Seasonal Impacts of Atmospheric Tides on High-Latitude Gravity Waves

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Introduction

High-frequency **atmospheric gravity waves (GWs) are core drivers of momentum and energy transport** in the middle and upper atmosphere. Due to observational constraints, questions remain regarding seasonal and multi-year interactions between these waves (wavelengths 10s – 100s km, periods < 60 min) and larger-scale atmospheric dynamics in the polar region.

The semidiurnal atmospheric tide (period ~12 hrs) is a **dominant winter driver of background wind modulation**, regularly exceeding 30 m/s in amplitude. As a result, the **conditions for effective** vertical **GW propagation will change with varying tides**.

This work presents a seasonal analysis of GW activity amid changing tidal amplitudes and phases, **improving our understanding of cross-scale coupling** at high latitudes.

At-a-Glance

This work investigates seasonal, high-latitude coupling between mesoscale atmospheric gravity waves (GWs) and the semidiurnal atmospheric tide.

GW spectral power is shown to be consistently lower at times of high semidiurnal tidal amplitude.

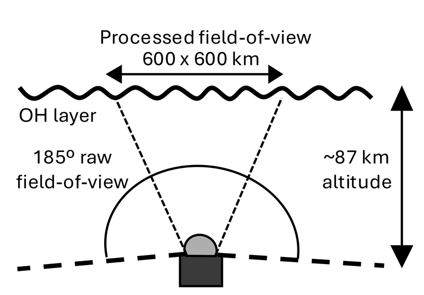
- Results are consistent across winters, directions, and altitudes near the mesopause (~87 km in altitude).
- Sampling improvements will enable future investigations into tidal phase dependencies and diurnal or terdiurnal tidal impacts on GW propagation.

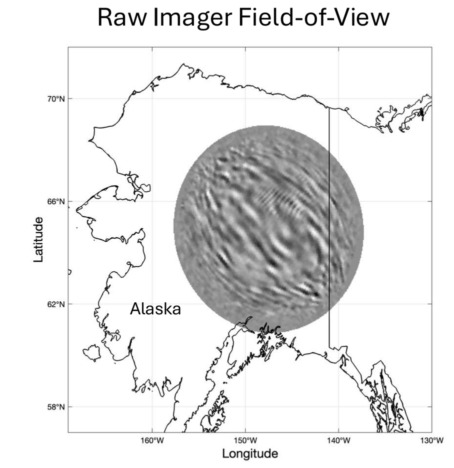
Methods - Keogram Analysis

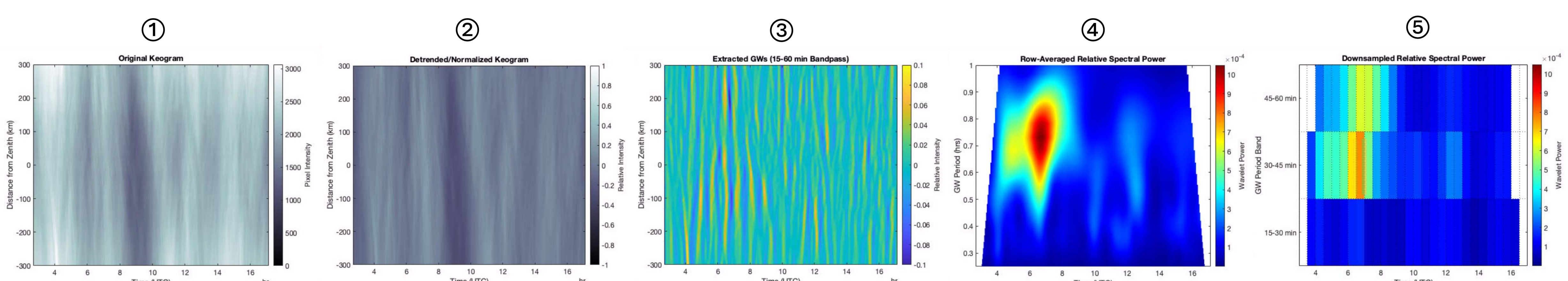
Images used to create keograms are taken by a hydroxyl (OH) all-sky imager located at the Poker Flat Research Range in interior Alaska (65.12 ° N, 147.43 ° W). This imager operates at a 10 s cadence during nighttime hours from September – April each winter, observing GW signatures in OH Meinel band emissions.

