

Modeling the Long-Term Variability of the D-Region Ionosphere During Solar Cycle 24

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The lower ionosphere, particularly the D-region (~60–90 km), is strongly controlled by solar radiation, yet its long-term response over a complete solar cycle remains comparatively less explored. We present a quantitative numerical investigation of D-region electron density variation during Solar Cycle 24 (C24), incorporating the contributions of solar extreme ultraviolet (EUV), including Lyman- α , and soft X-ray radiation. Solar EUV and X-ray fluxes are used to estimate altitude and time-dependent ionization rates, which are then incorporated into the electron continuity equation to obtain electron density (N_e) profiles. The calculations are performed for different seasons, altitudes, and two representative geographic locations, the equator and 45°N, and are compared with the solar sunspot number (SPN) and IRI-2020 electron density.

The modelled ionization rates closely follow the long-term evolution of solar activity. During solar minima, EUV/Lyman- α is the dominant source of ambient D-region ionization, whereas the relative contribution of soft X-rays increases substantially during solar maxima. The modelled N_e exhibits pronounced solar-cycle and seasonal dependencies, with values at 80 km varying by nearly a factor of two between solar minimum and maximum. Remarkably, the D-region N_e reproduces the dual-peak structure observed in the SPN and solar irradiance profiles, including the enhanced peak around 2011 and the broader maximum during 2013–2014. At 80 km, N_e shows an approximately linear dependence on SPN, with distinct latitude-dependent responses. Although the absolute N_e values differ from IRI-2020, their solar-cycle trends are broadly consistent. These results demonstrate that solar-cycle modulation leaves a measurable signature in the lower ionosphere and provide a quantitative baseline for future long-term VLF-based investigations of the D-region.