Time-Dependent Evolution of Compressible Turbulence in the Heliosheath and the Very Local Interstellar Medium

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Introduction

- Heliosphere formed by solar wind (SW) interacting with the local interstellar medium (LISM).
- Voyager observations show compressible turbulence is fundamental in inner heliosheath (IHS) and LISM.
- Goals are to characterize SW turbulence and relate those characteristic to plasma density, velocity, pressure, temperature.

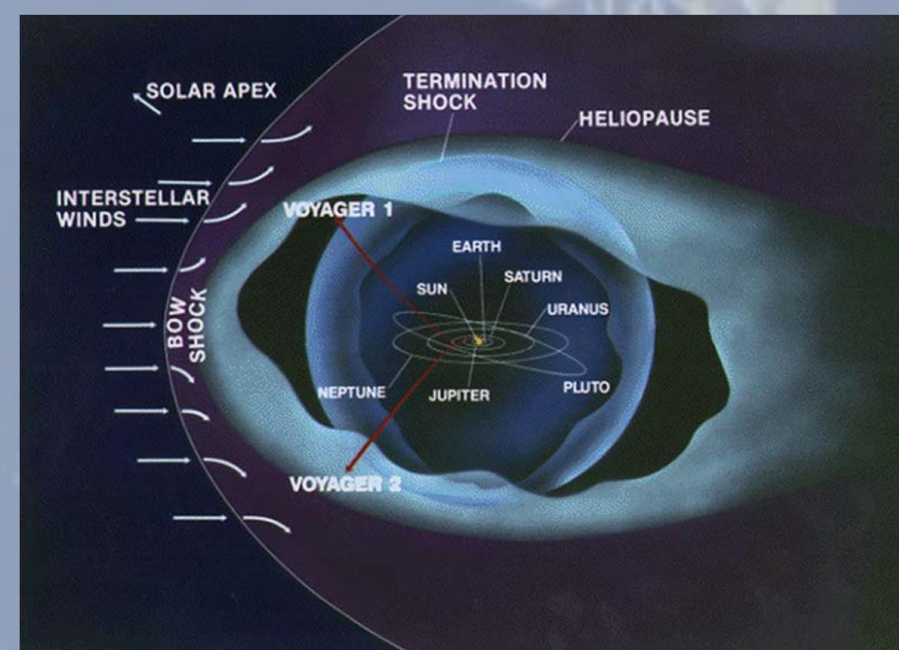

Figure 1. Cartoon of the heliosphere (from Frisch et al 2009).

- Examine SW turbulence variations with increasing distance from heliospheric termination shock (HTS) and HP.
- Used Voyager magnetic field data for Partial Variance of Increments (PVI) analysis to reveal temporal turbulence behavior.
- Cross-correlated plasma quantities and magnetic field data.

Methods

We analyzed Voyager magnetic field and SW plasma data by coupling two techniques:

1. Partial Variance of Increments (PVI):

- Calculates magnitude of increments in magnetic field vector over chosen time lag (1 hour used), normalized by the average value:

$$\mathrm{PVI}_{s,\tau} = \frac{|\Delta \mathbf{B}(s,\tau)|}{\sqrt{\langle |\Delta \mathbf{B}(s,\tau)|^2 \rangle}} \qquad \Delta \mathbf{B}(s,\tau) = \mathbf{B}(s+\tau) - \mathbf{B}(s)$$

- **B** is magnetic field, **s** is the space or time coordinate, **τ** is the spatial or temporal increment. We focusing on time increments.
- PVI analysis is applied in Figures 1-3 in the Results section.

2. Joint Probability Density Functions (PDFs)

- The second method consists of computing joint-PDFs, or histograms.
- Specifically, one or both correlated quantities are the increment of a physical variable with a specified time lag.
- Analyses shown in Fig. 4-7 allow investigation of the degree of correlation of certain quantities and their distributions within a single graph and are not affected by the numerous data gaps. No interpolation required.
- The joint PDFs involving the increments allow investigation of the scale-dependent correlation between turbulence and other quantities.
- Utilized routines developed by Fraternale (2016, 2017, 2019, 2021) in MATLAB.
- New function computes joint-PDF with increments of any quantity and plasma variables.

