Assessing the Relationship Between the Quasi-Biennial Oscillation and D-Region Electron Density

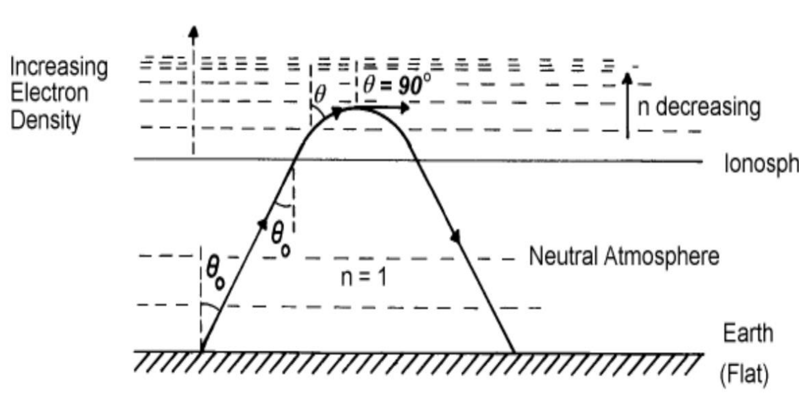
Natalie R. Wirth[1,2], Kyle E. Fitch[1], Daniel J. Emmons[1], Dong L. Wu[3], Jae N. Lee[3], and Cornelius C.J.H. Salinas[3]
[1] Department of Engineering Physics, Air Force Institute of Technology, Dayton, OH
[2] 2nd Weather Squadron, 557th Weather Wing, Offutt Air Force Base, NE
[3] NASA Goddard Space Flight Center (GSFC), Greenbelt, MD
Corresponding author: natalie.wirth@us.af.mil

SIGNIFICANT RELATIONSHIP BETWEEN QBO AND D-REGION ELECTRON DENSITY WITH HEMISPHERIC ASYMMETRY

INTRODUCTION

- Past research mostly focused on upper ionosphere
- D-region largely neglected, but closest layer to lower atmosphere and linked to both solar and terrestrial phenomena
- Radio wave propagation sensitive to **D-region electron density (N_e)** —especially high frequency (HF) waves—through refraction, attenuation, and fading; accurate N_e prediction critical for HF communications
- D-region N_e, in turn, sensitive to oscillations such as Quasi-Biennial Oscillation (**QBO**), which transports momentum into the upper stratosphere and mesosphere/lower thermosphere (MLT)
- Open research questions addressed here:
  1. How strong & predictable is the D-region N_e & QBO relationship?
  2. What are its latitudinal extent and hemispheric tendencies?

Fig 1. Snel's law for signals traversing varying electron densities



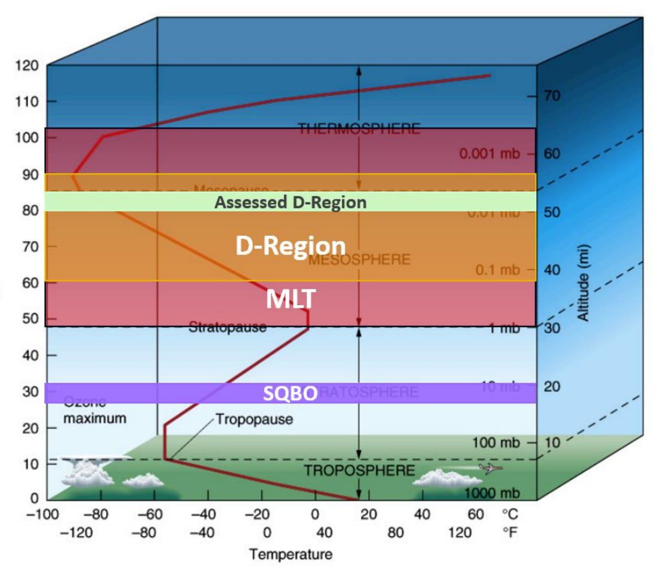


Fig 2. Regions of the atmosphere with areas of research overlayed.

