ETA Variability and Its Coupling with EIA during Sudden Stratospheric Warmings

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Background

Equatorial Ionosphere/Thermosphere anomalies (ETA/EIA) are unique natural laboratories for studying electrodynamics, ion-neutral coupling and atmosphere-space coupling.

- **Sudden stratospheric warmings (SSWs)** dramatically influence upper atmospheric dynamics, potentially altering neutral wind patterns that propagate into the ionosphere.
- Impact of SSWs on ETA is unknown.
- **Addressing this gap is essential** for advancing models of thermosphere-ionosphere electrodynamics and improving space weather forecasting. (Heliophysics Decadal Survey, 2024.)

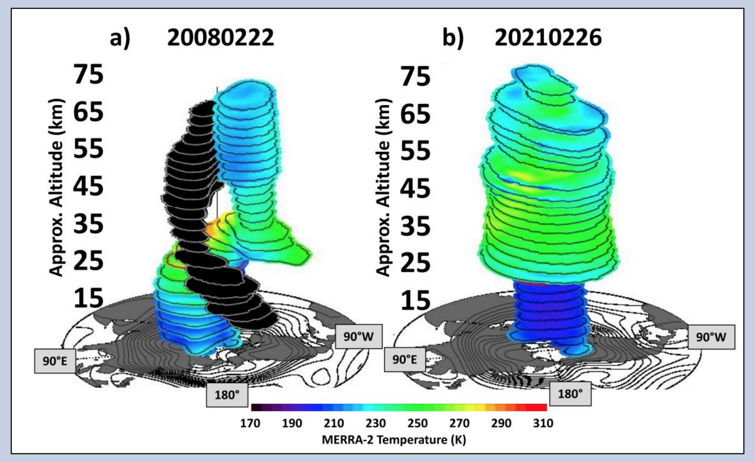


Fig 1. (a)Weak and (b) strong polar vortex using MERRA-2, taken from Greer et al., 2023.

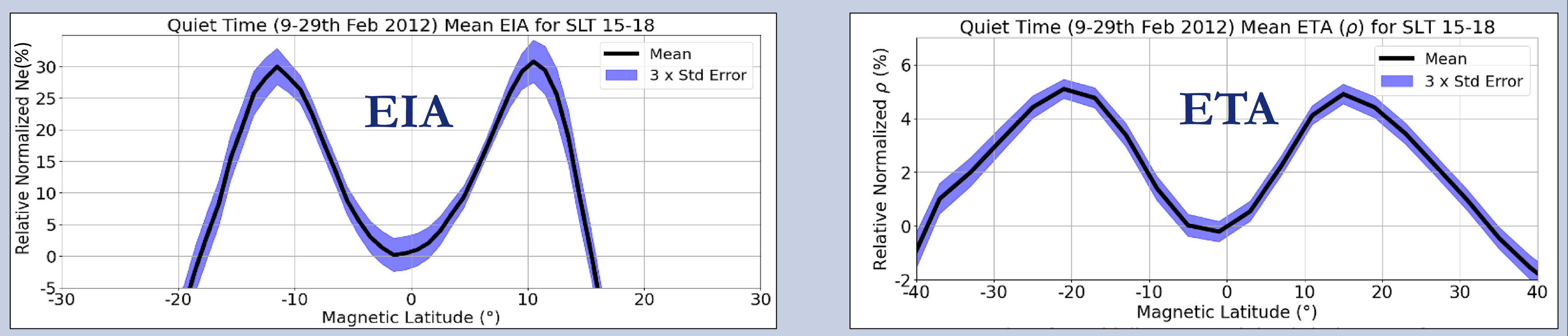


Fig 2. Averaged (a) EIA and (b)ETA using GRACE-A plasma and neutral density, respectively.

Science Questions

1. **Systematic response:** Does the ETA disappear and recover consistently across SSW events?
2. **Event dependence**: Does disappearance timing vary with SSW strength, type, or hemisphere?
3. **External drivers:** Does ETA behavior shift with solar flux or lunar tidal phase during SSWs?
4. **Closure:** Can the ETA serve as a robust tracer of whole-atmosphere coupling during SSWs?

Results: What is the Hidden Impact of SSW on ETA & EIA during 2013 Major SSW?

