Terrestrial Weather Influences on Ionospheric Space Weather: A COSMIC-2 Data Analysis and SD-WACCM-X Model Verification

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1. Abstract

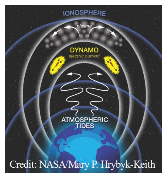
We analyze daily ionospheric tidal variability using COSMIC-2 GIS data, examining its relationship with the stratospheric polar vortex. A strong anti-correlation exists between the NAM index (a proxy for the polar vortex) and the ionospheric migrating semidiurnal tide (SW2). Using the SD-WACCM-X model, we compare ionospheric tidal responses under controlled geomagnetic and solar flux conditions to understand upper and lower atmospheric interactions. Ionospheric tidal responses are likely influenced by the E-region dynamo modulation or direct tidal propagation from the lower atmosphere.

Goal: Global response of F-region ionosphere to stratospheric polar variability.

2. Introduction

- Atmospheric tides: Global-scale periodic oscillations of the atmosphere (winds, T).
- Periods: 24hrs; Diurnal,12 hrs; Semidiurnal.

Tides ⟶ E-region dynamo ⟶ F-region electron density change at Equatorial Ionization Anomaly (EIA).



3. Data Used

- **COSMIC-2 GIS:** 2-D Fourier fitting of the hourly GIS electron density profiles at each altitude and magnetic latitude. **Tidal spectra every day.**
- **NAM index:** *Northern Annual Mode* Geopotential difference between polar and middle latitudes (10 hPa). Strong vortex: positive NAM index; weak vortex: negative NAM index.
- **SD-WACCM-X:** Specified dynamics (SD) WACCM-X version v2.1 simulation with nudging of (MERRA-2) data from the surface up to ~50 km. **Runs: Standard, Controlled (F10.7 = 75 sfu, Kp-index = 0.3).**

4. Semidiurnal Tides @ 15°N; 300 km

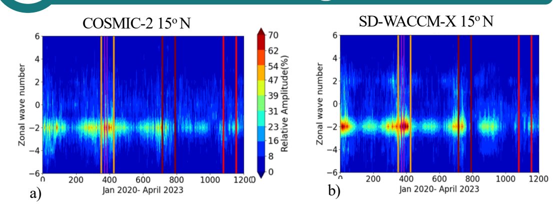


Figure 1: Time evolution of semidiurnal spectra at 15°N and 300 km, Jan 2020 – April 2023 for (a) COSMIC-2, (b) Same but for SD-WACCM-X standard runs. **Note: Negative wavenumbers are westwards propagating tides and positive wavenumbers are eastward propagating waves.** Purple lines indicate the 2020/21 SSW. **15 Dec 2020 - 01 March 2021**, **15 Dec 2021 – 01 March 2022**, **15 Dec 2022 - 01 March 2023.** Color notation will be followed through out the studies.

- **SW2 Tide Dominance:** The migrating semidiurnal (SW2) tide exhibits the strongest signal in the semidiurnal spectrum.
- **Model Performance:** While the model tends to overestimate the amplitudes of these tides, it accurately reproduces the seasonal and interannual variations of the F-region tides as observed by COSMIC-2.

5. SW2 @ 300 km

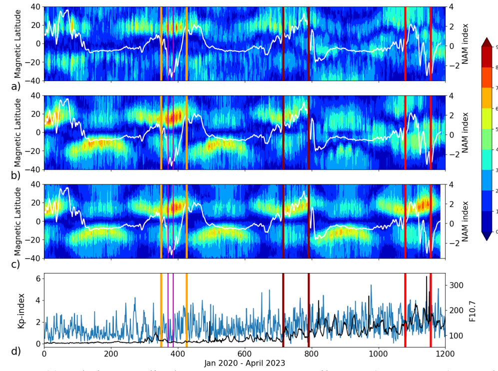


Figure 2: (a) Relative Amplitude SW2 Jan 2020 – April 2023 (COSMIC-2) overplotted NAM index (white), (b) same as (a) but for SD-WACCM-X standard runs, (c) SD-WACCM-X controlled runs (d) kp-index (blue), F10.7 (black). Purple lines indicate the SSW period, red lines are higher solar flux periods for 2022/23.

