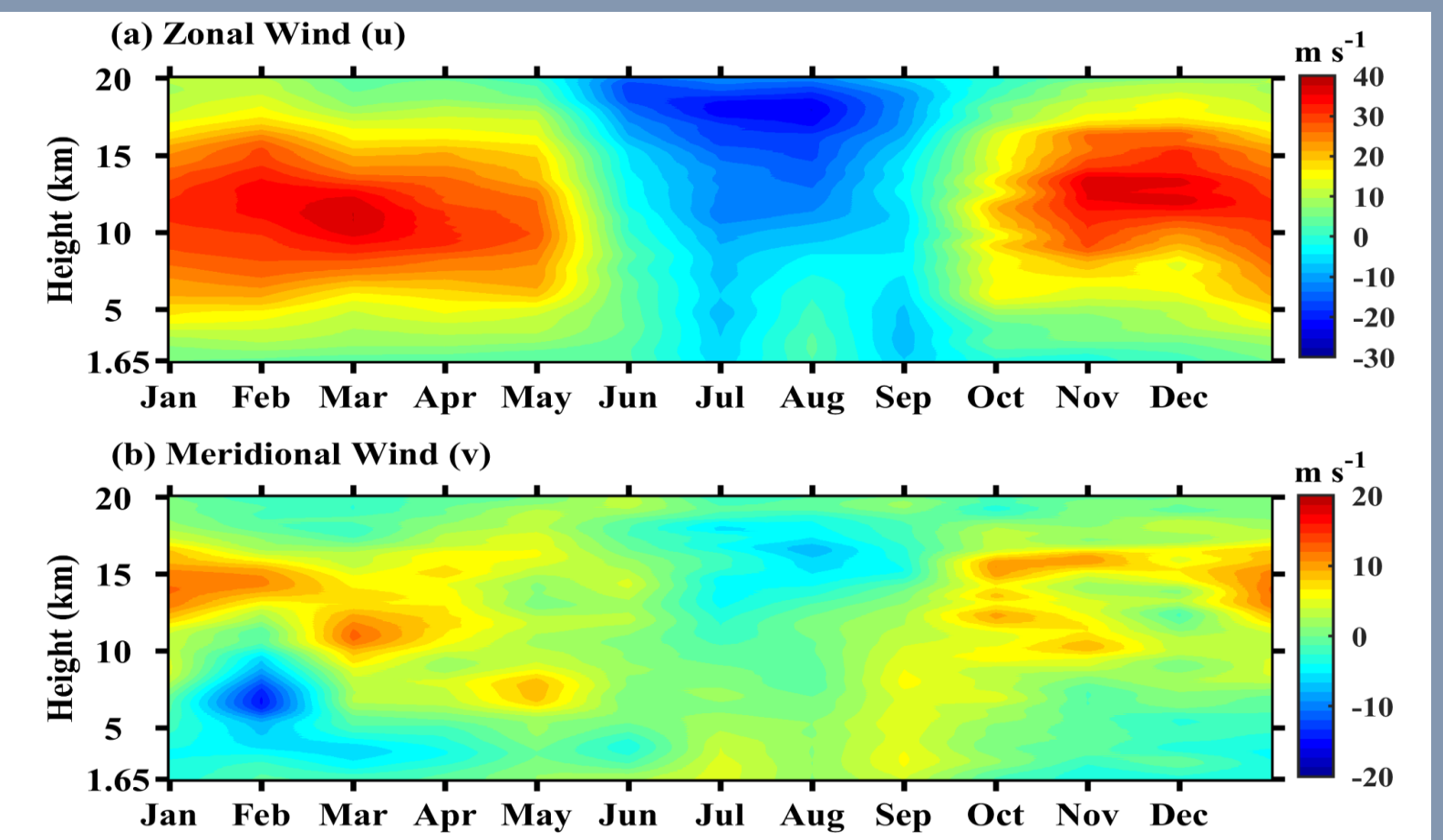


## Introduction

Vertical air motion is a key component of atmospheric dynamics, influencing weather through heat and moisture redistribution and governing air-mass transport across the tropopause via Stratosphere–Troposphere Exchange (STE). However, its direct measurement remains challenging because clear-air vertical velocities are 2–3 orders of magnitude smaller than horizontal wind components. The advent of Stratosphere–Troposphere (ST)/Mesosphere–Stratosphere–Troposphere (MST) radars has enabled precise, high-resolution measurements of vertical velocity. Beyond event-based studies of convection, cyclones, etc., long-term mean vertical motion has been investigated to characterize clear-air background circulation and its climatological implications. The Indo-Gangetic Plain (IGP) delta region, located near the deep convective region at the head of the Bay of Bengal, experiences contrasting large-scale circulations between seasons. During the summer monsoon, it lies along the southern flank of the Asian Summer Monsoon Anticyclone (ASMA) and is generally influenced by upper-tropospheric easterlies, whereas during the remaining seasons, particularly winter, the westerly Subtropical Jet (STJ) dominates the upper troposphere (Fig.1). These pronounced dynamical contrasts may substantially influence vertical air motion and air-mass transport.

Fig.1 Monthly mean characteristics of (a) zonal, and (b) meridional wind for 2023 at Haringhata



## Objectives

To utilize the high-power, high-resolution pulse Doppler 53 MHz ST radar at Haringhata in achieving the following:-

- Characterising the **mean background vertical air motion across all seasons** in this transition region.
- Understanding the implications of this motion towards the **feasibility of transport of airmass from troposphere to stratosphere and vice versa**.
- Understanding if jets play a role in **biasing or modulating this motion**.



Fig.2 53 MHz Haringhata ST Radar

### Technical Details of Haringhata ST Radar

| Parameter                        | Value                                   |
