# Electrodynamics and Field-Aligned Wind Drivers of the Ionospheric Lunar Tidal Response to the 2020–2021 Sudden Stratospheric Warming: Insights from COSMIC-2, ICON, SD-WACCM-X, and TIE-GCM

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## 1. Introduction and Background

Atmospheric tides are a major source of ionospheric variability and an important pathway for atmosphere–ionosphere coupling. Variability in electron density affects navigation, communication, and satellite operations. During SSW events, enhanced lunar semidiurnal tides (M2) can significantly modify the ionosphere, yet their global response and underlying driving mechanisms remain poorly understood. Using **COSMIC-2 GIS**, **ICON**, **SD-WACCM-X**, and **TIE-GCM**, we quantify the global M2 response during the 2020–2021 SSW and identify the dominant coupling mechanism.

**Novelty: Global M2 characterization + Quantitative pathway attribution.**

### Challenges

**Weak M2 Signal:** The M2 tide (12.42 h) is weaker than the SW2 tide (12.00 h), making their separation challenging.
**Limited Observations:** Previous studies lacked global, altitude-resolved measurements of the F-region.
**Uncertain Mechanisms:** The pathways linking lunar tides to F-region variability remain poorly quantified.

### Motivation

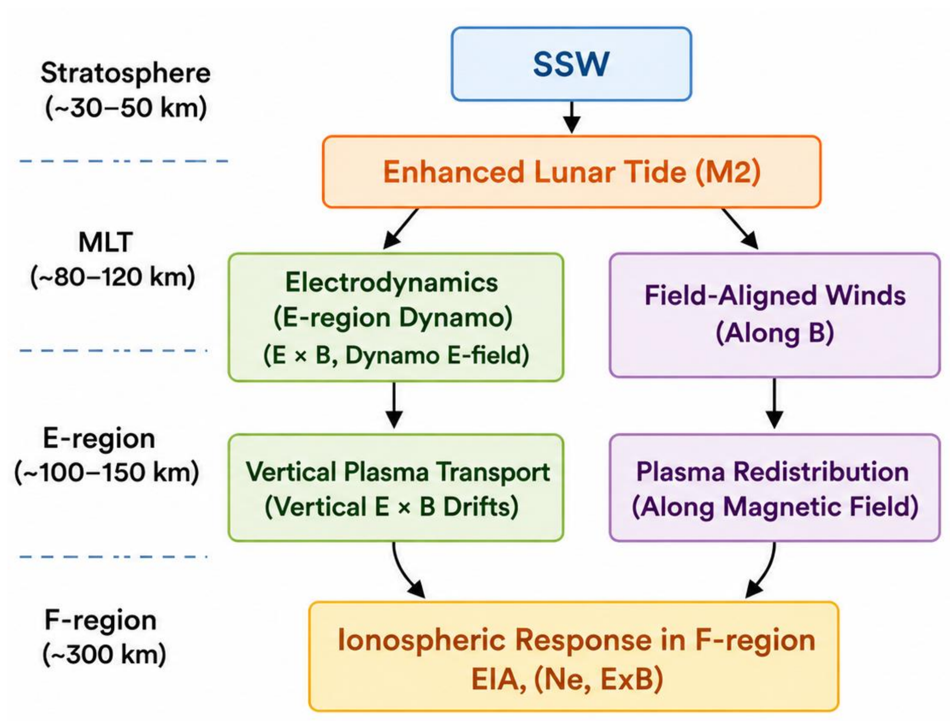
**Advanced Tidal Analysis:** Apply specialized M2 extraction techniques to isolate lunar tidal signatures from global observations.
**Global Perspective:** COSMIC-2 GIS provides global, altitude-resolved electron density observations.
**Mechanism Attribution:** Combine COSMIC-2, ICON, SD-WACCM-X, and TIE-GCM to quantify electrodynamic and neutral-wind contributions.

## 2. Science Question

How does the enhanced M2 during 2020/21 SSW affect the F-region ionosphere ?