METHODOLOGY

- Equatorially averaged the day and night electron density then **detrended** using a Savitzky-Golay filter (solar cycle removed).
- A Butterworth **low-pass filter** was also applied to the equatorially averaged electron density.
- Separated the **day and night electron density into 10-degree latitude bins** from -50 degrees to 50 degrees then detrended using a Savitzky-Golay filter.
- Applied a **fast Fourier transform (FFT)** to equatorially averaged detrended day and night electron density, QBO 10 mb, QBO 30 mb, and the binned electron density.
- After normalizing the equatorially averaged and detrended electron density and both QBO pressure levels, a **continuous wavelet transform (CWT)** was applied
- A **cross wavelet transform (XWT)** was also applied to each of the previously normalized datasets
- Amplitudes of frequency ranges corresponding to the **QBO** (.3 to .5 yr^{-1}), **annual** (.9 to 1.1 yr^{-1}), **semi-annual** (1.9 to 2.1 yr^{-1}), and **quarterly** (3.8 to 4.2 yr^{-1}) were summed for the equatorially averaged electron density and the binned electron density

Project supported by the Air Force Research Laboratory. These views are those of the authors and do not necessarily represent those of the Department of Defense or U.S. Government.

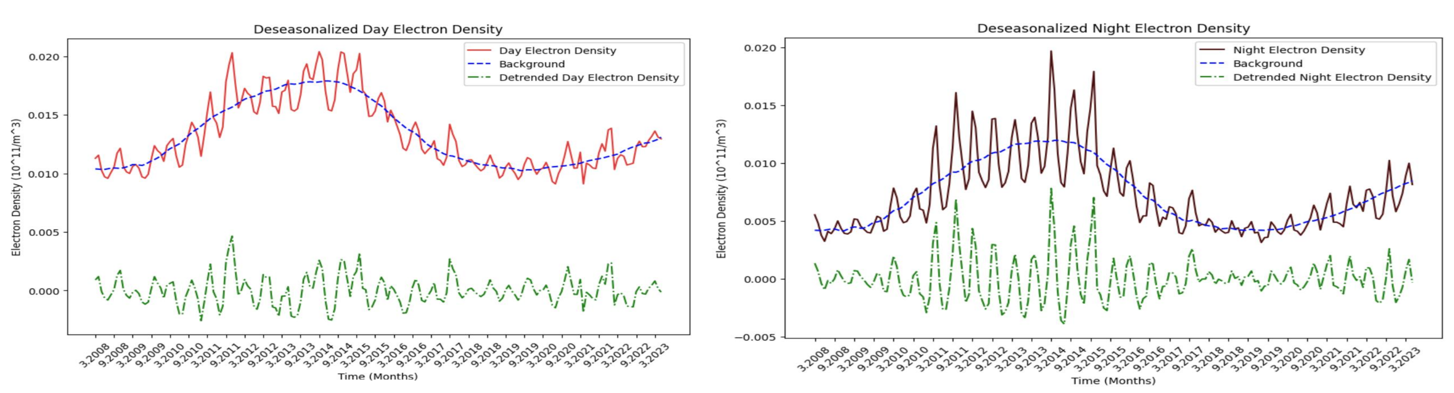


Figure 3. Detrended electron density data for day and night

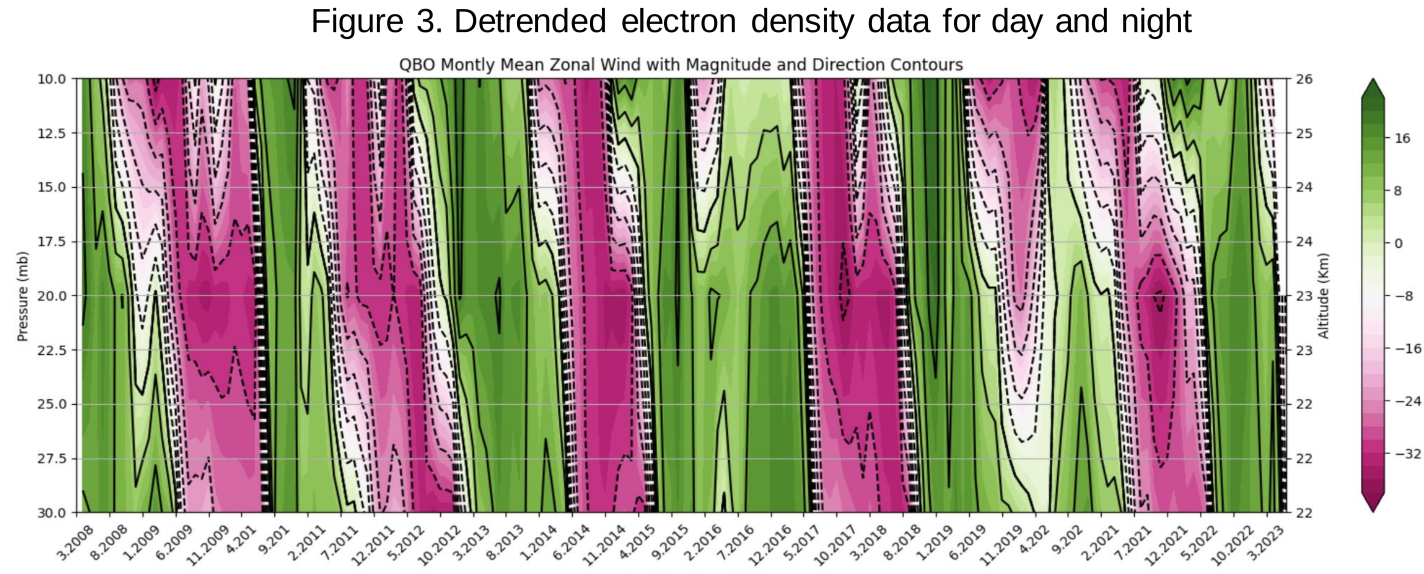


Figure 4. QBO monthly mean zonal average from 30 mb to 10 mb

RESULTS

- Notable frequencies within accepted QBO range were 0.33 yr−1 and 0.39 yr^{-1}, while 0.53 yr^{-1}, although anomalous, could be associated.
- Equatorially averaged day and night electron densities FFT analysis showed **peak frequencies** at ~2 yr^{-1}, indicating strong **semi-annual oscillations.**