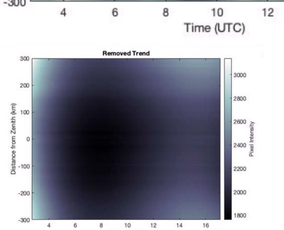
Nightly keograms are produced by taking the central slice of each image in the zonal or meridional direction, then by assembling slices as a forward progression in time using image timestamps. Keograms are de-trended and normalized, then processed using wavelet analysis to extract relative spectral power – a reasonable proxy for quantifying GW activity.

Temporal resolution: 10 s
Spatial resolution: 0.5 km
Pixel variable: Relative OH emission intensity







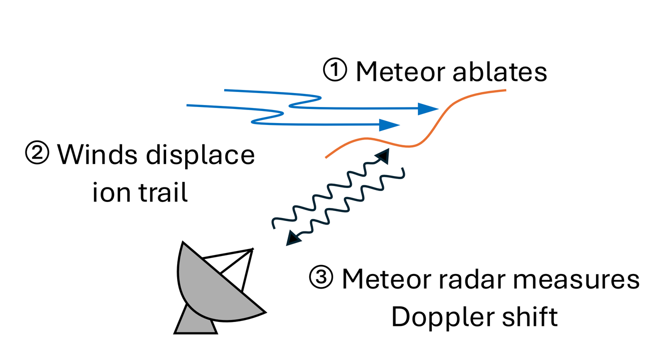


Example: Jan 12, 2024 - Zonal

Original keogram is detrended and normalized using row-by-row 3rd-degree polynomial fitting. → Normalized keogram is filtered using 4th-order 15-60 min Butterworth bandpass filter. → Filtered keogram is processed using continuous wavelet transform to extract spectral power. → Spectral power is down-sampled by 30-min time and 15-min GW period bins for write out to CSV.

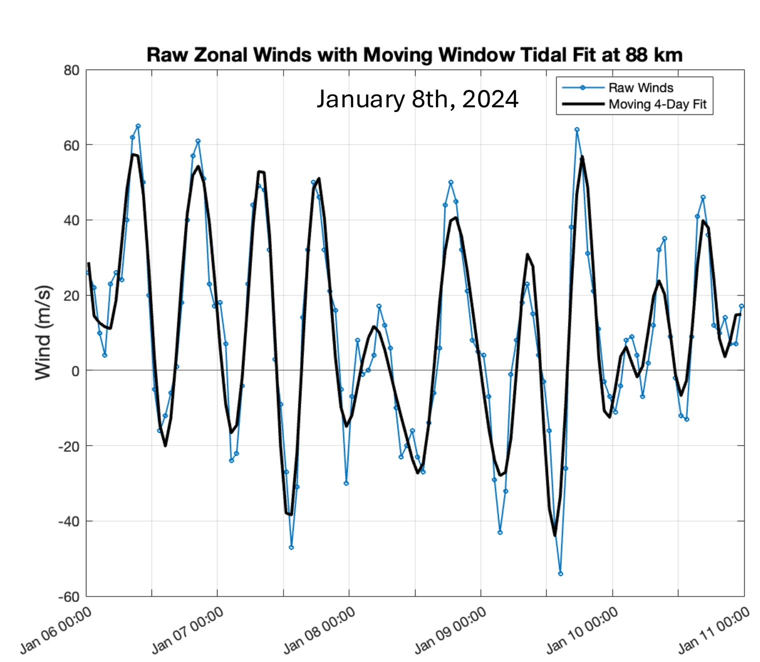
Methods – Harmonic Tidal Extraction

Background winds are recorded with the Poker Flat Meteor Radar (PFMR) by observing the Doppler shift of ablating meteoroids' ion trails. Tides are extracted from background winds by fitting a truncated Fourier series over a 4-day moving window with diurnal (24 hrs), semidiurnal (12 hrs), and terdiurnal (8 hrs) periods. Tidal amplitudes and phases are then calculated from fitted coefficients at keogram-extracted spectral power timestamps.