|----------------------------------|-----------------------------------------|
| Location                         | 22.94°N, 88.51°E                        |
| Frequency                        | 53 MHz                                  |
| No. of antenna elements          | 475                                     |
| Peak power                       | 950 kW                                  |
| Effective Area (A <sub>e</sub> ) | ~7000 m <sup>2</sup>                    |
| Peak power aperture product      | ~6.7 × 10 <sup>9</sup> W m <sup>2</sup> |
| Max Duty cycle                   | 5%                                      |
| Half-Power Full Beam             | 3.6°                                    |
| Width (one-way)                  |                                         |
| No. of FFT points                | 512                                     |
| No. of Range bins                | 150                                     |
| Range Resolution                 | 150 m                                   |
| No. of coherent integration      | 128                                     |
| No. of incoherent integration    | 4                                       |
| IPP                              | 250 μs                                  |
| Pulse width                      | 8 μs                                    |
| Baud length                      | 1 μs                                    |
| Velocity resolution              | 0.1731 m s <sup>-1</sup>                |
| Nyquist velocity                 | 44.2188 m s <sup>-1</sup>               |
| Scan Cycle                       | E10, W10, Z, N10, S10                   |

- Data for the year 2023 has been used in this study. (Fig.3)
- For uniformity observations made during 9–19 IST has been used for analysis.
- Only direct zenith observations are considered for analysis.
- To avoid any bias due to convection/precipitation signal on the clear air vertical velocity, a  $\pm 1$  m s<sup>-1</sup> filtration criteria has been considering velocities exceeding this bounds to be influenced by convective activity. (Fig.4)