1. **Quantification ?**
How much **Ne variability** is produced?

2. **Pathway?**
**Electrodynamics**
(E-region dynamo, Zonal Winds)
**Vs Field- Aligned Winds**
(Along B, Meridional Winds)




## 3. Data and Modeling Framework

| Source | Variable(s) | Scientific Role |
|---|---|---|
| COSMIC-2 GIS | Electron Density (Ne) | Quantifies the global F-region lunar tide (M2) response |
| ICON IVM | Vertical Plasma Drifts (E×B) | Observational evidence of electrodynamic variability |
| SD-WACCM-X | Ne, Winds, Drifts | Reproduces observed global M2 variability |
| TIE-GCM | Ion Continuity Equation Terms | Quantifies coupling pathways and mechanism attribution |

### Ion continuity equation (TIE-GCM)

*Transport of plasma

$$\underbrace{\frac{\partial O^+}{\partial t}}_{\text{Ne Proxy}} = \underbrace{Prod. - Loss + Amb\_diff}_{\text{Background (Prod., Loss, Ambipolar Diffusion)}} + \underbrace{Trans\_wind}_{\text{Field-Aligned Wind Transport}} + \underbrace{Trans\_E\times B}_{\text{ExB Drift Transport}}$$

### Scientific Framework

Quantify the M2 response (COSMIC-2 & ICON) → Reproduce the observed variability (SD-WACCM-X) → Identify the coupling mechanism (TIE-GCM)