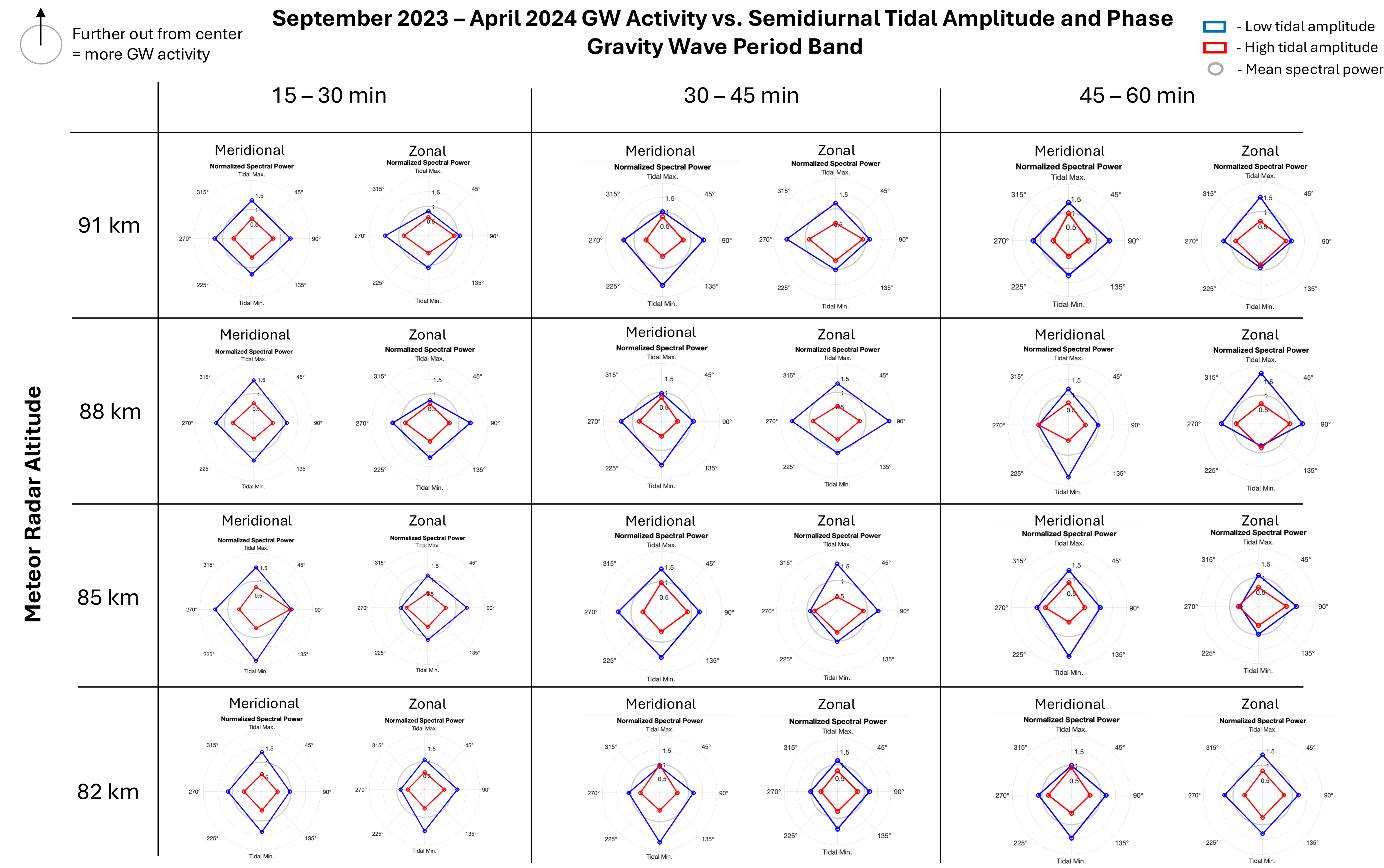


$$y(t) = a_0 + \sum_{k=1}^{3}\left[a_k \cos\left(\frac{2\pi k t}{24}\right) + b_k \sin\left(\frac{2\pi k t}{24}\right)\right]$$

a_k, b_k – fitted Fourier coefficients
y – fitted wind measurement
t – time
k – harmonic number ($k = 1, 2, 3$)
a_0 – mean wind level (offset/intercept)