  - The top frequency of 0.33 yr^{-1} was observed in both day and night electron density, suggesting a QBO influence.
- The binned electron density FFT produced the top QBO frequency of 0.33 yr^{-1} across most magnetic latitudes for both day and night data.
  - Other QBO frequencies were not prominent across all bins, indicating regional variations in QBO impact.
- Consistent phases for the QBO frequency of 0.33 yr^{-1} were observed, indicating a stable relationship over time.
  - Phases for other QBO frequencies varied between day and night datasets, suggesting diurnal variations in ionospheric response.
- For CWT there was mutual significance between QBO and electron density was observed, indicating phase relationships over time.
  - Significant correlations varied between lagging and anti-phase relationships across different time periods and latitudes.

	Prominent QBO Frequency (1/yr)									
	.3282		.5907		.3938		.5251		.2626	
Deseasonalized Day	-1.254 rad	-.61 months	-.863 rad	-.23 months	2.917 rad	1.18 months	.040 rad	.01 months	.987 rad	.60 months
Deseasonalized Night	-1.265 rad	-.61 months	-.689 rad	-.19 months	-3.116 rad	-1.26 months	.186 rad	.06 months	1.338 rad	.81 months
Deseasonalized & Annual Filter Day	-1.260 rad	-.61 months	-.881 rad	-.24 months	2.927 rad	1.18 months	.030 rad	.01 months	.993 rad	.60 months
Deseasonalized & Annual Filter Night	-1.279 rad	-.62 months	-.737 rad	-.20 months	-3.100 rad	-1.25 months	.164 rad	.05 months	1.368 rad	.83 months

Table 1. Top five QBO frequencies and the associated FFT phase in radians for detrended day and night electron density and additionally filtered day and night electron density

Table 2. Top five frequencies resulting from the FFT of the detrended night electron density data separated into magnetic latitude bins