Stratospheric Characterization of the 2013 SSW

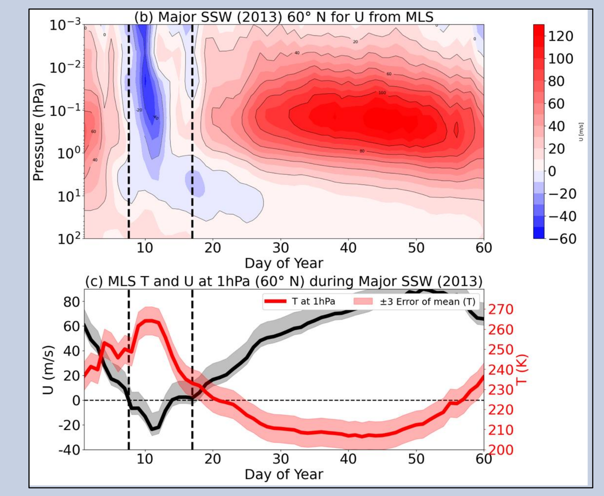
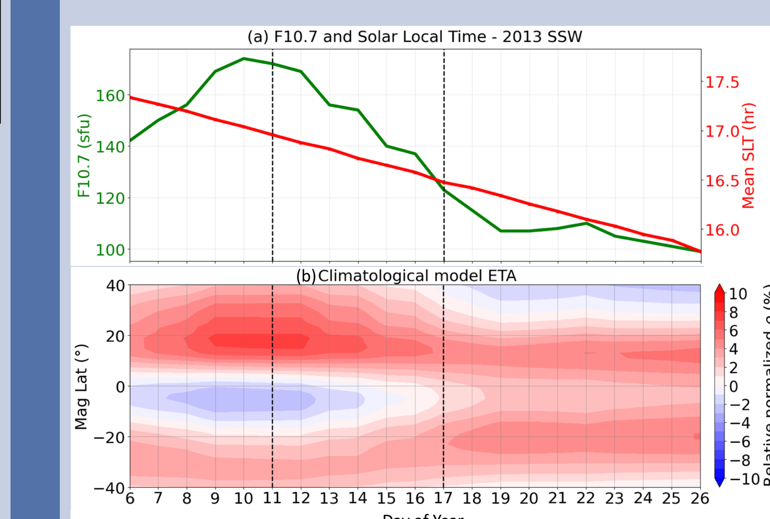


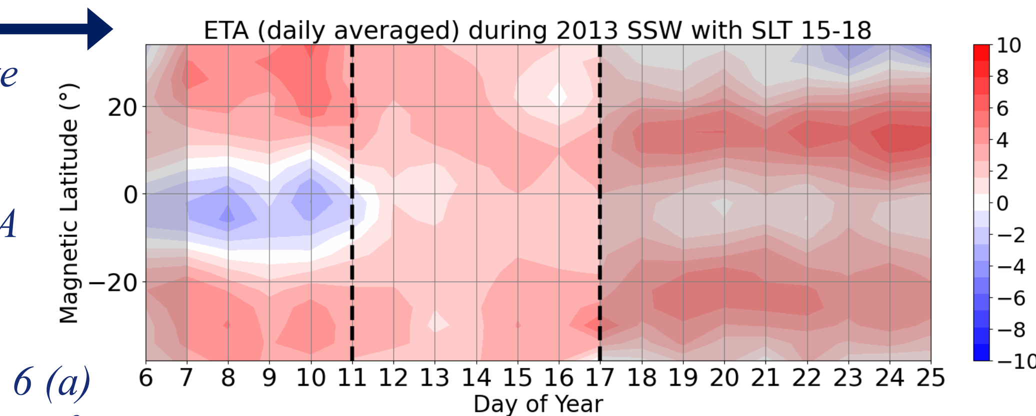
Fig. 3 (a) Zonal mean zonal wind (U) at 60°N contour plot and (b) U and temperature at 60°N 1 hPa from Microwave Limb Sounder (MLS) onboard NASA's AURA satellite.

SSW duration: 6th - 17th Jan 2013



Case Study of ETA Variability due to 2013 Major SSW

Fig. 5 Daily relative neutral density from GRACE-A satellite during SSW 2013.Unshaded area marks the SSW period. Dashed vertical lines show ETA disappearance.