- **Solar Flux Impact:** The increase in solar flux during 2022 and 2023 has resulted in more pronounced semi-annual variations in low-latitude SW2, likely due to the corresponding increases in O/N2 ratios (out of scope foe this study).
- **Solar-Lower Atmosphere Interaction:** The interplay between solar forcing and lower atmosphere forcing is evident when comparing SD-WACCM-X simulations. Specifically, the standard runs (b) and controlled runs (c) during the 2022/23 winter period (highlighted by red lines) show notable differences. These runs were performed with F10.7 fixed at 75 sfu and the Kp-index at 0.3

6. Results

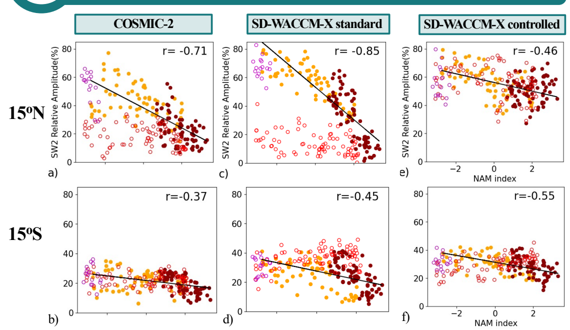


Figure 3: Correlation analysis between SW2 relative amplitudes and NAM index for (a), (b) COSMIC-2 GIS at 15°N and 15°S; (c), (d) SD-WACCM-X standard runs at 15°N and 15°S; (e), (f) SD-WACCM-X controlled runs at 15°N and 15°S.

- **Strong Anti-Correlation:** There is a strong anti-correlation between the NAM index and the SW2 tide in both hemispheres, particularly at EIA latitudes, when solar flux is low.
- **Model-Observation Consistency:** The correlations between NAM and SW2 observed in SD-WACCM-X standard model runs are highly consistent with those measured by COSMIC-2 GIS observations. It reduces to from -0.8 for standard runs to -0.46 for controlled runs.

7. Interpretation

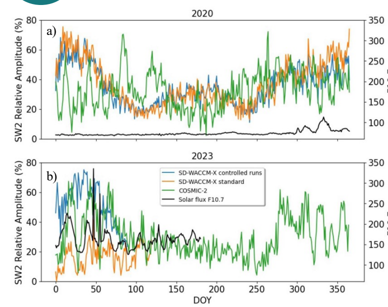


Figure 4: (a) COSMIC-2 GIS (green), SD-WACCM-X standard (orange), and SD-WACCM-X control (blue), F10.7 (black) for year 2020 (referenced as lower solar flux period). (b) same as (a) but for year 2023 (referenced as higher solar flux period).

- SW2 relative amplitudes for standard and controlled runs are comparable for year 2020 (lower solar flux).
- Overall SW2 relative amplitudes for controlled runs is higher as compared to standard runs for the year 2023 (higher solar flux).

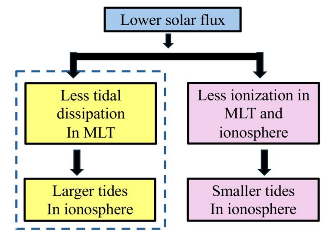


Figure 5: The block diagram shows the overall impact of solar flux on the ionospheric tides. **Note:** Blue dotted box shows the leading mechanism.

- **Inverse Relationship:** Lower solar flux is associated with increased relative tidal amplitudes in the ionosphere.
- **Tidal Dissipation:** Plays a significant role in the ionospheric tidal response to variability in the stratospheric polar vortex.
- **Atmospheric Coupling:** The E-region dynamo is likely facilitating the coupling between the lower atmosphere and the ionosphere.

8. Conclusion

- **Polar Vortex Influence:** The strength of the Northern Hemisphere stratospheric polar vortex significantly modulates F-region tides at EIA latitudes.
- **Correlation with SW2 Tides:** A strong anticorrelation is observed, with a value of -0.72 for SW2 tides in COSMIC-2 and -0.84 in SD-WACCM-X standard runs. This correlation weakens to -0.46 in SD-WACCM-X controlled runs.
- **Solar Flux and Tidal Amplitudes:** As solar flux decreases, relative tidal amplitudes in the ionosphere increase due to reduced tidal dissipation in MLT.
- **Leading Mechanism:** E-region dynamo is likely the primary mechanism facilitating the coupling between the lower atmosphere and the ionosphere.
- **Ionospheric Predictability:** Potential for the predictability for the ionospheric state.

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