Magnetic Latitude	#1	#2	#3	#4	#5
40° to 50°	.9846 (1.016 yrs)	.3282 (3.047 yrs)	.9189 (1.088 yrs)	1.9691 (.508 yrs)	.8533 (1.172 yrs)
30° to 40°	.9846 (1.016 yrs)	1.9691 (.508 yrs)	.3282 (3.047 yrs)	.9189 (1.088 yrs)	.2626 (3.808 yrs)
20° to 30°	.9846 (1.016 yrs)	1.9691 (.508 yrs)	.3282 (3.047 yrs)	.2626 (3.808 yrs)	2.0348 (.491 yrs)
10° to 20°	1.9691 (.508 yrs)	.3282 (3.047 yrs)	2.0348 (.491 yrs)	.2626 (3.808 yrs)	.8533 (1.172 yrs)
0° to 10°	1.9691 (.508 yrs)	2.0348 (.491 yrs)	.3282 (3.047 yrs)	.9846 (1.016 yrs)	1.0502 (.952 yrs)
0° to −10°	1.9691 (.508 yrs)	2.0348 (.491 yrs)	.9846 (1.016 yrs)	.3282 (3.047 yrs)	1.1815 (.846 yrs)
−10° to −20°	.9846 (1.016 yrs)	1.9691 (.508 yrs)	2.0348 (.491 yrs)	.2626 (3.808 yrs)	.3282 (3.047 yrs)
−20° to −30°	.9846 (1.016 yrs)	1.0502 (.952 yrs)	1.9691 (.508 yrs)	2.0348 (.491 yrs)	.2626 (3.808 yrs)
−30° to −40°	.9846 (1.016 yrs)	1.0502 (.952 yrs)	1.9691 (.508 yrs)	.9189 (1.088 yrs)	.2626 (3.808 yrs)
−40° to −50°	.9846 (1.016 yrs)	1.0502 (.952 yrs)	1.9691 (.508 yrs)	.9189 (1.088 yrs)	.2626 (3.808 yrs)

Fig 5. Top five frequencies resulting from the FFT of the detrended day electron density data separated into magnetic latitude bins

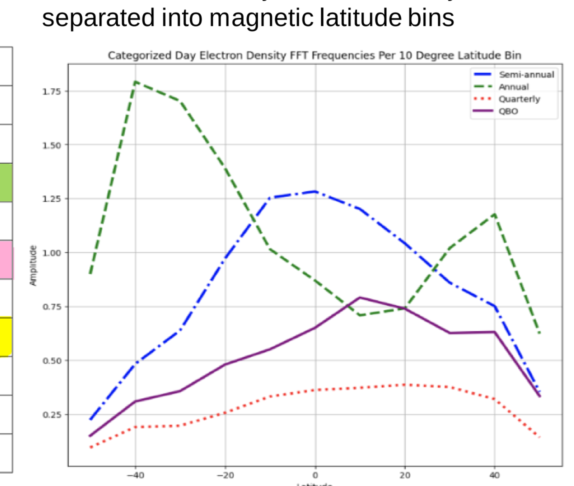


Table 3. Top five frequencies resulting from the FFT of the detrended night electron density data separated into magnetic latitude bins

Magnetic Latitude	#1	#2	#3	#4	#5
40° to 50°	.9846 (1.016 yrs)	.3282 (3.047 yrs)	1.0502 (.952 yrs)	2.1004 (.476 yrs)	1.1158 (.896 yrs)
30° to 40°	.9846 (1.016 yrs)	2.1004 (.476 yrs)	.3282 (3.047 yrs)	.2626 (3.808 yrs)	1.9691 (.508 yrs)
20° to 30°	1.9691 (.508 yrs)	2.0348 (.491 yrs)	2.1004 (.476 yrs)	.2626 (3.808 yrs)	.9189 (1.088 yrs)
10° to 20°	1.9691 (.508 yrs)	2.0348 (.491 yrs)	.3282 (3.047 yrs)	2.1004 (.476 yrs)	.9189 (1.088 yrs)
0° to 10°	1.9691 (.508 yrs)	2.0348 (.491 yrs)	2.1004 (.476 yrs)	.3282 (3.047 yrs)	1.9035 (.525 yrs)
0° to −10°	1.9691 (.508 yrs)	2.0348 (.491 yrs)	2.1004 (.476 yrs)	.3282 (3.047 yrs)	4.0039 (.250 yrs)
−10° to −20°	1.9691 (.508 yrs)	2.0348 (.491 yrs)	2.1004 (.476 yrs)	1.9035 (.525 yrs)	.9189 (1.088 yrs)
−20° to −30°	2.0348 (.491 yrs)	1.9691 (.508 yrs)	.9846 (1.016 yrs)	.1313 (7.616 yrs)	2.1004 (.476 yrs)
−30° to −40°	.9846 (1.016 yrs)	1.0502 (.952 yrs)	.9189 (1.088 yrs)	.1969 (5.079 yrs)	.1313 (7.616 yrs)
−40° to −50°	.9846 (1.016 yrs)	1.0502 (.952 yrs)	1.9691 (.508 yrs)	2.0348 (.491 yrs)	.9189 (1.088 yrs)