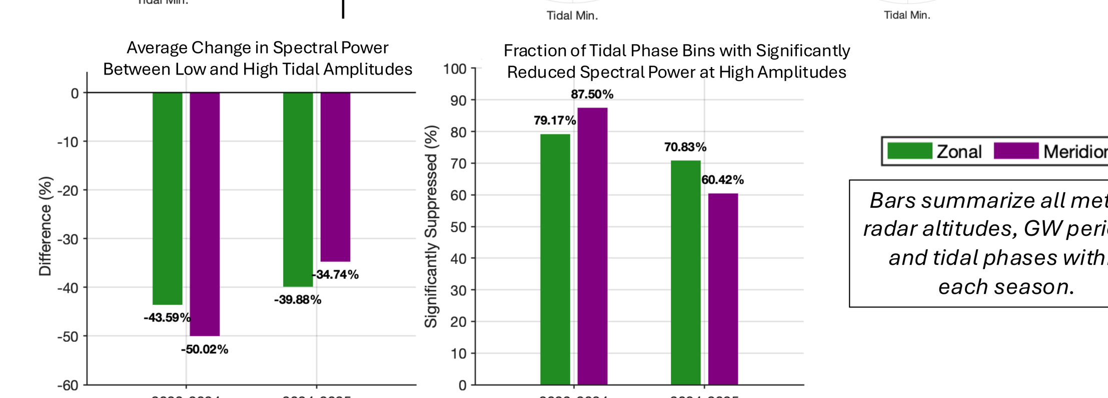
Results - Gravity Wave Activity vs. Tidal State



Spectral power observations and tidal wind measurements are time-matched and compared by:

1) Normalizing observations by the sample mean of spectral power (to highlight GW enhancement or suppression).
2) Grouping observations relative to tidal phase (± 45º).
3) Splitting observations by tidal amplitude into lowest and highest terciles to ensure reasonable separation (generally separated as <20 m/s and >25 m/s).

Normalized **spectral power is consistently lower at times of high tidal amplitude**. This suggests that **stronger tidal modulation of background winds may suppress GW activity**. This result is consistent across two winters in both zonal and meridional directions, with a majority percent differences between tidal amplitude groups being statistically significant.



Left: Average change in normalized spectral power between low (blue) and high (red) tidal amplitude conditions, averaged across all ± 45º tidal phase bins, radar altitudes, and GW period bands. Negative values indicate lower spectral power during stronger tides.

Right: Percentage of ± 45º tidal phase bins which show significant reductions in spectral power during high-amplitude tides. A tidal phase bin is considered significantly reduced when spectral power remains lower during high-amplitude tides after accounting for uncertainty due to sample variability and size.

"The Chicken or the Egg?"

Do gravity waves suppress tides, or do tides suppress gravity waves?

GW momentum deposition may suppress tidal amplitudes near the mesopause. In contrast, **tidal modulation of background winds may suppress GW activity**. While a combination of both is likely true, concluding which effect is dominant requires an investigation of event-specific GW-tide phase interactions [1][2][3][4][5].

High amplitude tides → Strong background wind modulation → GWs are filtered

vs.

Strong GW activity → GW drag impacts slow-varying winds → Tidal amplitude is reduced

Conclusions

GW spectral power was lower across all spectral ranges and all altitudes **during times of high semidiurnal tidal amplitude**.

- This result is consistent for analyzed winter observations from 2023 – 2024 and 2024 – 2025, as well as for zonal and meridional directions.
- Questions remain regarding which dynamic drives the other – GWs may reduce tidal amplitudes, or tides may suppress GWs.
- Keogram sampling improvements may contribute to future work analyzing diurnal and terdiurnal tidal impacts, as well as potential tidal phase dependency for GW enhancement or suppression.

Acknowledgements

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