Results

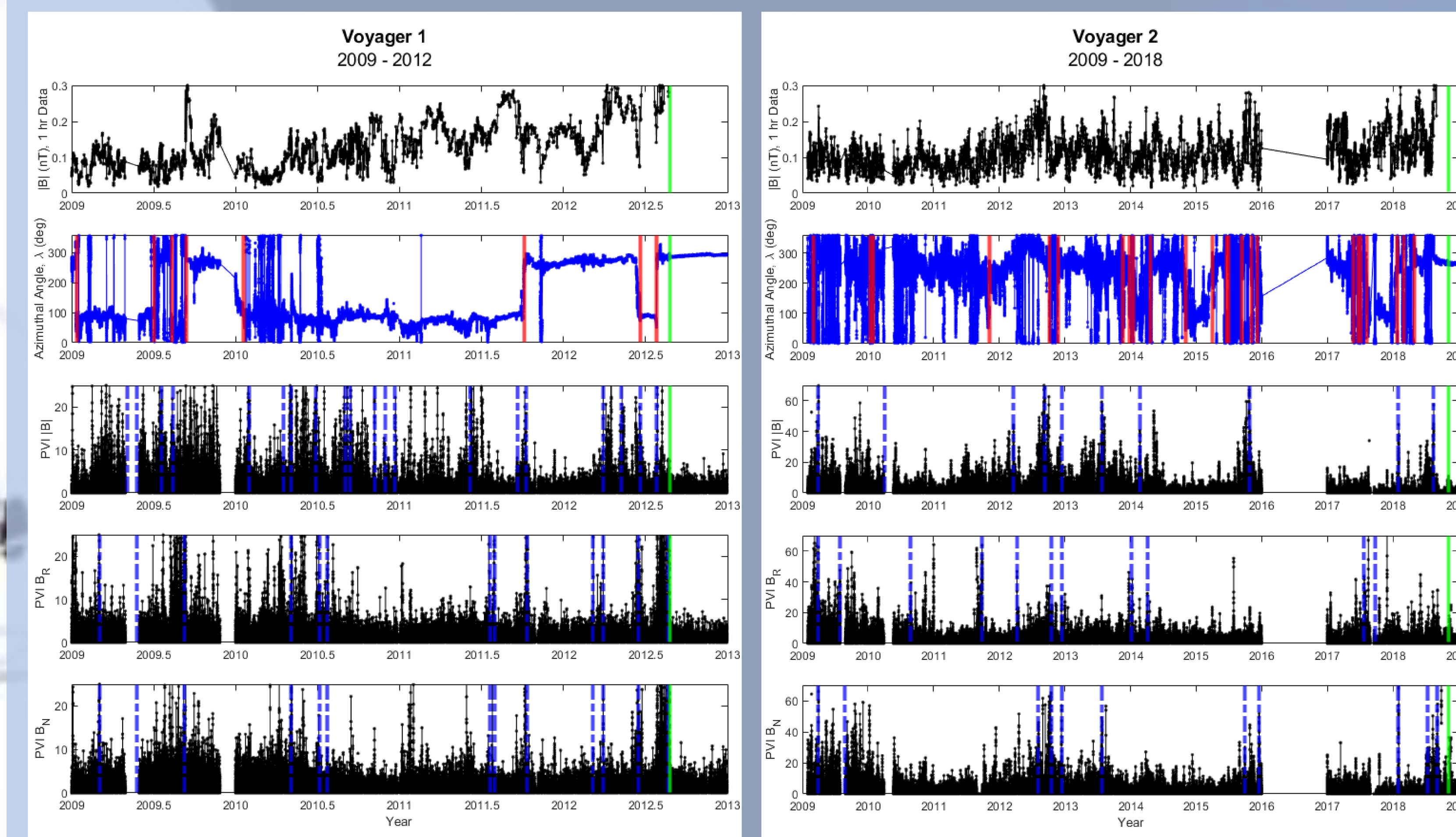

Figure 2: PVI analysis of V1 (left) and V2 (right) magnetic field data in the IHS. From the top to the bottom, panels show: (1) |B|, (2) HMF azimuthal angle, (3-5) PVI analysis for HMF magnitude and components. Lines indicate the HP crossings (green), HCS crossings (red), and local PVI spikes (blue).