## 4. Methodology: Isolating the Lunar Semidiurnal Tide (M2)

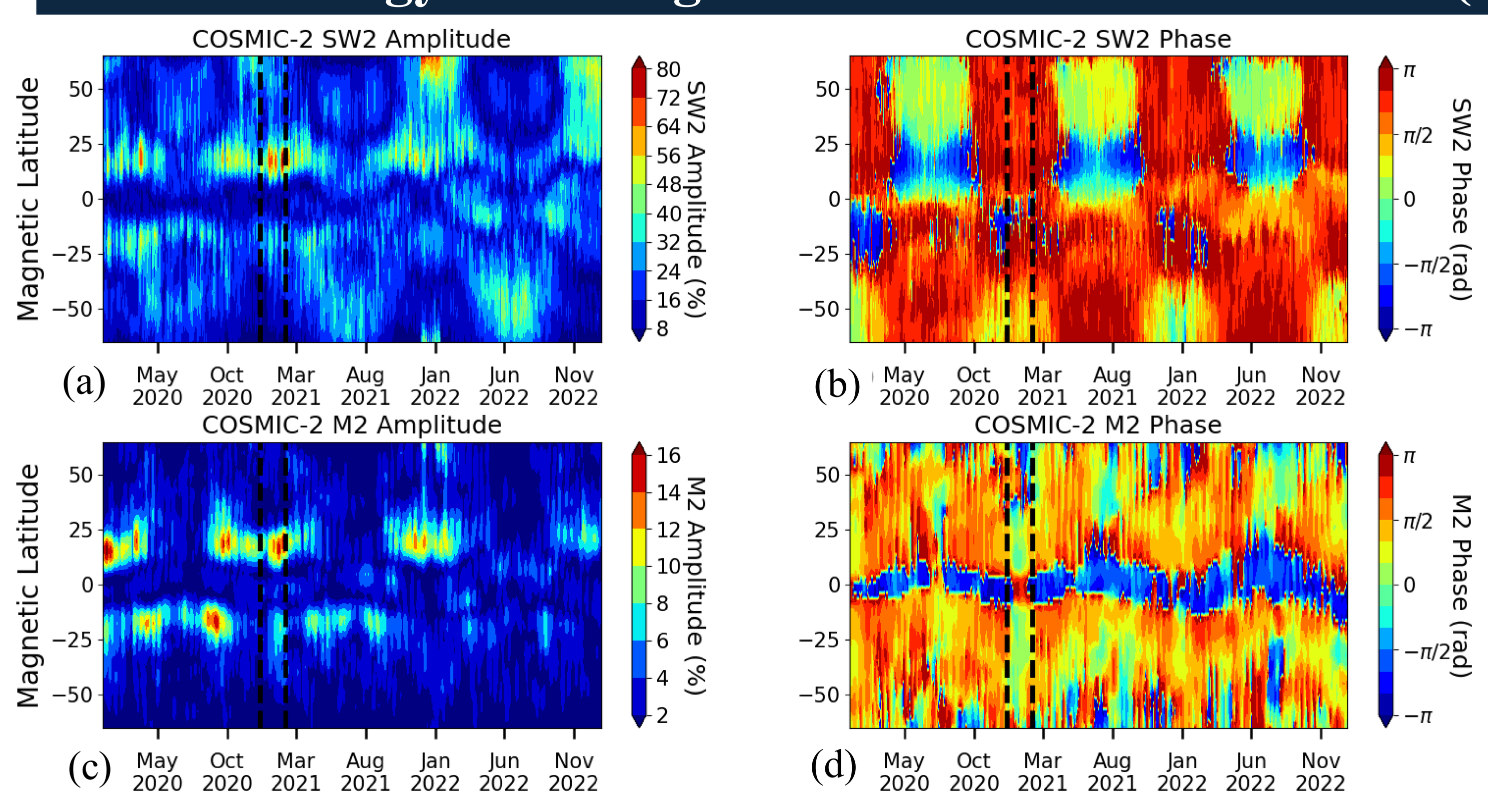



***Figure 1 (Lat vs DOY):*** *SW2 (a,b) and M2 (c,d) amplitude and phase derived from COSMIC-2 GIS electron density at 300 km (2020-2022).* ***The markedly different phase structures of SW2 and M2 indicate minimal aliasing between the two tides, demonstrating successful isolation of the lunar semidiurnal tide (M2).*** *Vertical dashed lines mark the 2020–2021 SSW period.*

### Stage I: Solar Tide Removal

1. **27-day running FFT** to hourly data (COSMIC-2, SD-WACCM-X, TIEGCM)
2. Determine solar harmonics coefficients **(24-, 12-, and 8-hour tides)**
3. **Residual signal**: (Data − Solar Harmonics).
4. *Normalize by the mean state (For Ne) (Obtain **relative perturbations (%))**

### Stage II: Lunar Tide Extraction

1. **29-day lunar window** and bin data by **LLT**
2. **Apply a least-squares fit**: $A\cos(2\pi t/12 - \phi)$
3. **Derive M2 amplitude ($A$) and phase($\phi$)**

*27 days ≈ solar rotation period, minimizing solar leakage; 29 days ≈ lunar month, sampling all lunar local times.

**ICON IVM (ExB Drifts):** Different sampling approach
9-day filtering removes solar variability | Adjacent sequences combined for 24-hr local time coverage | Bin in LLT

## 5. Results I (Quantification)

***Figure 2 (Latitude vs DOY):*** *(a) M2 amplitudes (%) in* ***Ne*** *from COSMIC-2 GIS (b) and SD-WACCM-X at 300 km,* ***NAM index (SSW Proxy)****. Dashed lines indicates SSW period.*