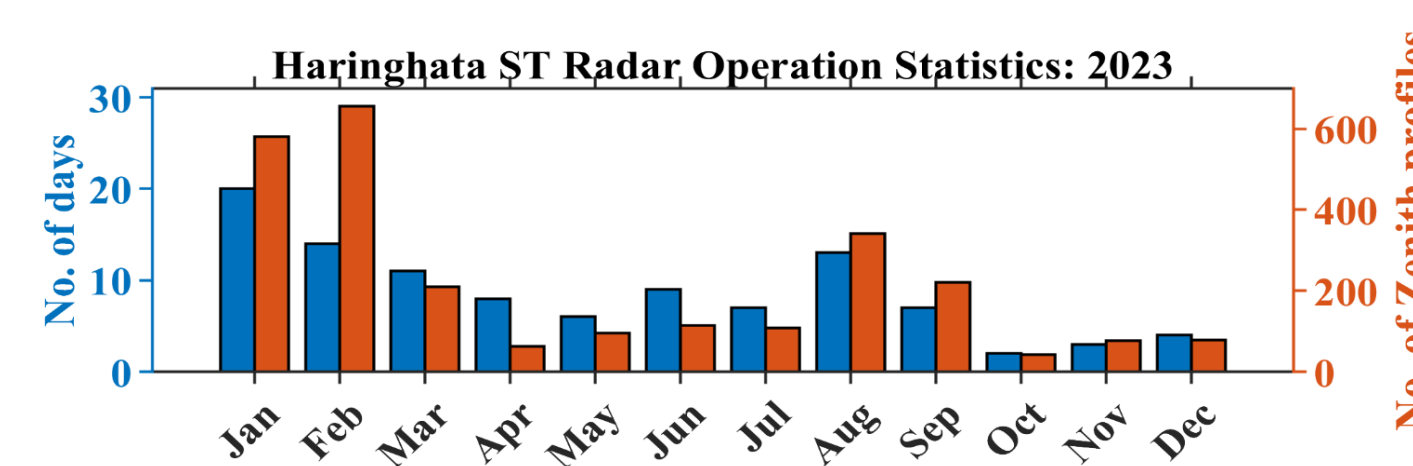


Fig.3 Operation statistics of the radar considered for analysis in the year 2023.