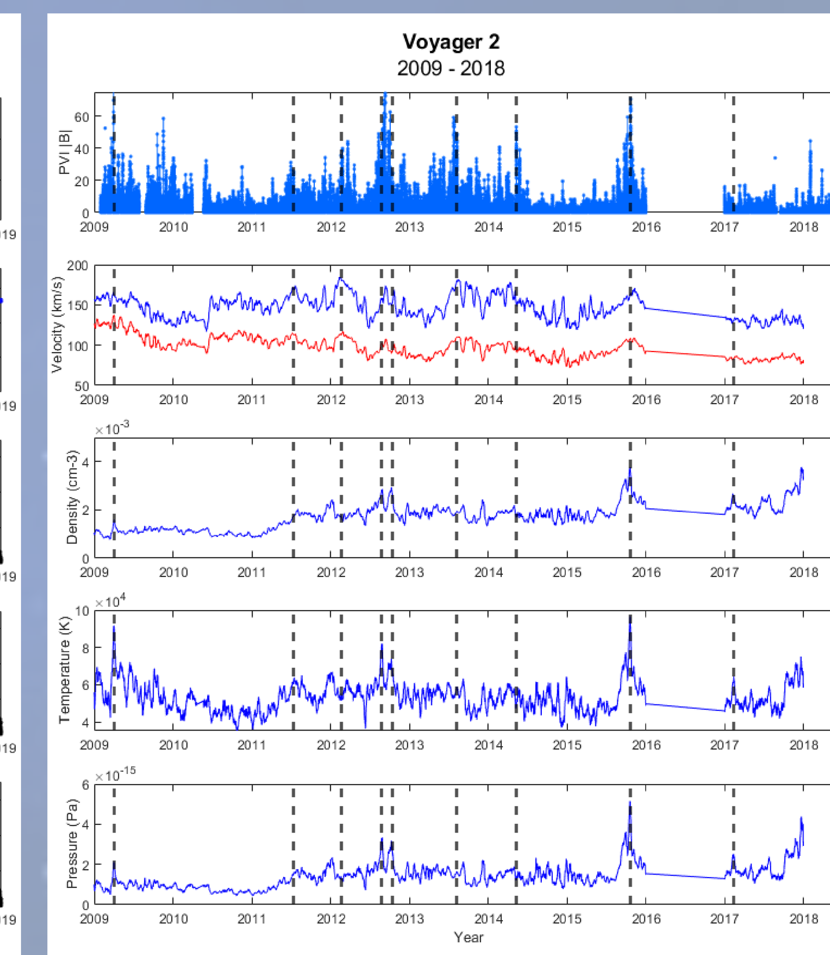

Figure 3: Comparison of |B| vs. V2 SW observations. Panels show: 1) PVI of |B|, 2) Velocities, 3) Density, 4) Temperature, 5) Pressure. Black lines indicate correlated PVI and plasma peaks.

