From Stratosphere to Space: The Hidden Impacts of SSWs on Equatorial IT Anomalies

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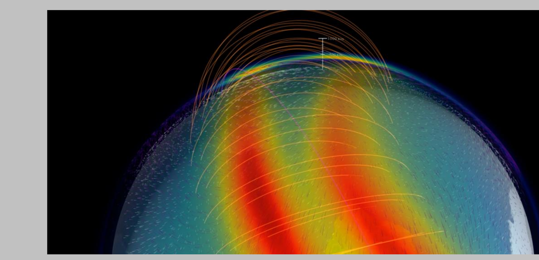
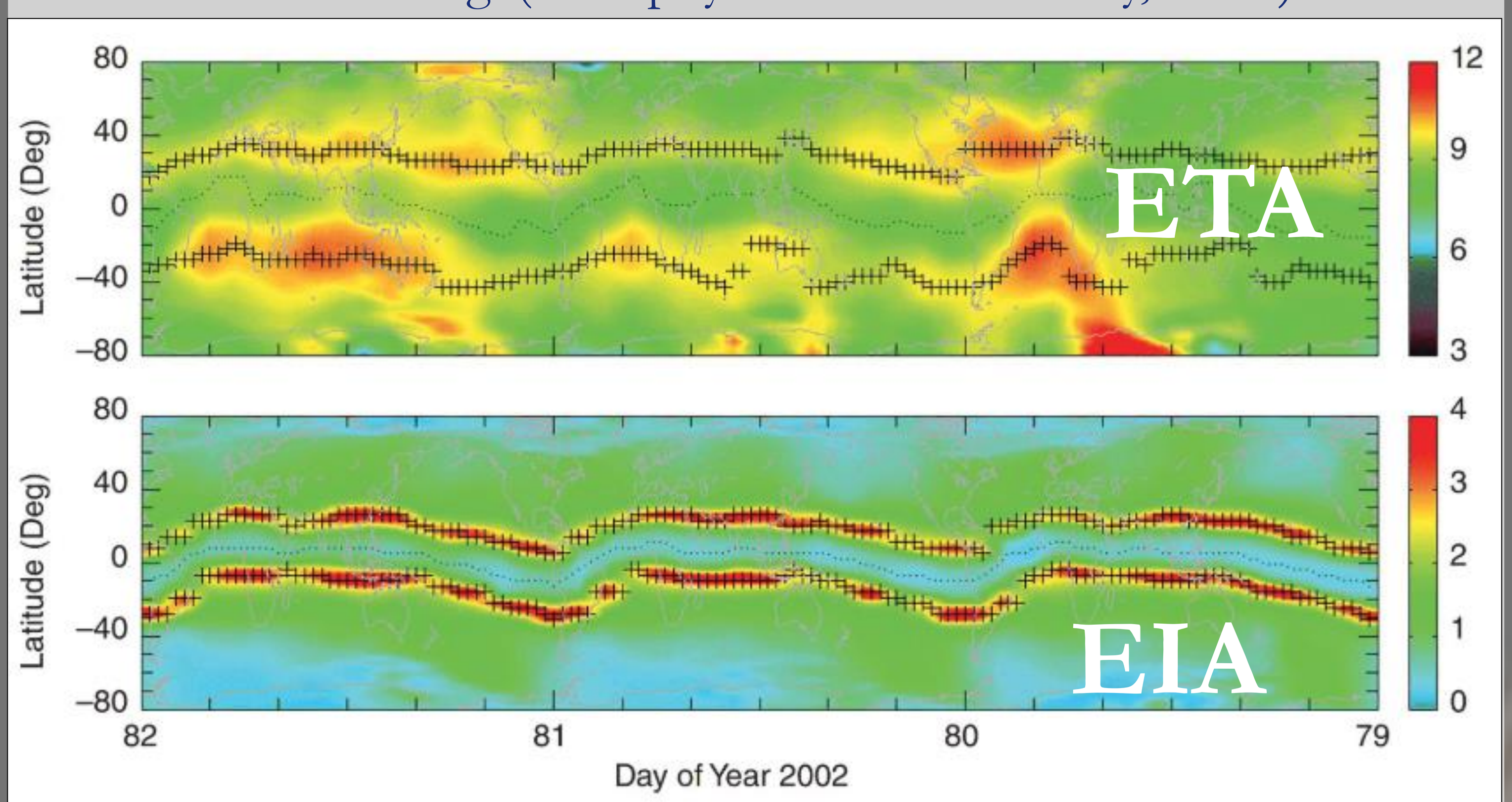


Background

- **Equatorial Ionosphere/Thermosphere anomalies (ETA/EIA) affect satellite drag and GPS signals**, posing risks for civilian, commercial, and military systems—especially during geomagnetic storms.
- **Sudden stratospheric warmings (SSWs)** dramatically influence upper atmospheric dynamics, potentially altering neutral wind patterns that propagate into the ionosphere.
- Despite frequent SSW occurrences, **their role in ETA formation is largely unexplored**, leaving a critical gap in understanding lower atmosphere–ionosphere coupling. (Goncharenko et al., 2020)
- **Addressing this gap is essential** for advancing models of thermosphere-ionosphere electrodynamics and improving space weather forecasting. (Heliophysics Decadal Survey, 2024.)