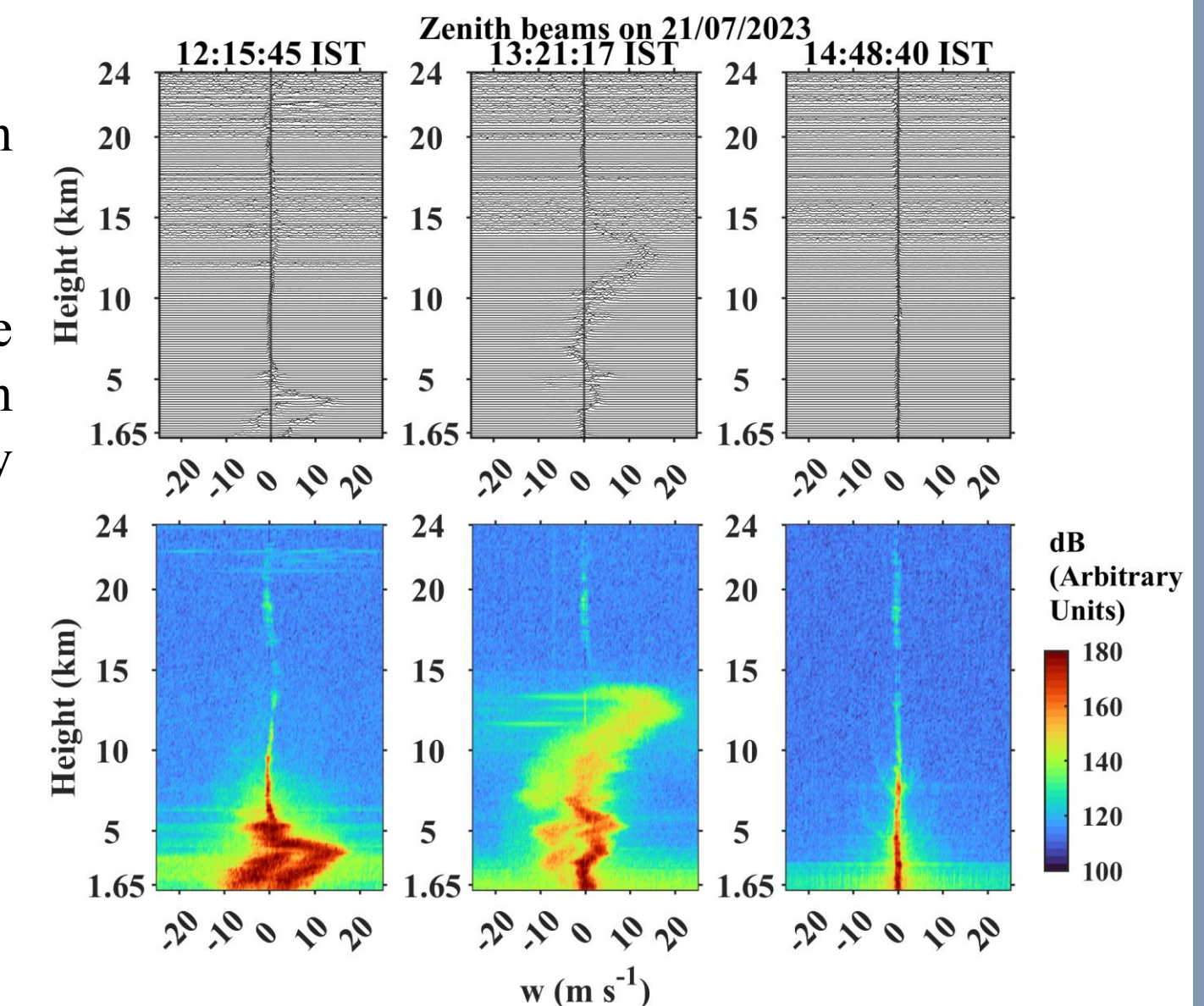


Fig.4 Zenith beam line spectra (top) and 2D color spectra (bottom) observed during simultaneous convection and precipitation, strong convection and clear-air conditions.

