure of ΔNe were mainly caused by in situ physical processes in the ionosphere and thermosphere, i.e., through transport of the plasma along the magnetic field by neutral winds, as well as through neutral composition changes. Thus, tidal effects from the troposphere are not discussed in the present work.

1 Data and model

1.1 COSMIC

COSMIC was launched with six microsatellite constellations on April 15 2006 into a circular low earth orbit at an inclination of 72°. The vertical altitudinal profile of *Ne* can be retrieved through the radio occultation inversion technique by using the changes in frequency and amplitude of the GPS signal [15, 16]. The electron density profiles from all satellites were collected within 61 days around the September Equinox over a period of three years from 2007 to 2009. The data within geomagnetic latitudes (40°–60° MLat) at altitudes from 100 to 500 km were collected within 15° in longitude, 1 h in MLT, and 10 km in altitude. The longitudinal mean value was subtracted from each MLT sector to be able to better explore the zonal variation of the electron densities (ΔNe).

1.2 GITM model

Global Ionosphere–Thermosphere Model (GITM) is a three-dimensional and non-hydrostatic model developed at the University of Michigan that simulates the ionosphere and the thermosphere [17]. The model solves the continuity, momentum, and energy equations in the thermosphere and ionosphere with realistic source terms. In particular, the ion momentum equation is solved by considering the gradient in pressure, gravity, neutral winds, and electric fields. It is driven by the high-latitude electric field [18], auroral particle precipitation [19], and solar extreme ultraviolet light (EUV). It is initiated by using Mass Spectrometer–Incoherent Scatter (MSIS) [20] and International Reference Ionosphere (IRI) [21] neutral and ion densities and temperatures. The magnetic topology is described by the International Geomagnetic Reference Field (IGRF) [22]. The model is run with 1° latitude by 5° longitude resolution and with a stretched altitude, resolving the vertical scales with approximately 1/3 of a scaled height ranging from 100 km to roughly 600 km. The model is run for 48 h to reach a quasi-steady state, then continued from the startup simulation for another 24 h, which are the hours used for analysis. The input parameters are averaged over a length of 61 days centering on September 21, 2008, and are as follows: IMF $Bx = 0.62$ nT, IMF $By = -0.58$ nT, IMF $Bz = 0.22$ nT, solar wind velocity, $Vx = 400$ km/s, F107 = 68.8 W m^{-2} Hz^{-1}, hemispheric power, and