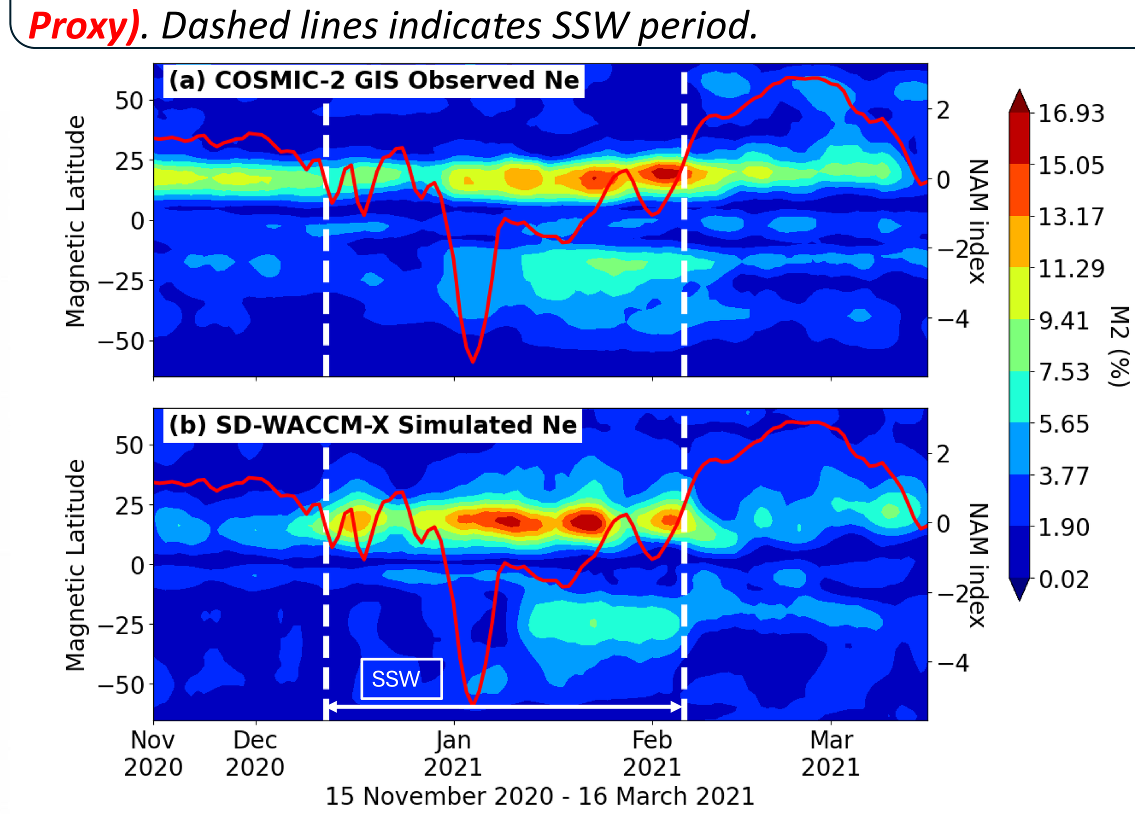