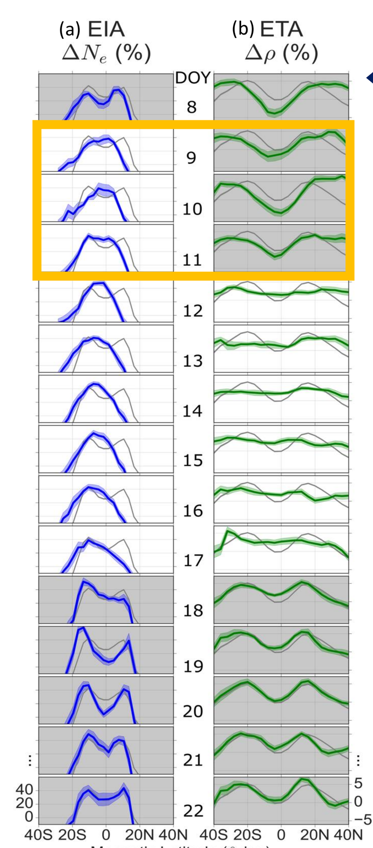


Fig. 6 (a) Line plots of relative plasma density (EIA) measured from K-band ranging (KBR) on GRACE and (b) relative neutral density (ETA) in their daily progression. The unshaded boxes show EIA and ETA weakening and disappearances.

ETA persists 3 days without EIA!

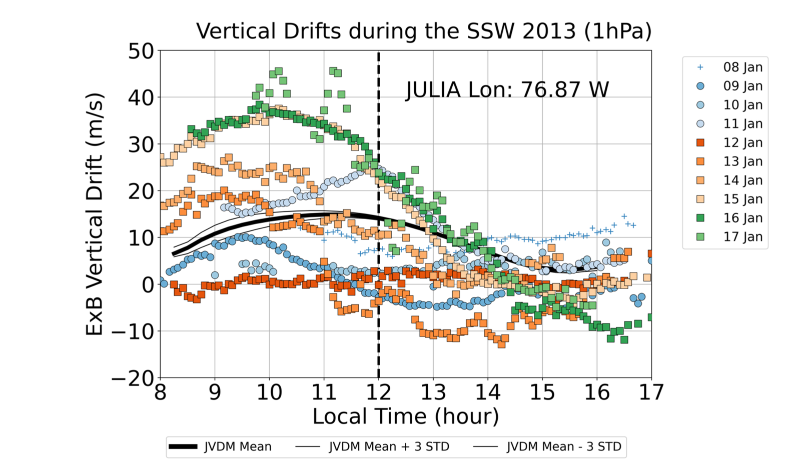
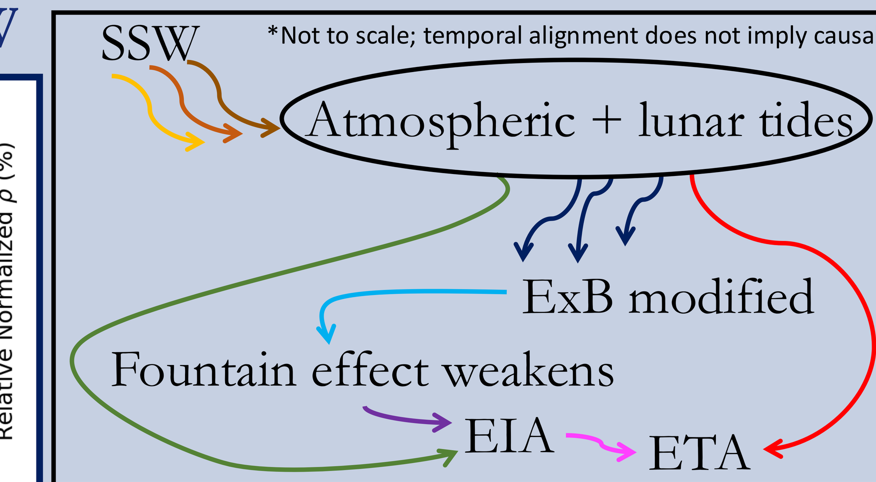


Fig. 7 Vertical drifts from JULIA radar system during SSW. Mean ± standard error from the Julia Vertical Drifts Model (JVDM) (Alken, 2009) to show modulation in ExB drifts.

Fig. 4 (a)F10.7 solar flux and GRACE-A local time coverage during the SSW period. (b) A climatological model of ETA made with GRACE-A data from 2004-2017 using Alken (2009) methodology. This model takes F10.7 and local time as inputs and gives out geomagnetic and terrestrial quiet ETA.

How ETA would have looked in January 2013 in the absence of SSW!