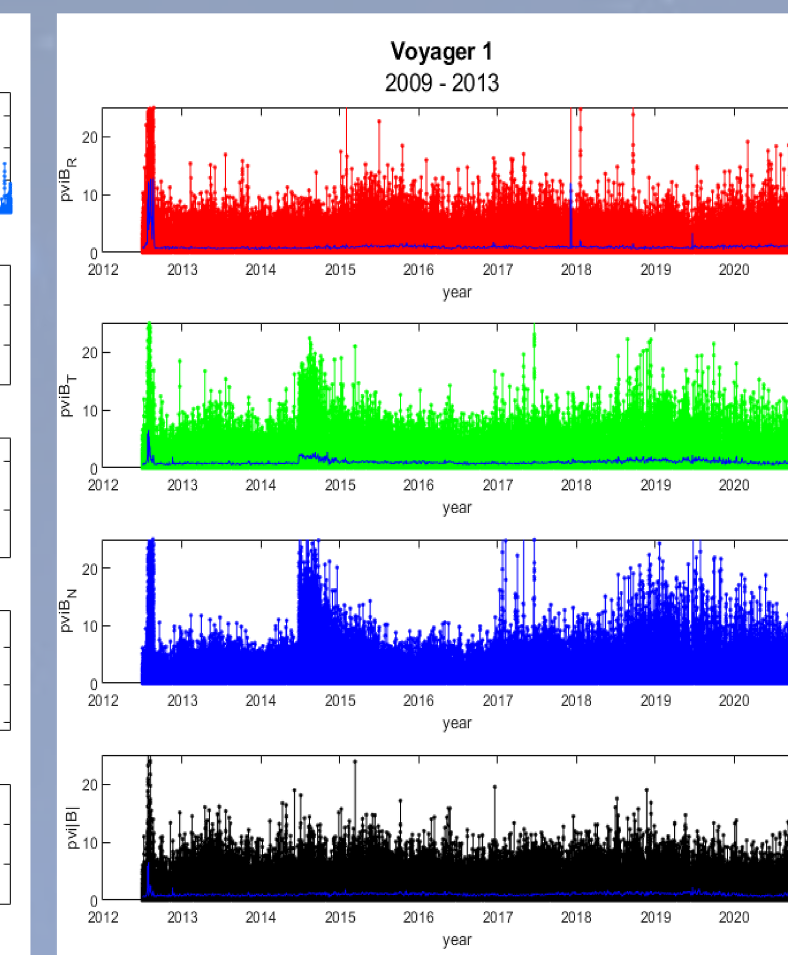

Figure 4: PVI analysis of V1 magnetic field data in the VLISM after crossing the HP. From top to bottom, panels show the PVI of BR, BT, BN, and | **B** |.