Fig 6. Top five frequencies resulting from the FFT of the detrended night electron density data separated into magnetic latitude bins

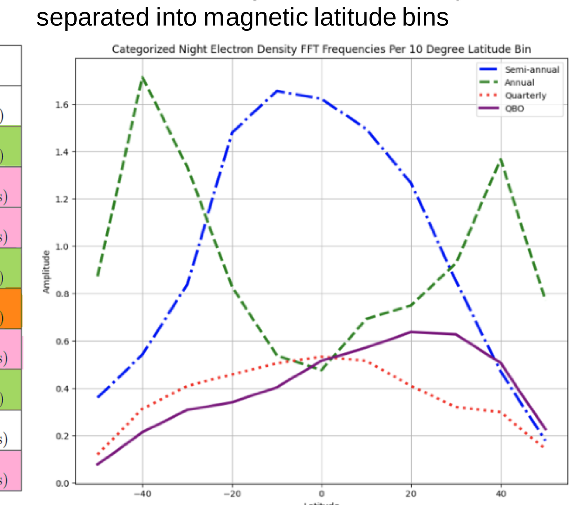
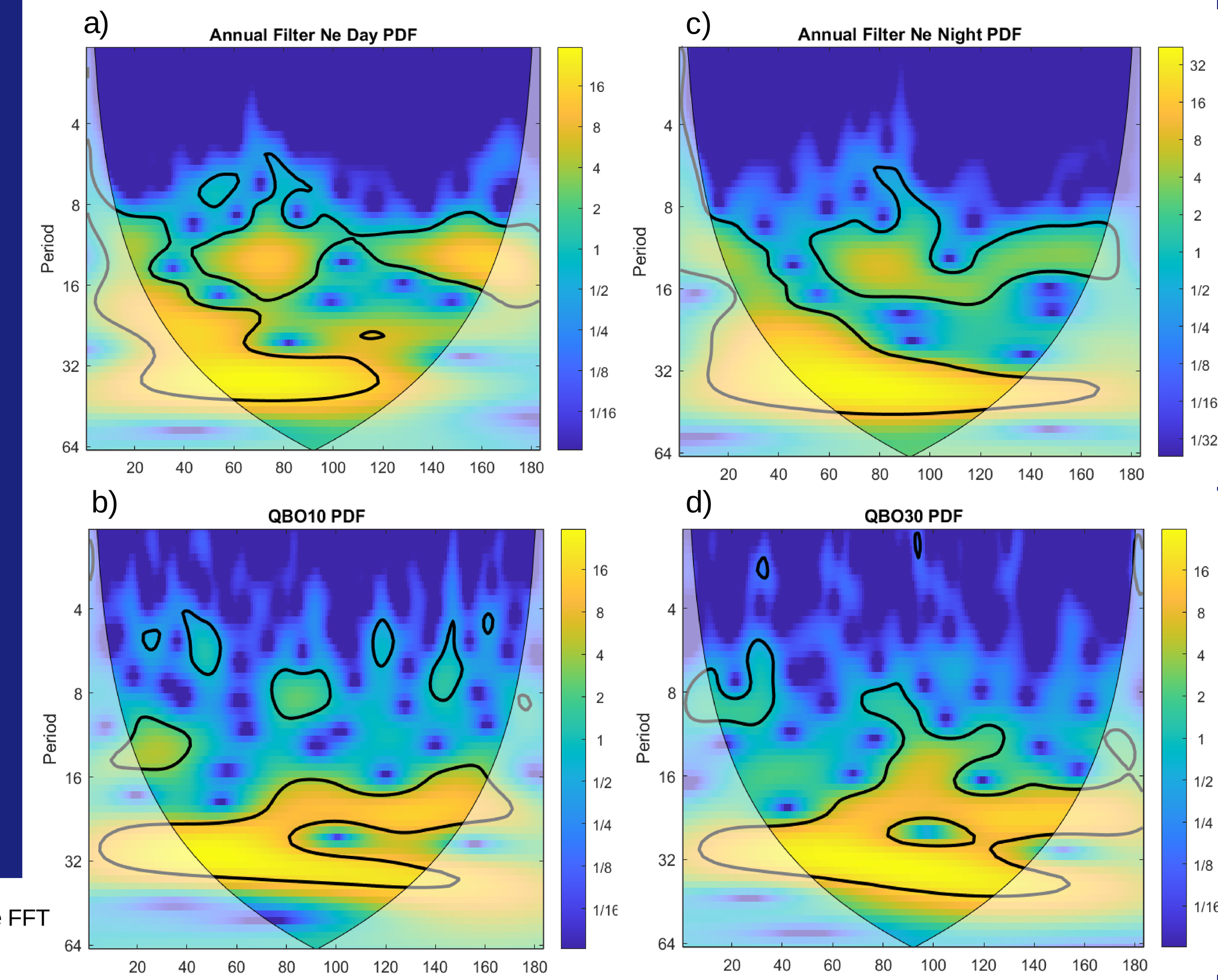