Proposed secondary driver: SSW-enhanced tides (specifically SW2) can sustain ETA independently of EIA.

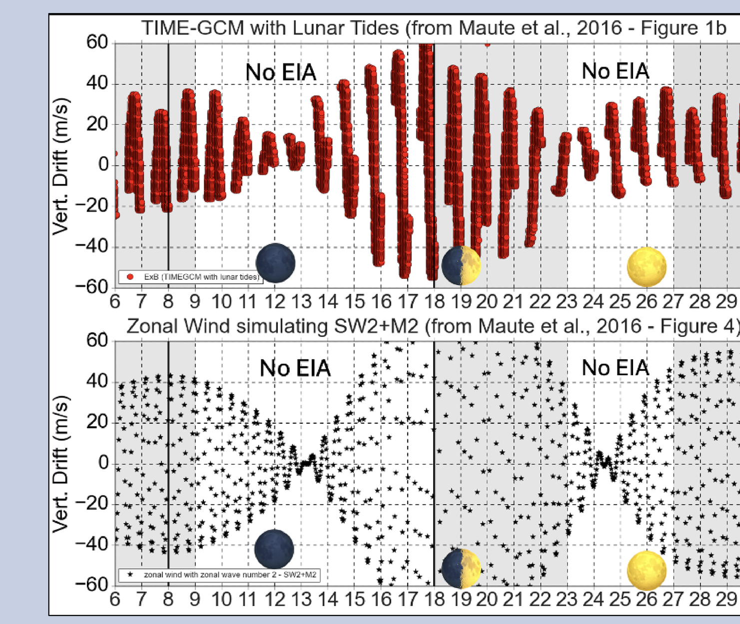


Fig. 8. Results from Maute et al. 2016 overplotted with ETA/EIA disappearance timeline

Without SSW, tides might be too weak to sustain ETA alone.

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.

$$\rho_{norm_{alt}} = \rho_{sat_{alt}} e^{(sat_{alt} - 453.83)/H} \quad (1)$$

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). For EIA, pyIRI (Forsythe et al., 2024) is used for normalization.

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

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

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)

SSW events with elevated stratopause selected for this analysis (Harvey et al., 2025)

SSW	NH/SH	Major/Minor	Solar Phase	Onset Date (using MLS)	Satellites	Next New Moon (+ days)	QBO Phase*
Jan 2006	NH	Major	Solar min	2006-01-17	GRACE	8	East
Jan 2009	NH	Major	Solar min	2009-01-20	GRACE	2	West
Jan 2010	NH	Major	Solar min	2010-01-28	GRACE	21	East
Jan 2013	NH	Major	Solar max	2013-01-06	GRACE	5	East

SSW definition: at 60°N, zonal mean zonal wind at 1hPa <0

* Siddiqui et al., 2018

Results: Do all SSWs impact the ETA in the same way?

Preliminary Analysis of SSWs with Elevated Stratopause (2006 and 2010)