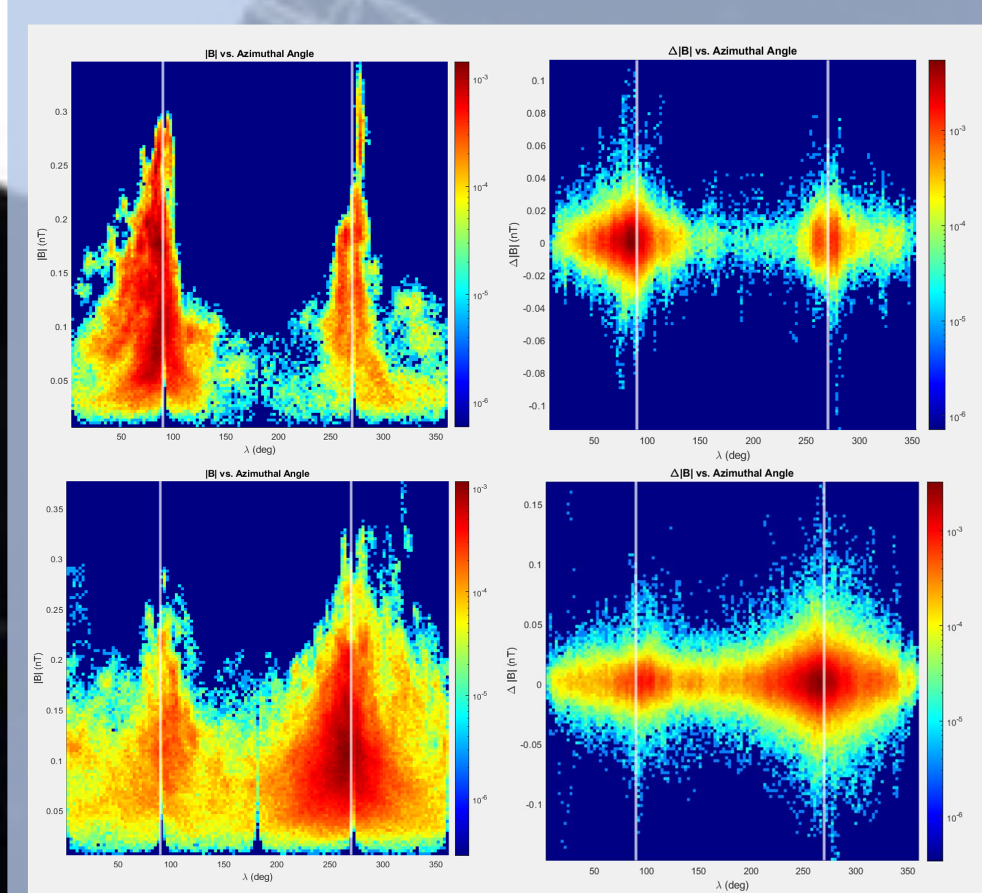

Figure 5: Joint PDFs of: (Top left to right) |B| and Δ|B| vs Azimuthal Angle from V1; (Bottom left to right) |B| and Δ|B| vs Azimuthal Angle from V2. For each quantity, Q: ΔQ = Q(t) - Q(t+τ) , where Δ = 1 hour increment.

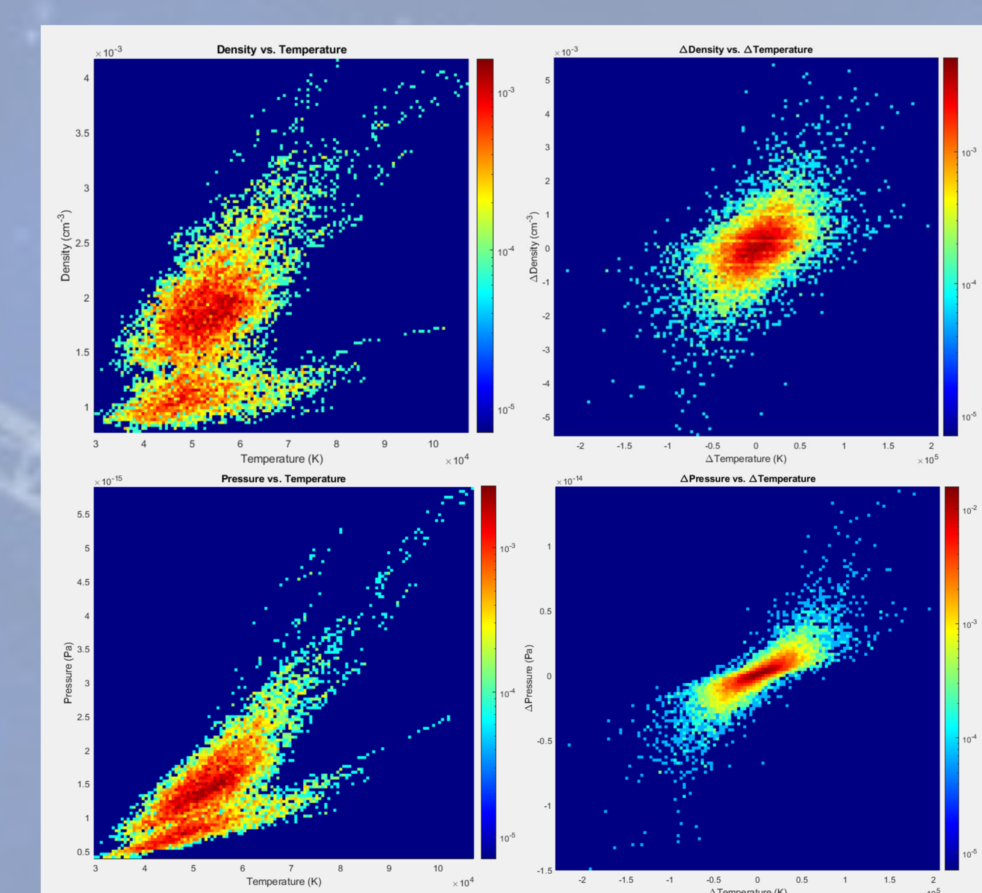

Figure 6: Joint PDFs of: (Top left to right) Density vs. Temperature and ΔDensity vs. ΔTemperature; (Bottom left to right) Pressure vs. Temperature and ΔPressure vs. Δtemperature.