Table 4. Top five frequencies resulting from the FFT of the equatorially averaged, detrended and additionally filtered electron density data and QBO

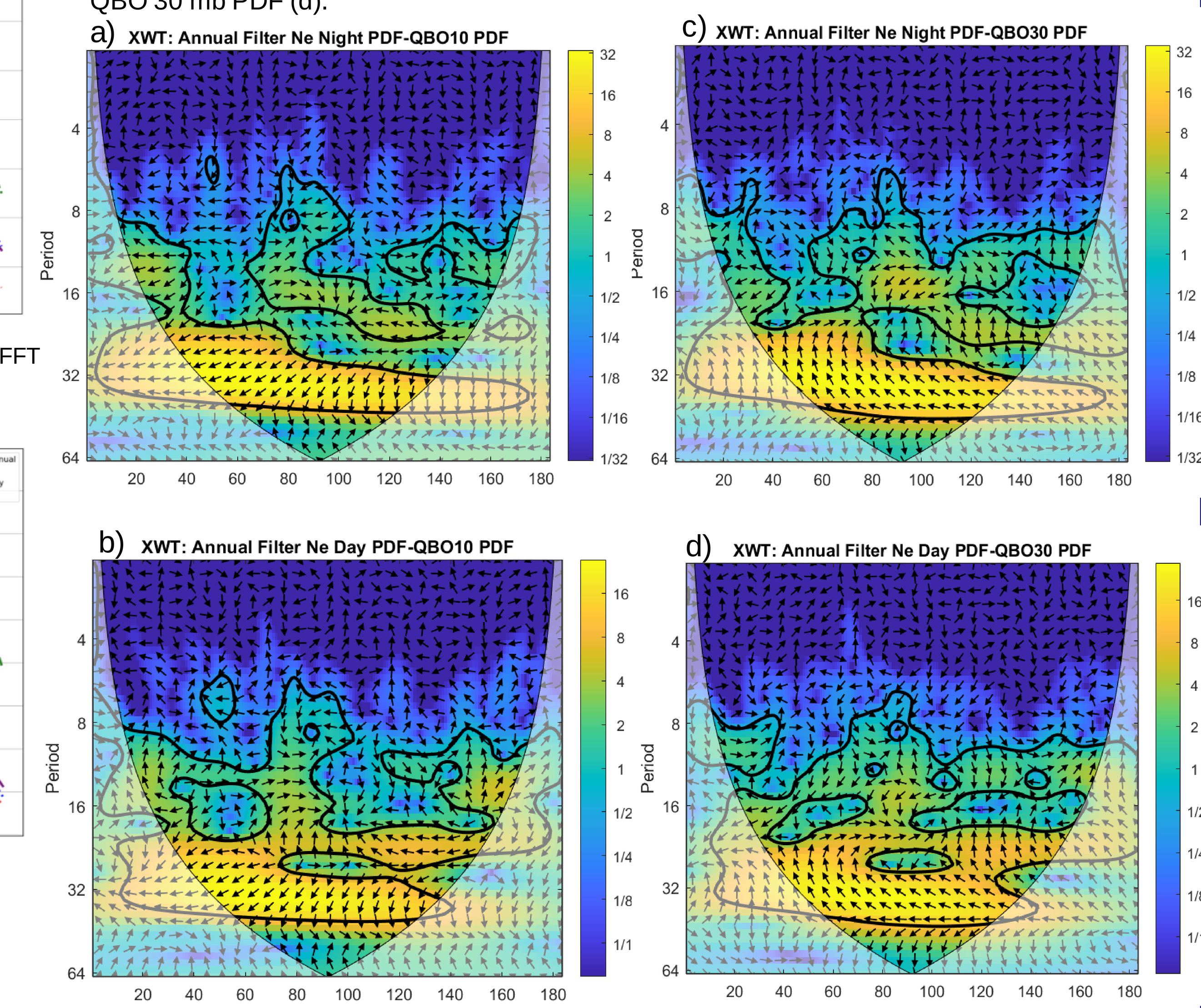
Dataset	#1	#2	#3	#4	#5
Deseasonalized Day Electron Density	1.9691 (.507 yrs)	2.0348 (.491 yrs)	0.9846 (1.015 yrs)	0.3282 (3.047 yrs)	0.5251 (1.904 yrs)
Deseasonalized Night Electron Density	1.9691 (.507 yrs)	2.0348 (.491 yrs)	2.1004 (.476 yrs)	.3282 (3.047 yrs)	1.9035 (.525 yrs)
Deseasonalized & Annual Filtered Day Electron Density	.3282 (3.047 yrs)	.9846 (1.015 yrs)	.5251 (1.904 yrs)	0.2626 (3.808 yrs)	.3938 (2.539 yrs)
Deseasonalized & Annual Filtered Night Electron Density	.3282 (3.047 yrs)	.3938 (2.539 yrs)	.8533 (1.172 yrs)	.5251 (1.904 yrs)	.9846 (1.015 yrs)
10mb QBO	.3282 (3.047 yrs)	.5907 (1.693 yrs)	.3938 (2.539 yrs)	.5251 (1.904 yrs)	.2626 (3.808 yrs)
30mb QBO	.3282 (3.047 yrs)	.3938 (2.539 yrs)	.2626 (3.808 yrs)	.5251 (1.904 yrs)	.5907 (1.693 yrs)