(EIA and ETA as observed by CHAMP taken from Lei et al., 2021)

Methodology

- **Several factors can affect ETA and EIA derivations**
  1. **Orbit eccentricity** – to counter this the density is normalized to the mean satellite altitude using Eq 1.

$$\rho_{mean_{alt}} = \rho_{o,x} e_o^{(h_o - mean_{alt})/H} \quad (1)$$

NRL's MSIS 2.0 (Mass Spectrometer, Incoherent Scatter Radar Extended Model) is used for this normalization. (Buynovskiy et al., 2024 and the references therein)

  2. **Large Scale variations** – A low pass filter with a 990s window is used for every orbit to remove any solar flux variances from the anomaly signal given in Eq. 2

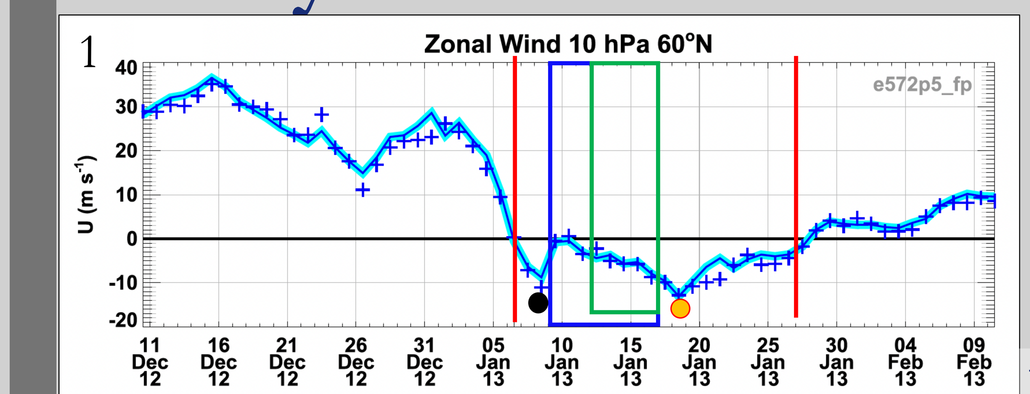
$$\rho_{ETA}\% = \left(\frac{\rho}{\rho_{bckg}} - 1\right) \times 100 \quad (2)$$

3. Solar local time (SLT) variations – EIA and ETA peak on the dayside; accurate local time coverage is key to capturing their structure and daytime evolution, as ETA closely follows the EIA and fades after sunset. (Hsu et al., 2014)

4. Geomagnetic variations – affect ETA and EIA (Liu et al., 2010) so the data is filtered for $K_p <= 3$.

5. Solar cycle variations – ETA and EIA intensify during periods of high solar flux, so analyses are conducted under similar solar cycle conditions to ensure consistency and comparability. (Hsu et al., 2014)

Analysis and Results: What is the Hidden Impact of SSW on ETA & EIA?



Case Study: Major SSW (NH) of Jan 2013

SSW duration: Jan 6th – 27th, 2013 (marked in red bars) as per Coy and Pawson, 2015.

Quiet time dates chosen: Jan 1st to March 31st, 2012 since 2012 and 2013 had similar solar flux.

SSW starts on 6th, EIA disappears on 9th, ETA disappears on 12th. Both anomalies recover by 18th - the same day the zonal wind at 10hPa shows a second dip.

Fig 1. SSW duration shown by zonal wind reversal at 10hPa and 60°N (taken from Coy and Pawson, 2015)

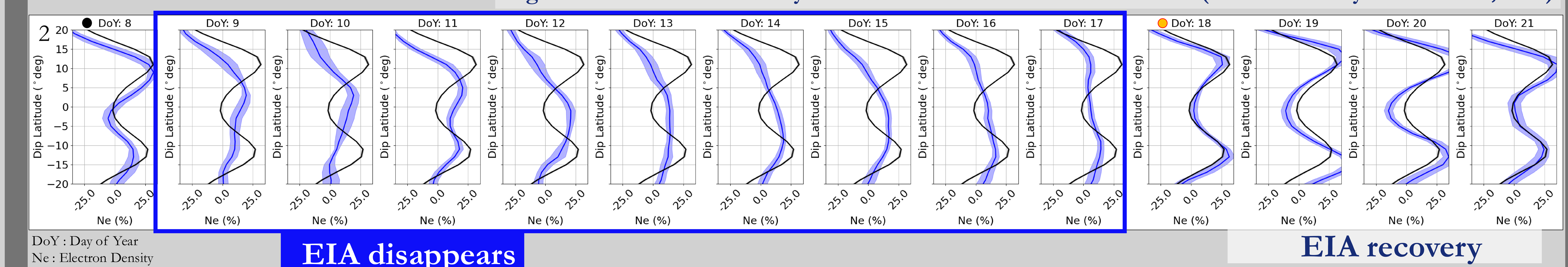


Fig 2. Mean EIA for each day during SSW shown in blue (with lighter blue as standard error) and mean EIA during quiet time (no SSW) shown in black (with grey as standard error) using GRACE data. The mean SLT is 16.5 hours. The blue box marks EIA disappearance.