## Results and Discussion

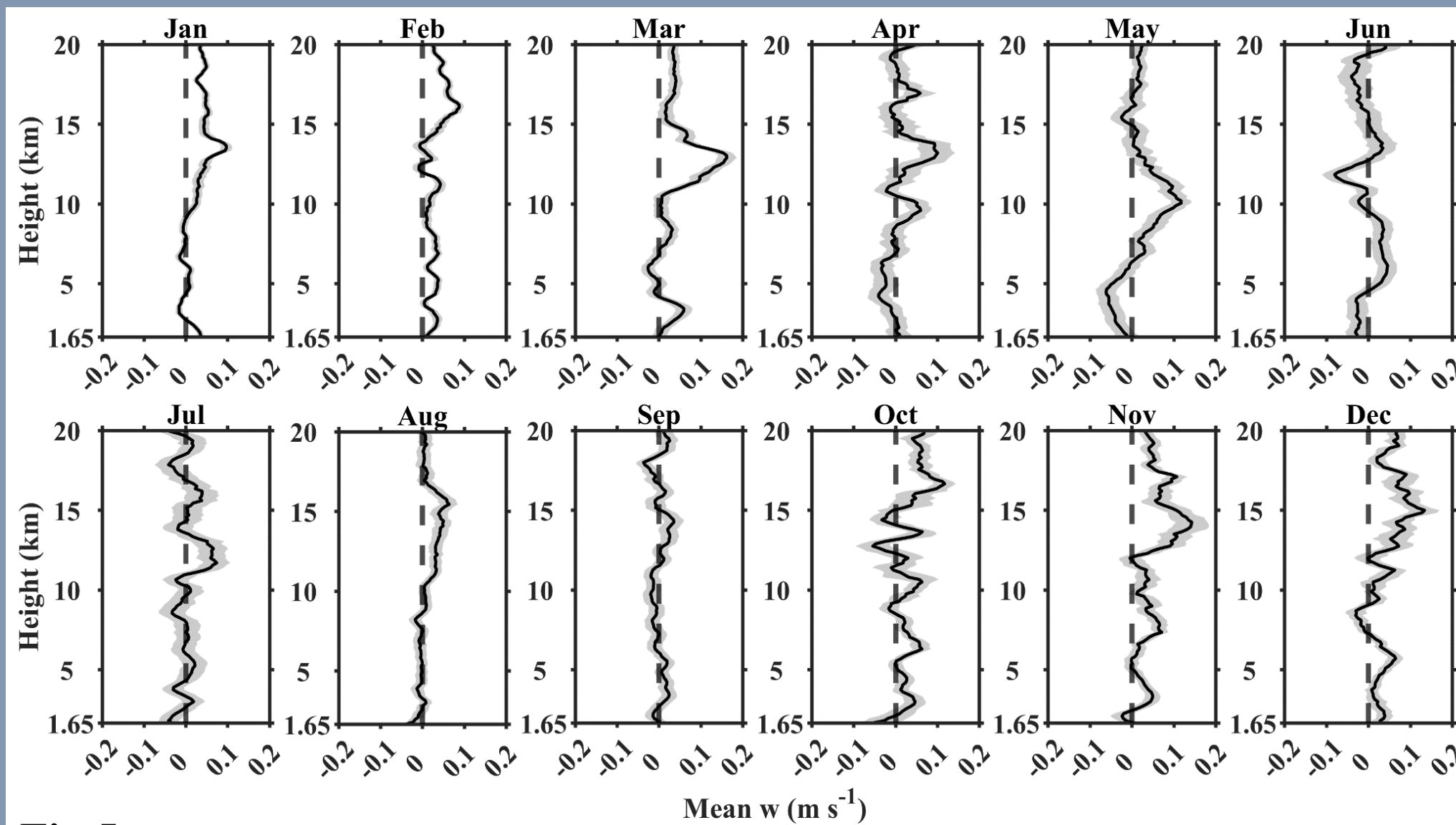


Fig.5 Monthly mean vertical velocity for the year 2023. (Standard error shaded in grey)

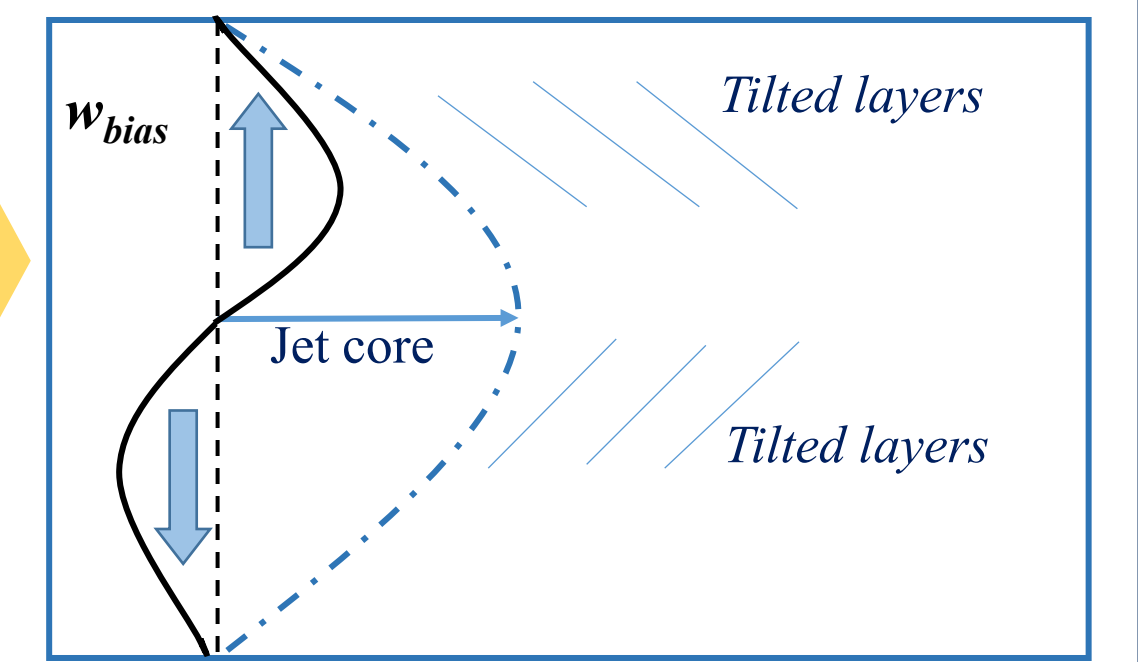
- Mean vertical velocity values are generally less than 10 cm s<sup>-1</sup> in magnitude. (Fig.5)
- In the upper troposphere up to stratospheric heights, general updrafts are seen for most of 2023, except during May–September.
- Unlike similar studies, a persistent downdraft (updraft) below (above) the jet maximum is not clearly evident in the mean profiles of vertical motion.