DISCUSSION

- Strong matching QBO frequencies indicate similar oscillation patterns between D-region electron density and QBO
- QBO Frequencies concentrated between 10 and 50 degrees for both day and night dataset
  - Second greatest frequency within these lat bins
- Uneven distribution of QBO frequencies displayed in binned electron density data
- The longest QBO frequency of .33 (3.05 years) showed very consistent negative phase at approximately -1.2 radians for each dataset with a spread of .025
  - Consistent with XWT results
- Negative night phases with .39 consistent with XWT results but positive day phases inconsistent



Figures 7: Continuous wavelet transform results for the detrended and filtered day electron density PDF (a), detrended and filtered night electron density PDF (c), QBO 10 mb PDF (b), and QBO 30 mb PDF (d).



Figures 8: Cross wavelet transform results for the detrended and filtered night electron density PDF and QBO 10 mb PDF (a), detrended and filtered day electron density PDF and QBO 10 mb PDF (b), detrended and filtered night electron density PDF and QBO 30 mb PDF (b), detrended and filtered day electron density and QBO 30 mb PDF (d).

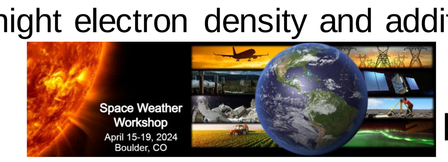
Future Work:

- Expanding the latitude bins
- Additional filtering of datasets to remove other oscillation cycles
- Investigating the relationship between atmospheric components such as ozone or nitroxide could reveal additional relationships between the QBO and the lower ionosphere
- Exploring the seasonal and climatological migration of the QBO and the impact of electron density on these shifts

References:

Baldwin, M., Gray, L., Dunkerton, T., Hamilton, K., Haynes, P., Randel, W., and others. (2001). The Quasi-Biennial Oscillation. Reviews of Geophysics, 39 (2). doi: 10.1029/1999RG000073

Tascione, T. F. (2010). Introduction to the Space Environment (2nd ed.). Malabar, USA: Krieger Publishing Company



Presented at the 2024 Space Weather Workshop 15-19 April 2024