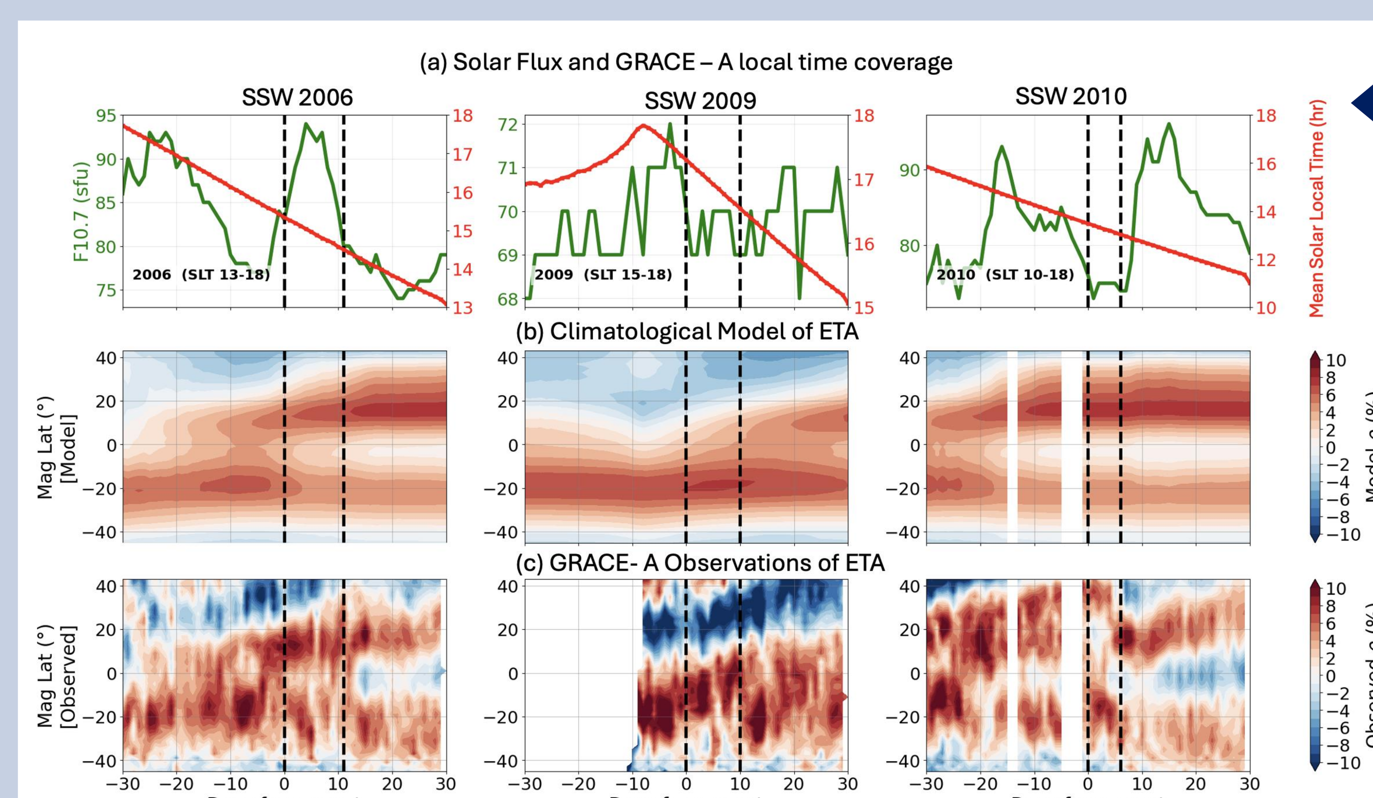


Fig. 9(a) Solar flux and GRACE-A solar local time coverage during 2006 (left), 2009 (middle) and 2010(right) SSWs. Preliminary plots of (b) climatological model of ETA (same method as above) for the three SSWs. (c) GRACE-A ETA observations days before and after SSW onset.

- GRACE-A solar local time coverage during 2009 SSW was same as 2013. The only difference between the two model contour plots is the different F10.7 inputs.
- During lower solar flux, the local time variations overpower the model.
- There is some local time variation seen in both model and observations.
- ETA recovers within a few days after the SSW in 2006 and 2010 case.

Several factors could be contributing to the ETA variability during an SSW:

1. Strength of the SSW and whether it has an elevated Stratopause
2. Lunar tide phase
3. QBO phase
4. Solar flux
5. Local time coverage available during observations and
6. Geomagnetic storm conditions
7. Presence of solar flares

3 competing pathways for ETA:

1. E-region dynamo
2. Direct Tidal forcing
3. Compositional changes

Conclusions and Key Takeaways

1. First observational evidence of ETA disappearing 6 days after the onset of major sudden stratospheric warming in 2013.
2. EIA disappears first and after 3 days ETA disappears., revealing complex ETA-EIA coupling in geomagnetically quiet conditions.
3. SSW-modulated tides can independently sustain ETA in the absence of EIA.
4. We propose a dual-mechanism for ETA: ion drag from EIA is the primary driver, but SSW-enhanced SW2 tides can act as a secondary mechanism that temporarily sustains ETA when the primary driver is disrupted, until lunar M2 interference overwhelms it.

What's Next?

- Look into more SSW cases
- Complete ETA characterization during all different types of SSWs
- Use TIEGCM to simulate and compare observations of ETA/EIA along with tidal analysis.

Selected References:

1. Greer et al., 2023
2. Lei et al., 2012.
3. Hsu et al., 2014.
4. Coy and Pawson, 2015
5. Lei et al., 2021.
6. Heliophysics Decadal Survey (2024).
7. Goncharenko et al., 2020.
8. Gan et al., 2024.
9. Buynovskiy et al., 2024.
10. Navarro et al., 2023.
11. Oberheide et al., 2021.
12. Siddiqui et al., 2018
13. Sunkara et al., 2024

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