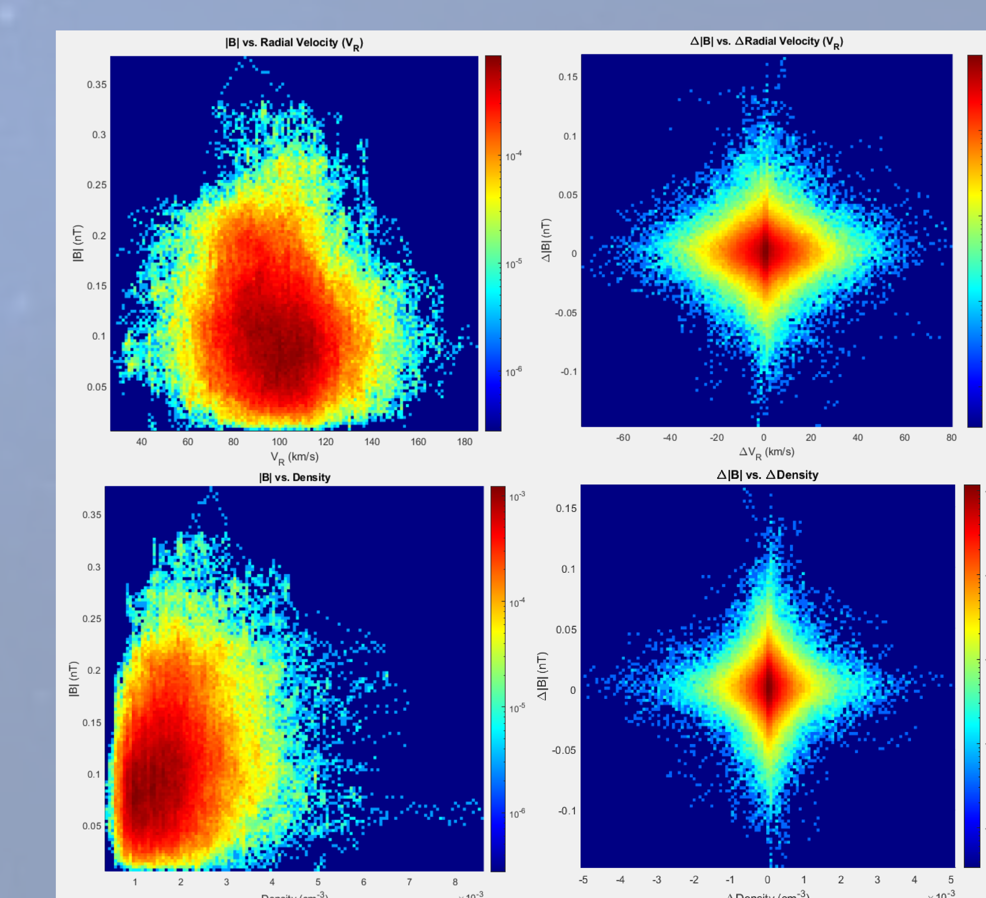

Figure 7: Joint PDFs of: (Top left to right) |B| vs. Radial Velocity and Δ|B| vs. Δ Radial Velocity, & (Bottom left to right) |B| vs. Density and Δ|B| vs. Δdensity.

Conclusions

- Our PVI analysis demonstrates that small-scale (MHD) turbulent fluctuations of **B** in the IHS are correlated with (i) long term changes in plasma quantities (ii) local pressure pulses.
- Turbulence is enhanced in the sector regions.
- Enhancements in small-scale turbulence are observed in the VLISM after 2018, which are likely related to solar the cycle effects and, possibly, enhanced PUI production.
- Fine-scale turbulence appears to be strongest when background HMF is perpendicular to the radial direction, which may indicate wavenumber anisotropy in the IHS.
- Joint PDFs split in two branches, which may be either associated with the time intervals of alternating HMF polarity or the solar cycle
- Strong positive correlation exists between the density and pressure increments vs. temperature increments in the thermal SW, even at 1-hour scale.

References & Acknowledgements

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