*The well-calibrated radar and averaging over multiple hours and seasons minimize possible technical and intermittent gravity-wave biases, leaving persistent dynamical features as the most plausible source of bias in the mean background vertical motion and its interpretation.*

### Possible bias due to influence of prevailing jet dynamics

Muschinski (1996) proposed a model of KHI being generated in high-shear regions of strong jets, producing tilted layer of scatterers above and below the jet core. This *effectively tilts* the radar beam from absolute zenith to a slight off-zenith angle. Consequently, apparent updrafts(downdrafts) arise above(below) the jet core (westerly), with motion reversal near the jet peak.

Luce et al. (2025) extended and improved this model using various functions of Richardson number (Ri) and vertical shear of horizontal wind (S) to represent the KHI modulating probability



## Does the jet “bias” the observation or modulate it?

The estimated bias is minimal ( $<1$  cm s<sup>-1</sup>) across all months. The magnitude and structure of the bias profiles poorly match observed profiles, indicating no significant change in the observed vertical-velocity magnitude or direction.

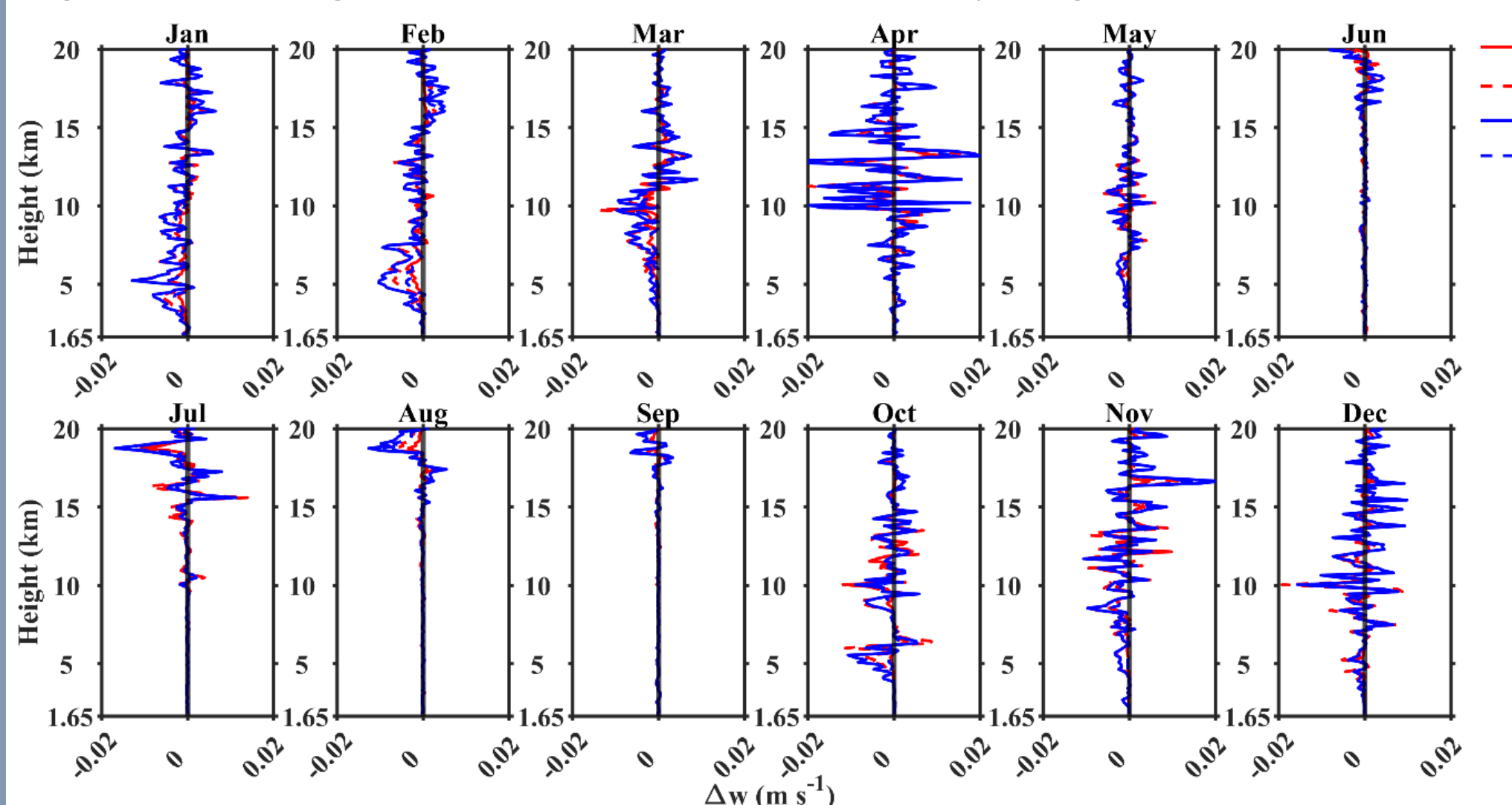
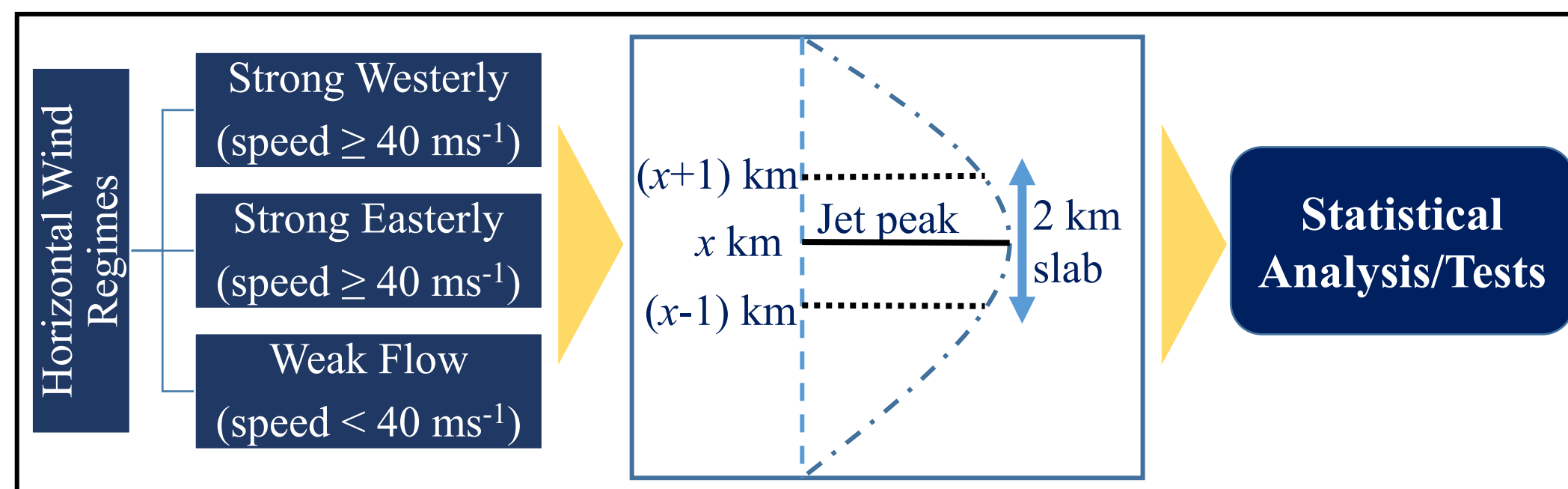