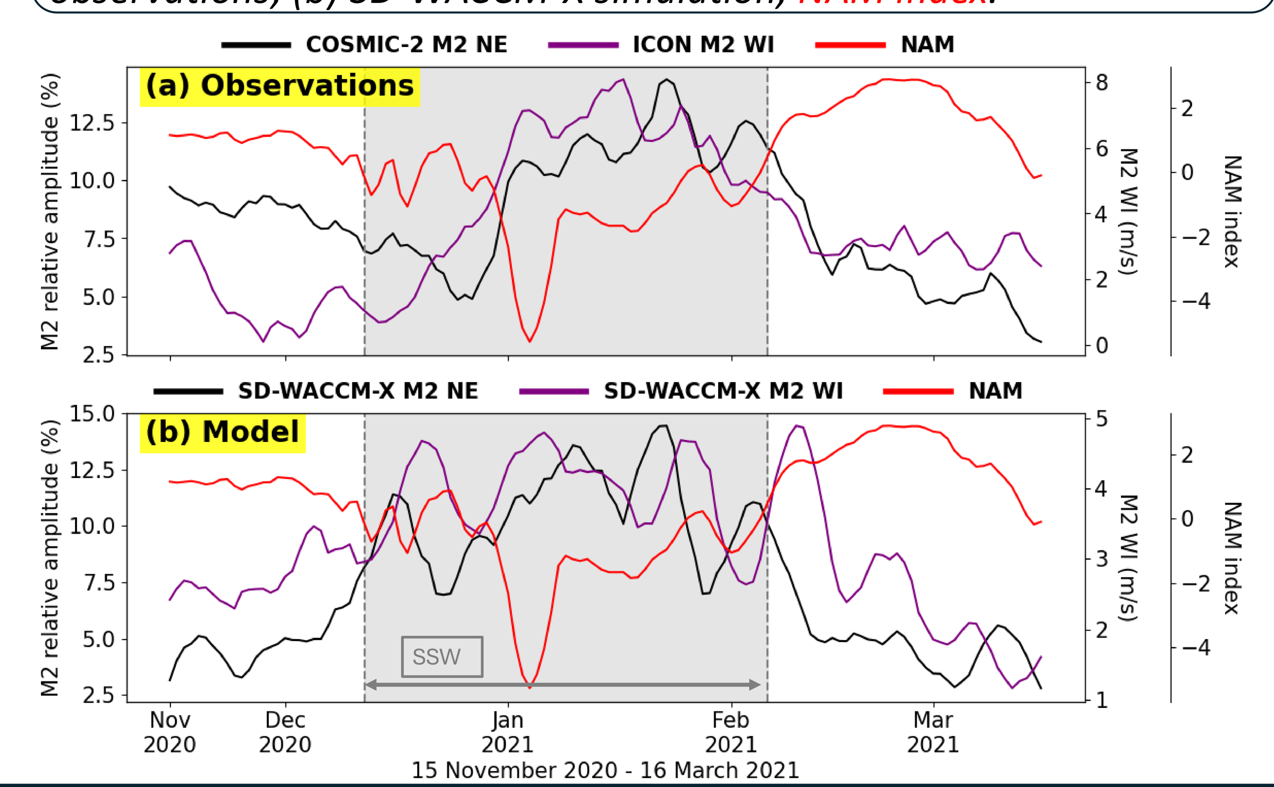