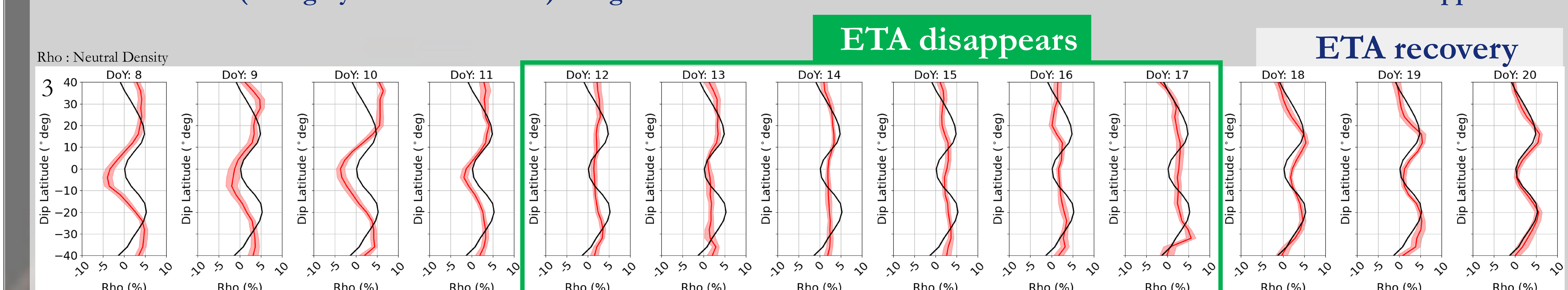


Fig 3. Mean ETA for each day during SSW shown in red (with lighter red as standard error) and mean ETA during quiet time (no SSW) shown in black (with grey as standard error) using GRACE data. The mean SLT is 16.5 hours. The green box marks the ETA disappearance.

Do all SSWs have an Impact? How?

The impact depends on both the phase of the solar cycle and the intensity of the SSW event—whether it is classified as major or minor—among other key drivers. Preliminary analysis using GRACE data reveals some effects associated with the major SSW event of January 2003.

	SSW	Major/Minor	NH/SH	Solar cycle phase	Satellite
1.	Mar 2023	Major	NH	Max	GRACE-FO, GOLD
2.	Feb 2024	Minor	NH	Max	GRACE-FO, GOLD
3.	Jul 2024	Minor	SH	Max	GRACE-FO, GOLD
4.	Jan 2021	Major	NH	Min	GRACE-FO
5.	Sep 2019	Minor	SH	Min	GRACE-FO

The table shows a few selected SSW cases that are currently under investigation for any trends in impact of SSW on ETA and EIA under different cases.

Conclusions and Key Takeaways

1. **First observational evidence to show that ETA disappears following EIA disappearance (well known e.g. Gan et al., 2024) during a major SSW event.**
2. Both EIA and ETA exhibit stable, recurring patterns under normal conditions but are significantly disrupted by terrestrial forcing associated with SSW events.
3. EIA vanishes ~3 days after SSW onset; ETA follows ~6 days (preliminary).
4. The reversal of zonal winds in the middle atmosphere during SSW events weakens the vertical coupling mechanisms that sustain equatorial ionospheric and thermospheric anomalies.
5. **These findings underscore the sensitivity of equatorial upper atmospheric structures to lower atmospheric dynamics, highlighting the importance of cross-layer coupling in space weather variability**

What's Next?

- Complete the investigation of different cases of SSW events.
- Investigate the time delay of ETA and EIA disappearance by looking at different pressure levels for zonal wind reversals for SSW instead of 10hPA.
- Improve the filter sensitivity to extract ETA/EIA during solar minima cases with methods such as PCA or ADA. (Buynovskiy et al., 2024)
- Tidal analysis of before-during-after SSW to see the impact of tides on ETA/EIA and their coupling. (Navarro et al., 2023, Oberheide et al., 2021)
- Use TIEGCM to simulate and compare observations of ETA/EIA

Selected References:

1. Lei et al., 2012.
2. Hsu et al., 2014.
3. Coy and Pawson, 2015
4. Lei et al., 2021.
5. Heliophysics Decadal Survey (2024).
6. Goncharenko et al., 2020.
7. Gan et al., 2024.
8. Buynovskiy et al., 2024.
9. Navarro et al., 2023.
10. Oberheide et al., 2021.

Background image credit: ICON/NASA

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