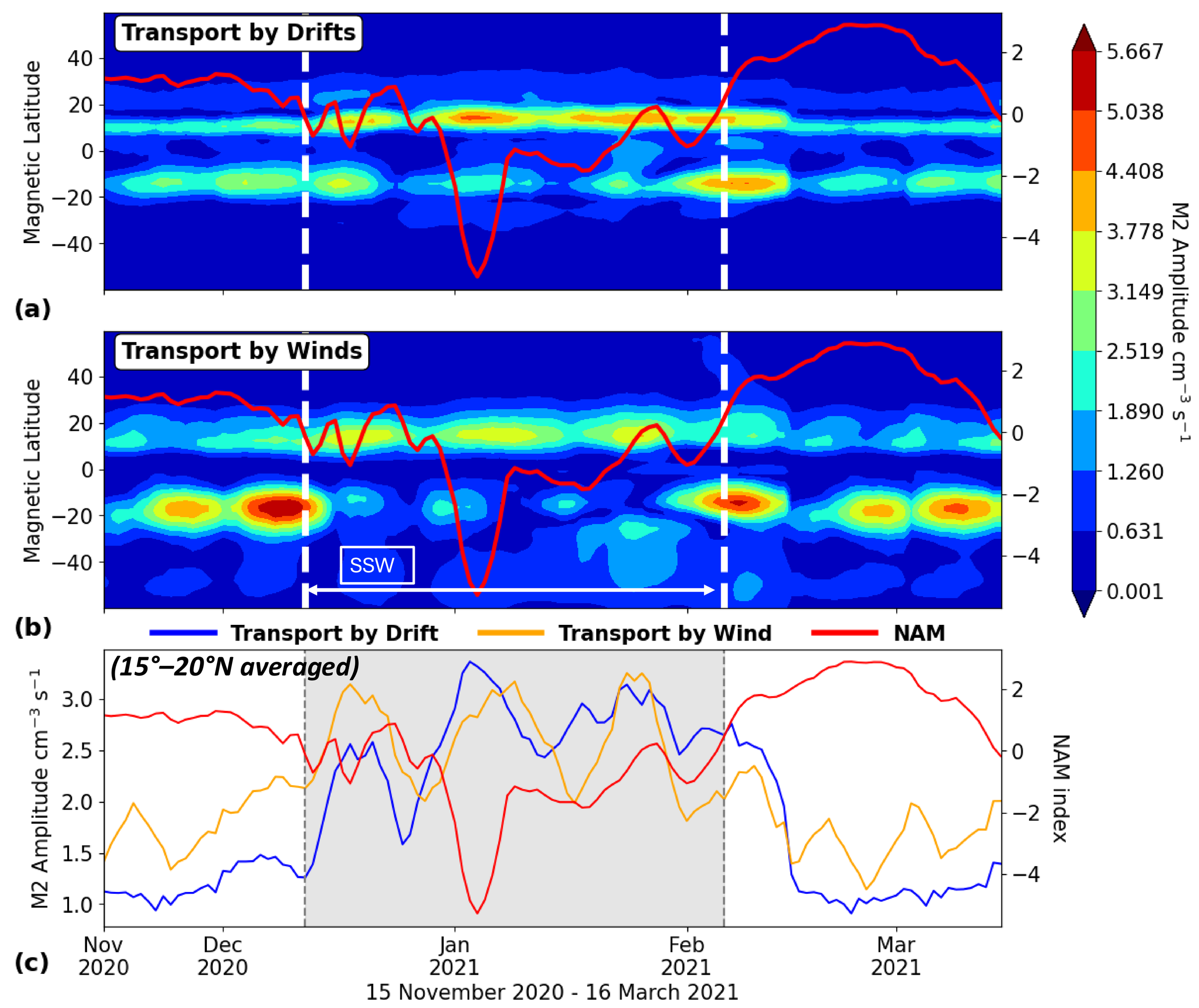

***Figure 3 (Latitude-averaged):*** *M2 amplitudes of* ***Ne*** *and* ***vertical drifts*** *in the Northern EIA (15°–20°N). (a) COSMIC-2 GIS and ICON observations; (b) SD-WACCM-X simulation,* ***NAM index****.*




### Conclusion I: Global M2 Response During the 2020–2021 SSW

1. Ne M2 amplitudes **increased by ~16%** during the 2020–2021 SSW in the F-region (~ 300 km).
2. Vertical drift amplitudes increased from **~2 to 6–8 m s$^{-1}$**, coincident with enhanced Ne variability.
3. SD-WACCM-X reproduces COSMIC-2 and ICON observations and provides the basis for TIE-GCM pathway analysis.

## 6. Results II (Pathway)




Enhancement (%) = $(\langle M2\rangle_{SSW} - \langle M2\rangle_{non\text{-}SSW})*100 / \langle M2\rangle_{non\text{-}SSW}$

### Conclusion II: Mechanism Attribution (TIE-GCM)

4. **Ion-continuity equation analysis:**
   - **E×B** drift transport increased by **~114%**.
   - **Field-Aligned** wind transport increased by **~43%**.

5. Enhanced E-region dynamo electrodynamics, manifested as stronger E×B plasma drifts, represents the dominant pathway for transmitting lunar tidal variability into the F-region ionosphere during the 2020–2021 SSW.

***Figure 4 (Latitude vs DOY) :*** *(a) M2 amplitudes associated with* ***transport by vertical E×B drifts*** *(b) and* ***transport by Field-Aligned winds*** *at 300 km from TIE-GCM. Panel (c) shows the corresponding latitude-averaged amplitudes (15°–20°N) derived from panel (a)* ***transport by vertical E×B drifts*** *and (b)* ***transport by Field-Aligned winds*** *and the* ***NAM index.***

**Reference:** Aggarwal, D., Kumar, S., Martinez, B. C., Pedatella, N., Lu, X., & Oberheide, J. (2026). *The ionospheric lunar tidal response to the 2020–2021 sudden stratospheric warming observed by COSMIC-2, ICON, and modeled by SD-WACCM-X and TIE-GCM.* Journal of Geophysical Research: Space Physics, 131, e2025JA034731.
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