Fig.6 Mean bias of vertical velocity is estimated for all the months in 2023

*If strong jets modulate vertical motion, their influence should manifest as correlated jet–vertical velocity variability, necessitating profile-wise statistical analysis.*



Particular statistical tests used :

- Wilcoxon signed-rank test (Test-1)
- Two-proportion z-test (Test-3)
- Wilcoxon rank-sum test (Mann–Whitney U test) (Tests -4,5,6)

### Detailed outcome of statistical tests performed to assess the structure of the vertical velocity in the presence of strong westerly and strong easterly jets against weak flow.

| Test-1: Is the vertical velocity structure asymmetric across the wind maximum?                                               |                                      |                                      |                                      |                                      |
|------------------------------------------------------------------------------------------------------------------------------|--------------------------------------|--------------------------------------|--------------------------------------|--------------------------------------|
| Parameters                                                                                                                   | Weak                                 | Strong Westerly                      | Strong Easterly                      |                                      |
| Total instances (N)                                                                                                          | 875                                  | 845                                  | 66                                   |                                      |
| Median ( $\Delta$ )                                                                                                          | 0.0321 m s <sup>-1</sup>             | 0.0602 m s <sup>-1</sup>             | 0.0284 m s <sup>-1</sup>             |                                      |
| p-value                                                                                                                      | ~10 <sup>-3</sup>                    | ~10 <sup>-18</sup>                   | 0.1808                               |                                      |
| Effect Size (r)                                                                                                              | 0.142                                | 0.300                                | 0.165                                |                                      |
| Test-2: Does the vertical velocity reverse direction across the wind maximum?                                                |                                      |                                      |                                      |                                      |
| Parameters                                                                                                                   | Weak                                 | Strong Westerly                      | Strong Easterly                      |                                      |
| Mean w (Above)                                                                                                               | 0.0413 m s <sup>-1</sup>             | 0.0684 m s <sup>-1</sup>             | 0.0282 m s <sup>-1</sup>             |                                      |
| Mean w (Below)                                                                                                               | 0.0115 m s <sup>-1</sup>             | 0.0125 m s <sup>-1</sup>             | -0.0034 m s <sup>-1</sup>            |                                      |
| Test-3: Does the occurrence of a specific vertical velocity sign configuration differ between jet and weak flow conditions?  |                                      |                                      |                                      |                                      |
| Parameters                                                                                                                   | Strong Westerly vs Weak (-ve to +ve) | Strong Westerly vs Weak (+ve to -ve) | Strong Easterly vs Weak (-ve to +ve) | Strong Easterly vs Weak (+ve to -ve) |
| Fraction(Weak)                                                                                                               | 0.20                                 | 0.14                                 | 0.20                                 | 0.14                                 |
| Fraction(Strong)                                                                                                             | 0.22                                 | 0.12                                 | 0.20                                 | 0.11                                 |
| p-value                                                                                                                      | 0.3973                               | 0.3435                               | 0.9350                               | 0.4910                               |
| z-value                                                                                                                      | 0.846                                | -0.947                               | -0.082                               | -0.689                               |
| Test-4: Does vertical motion become stronger in the region surrounding the jet?                                              |                                      |                                      |                                      |                                      |
| Parameters                                                                                                                   | Strong Westerly vs Weak              |                                      | Strong Easterly vs Weak              |                                      |
| p-value                                                                                                                      | 0.0012                               |                                      | 0.0007                               |                                      |
| Mean RMS (Weak)                                                                                                              | 0.2754 m s <sup>-1</sup>             |                                      | 0.2754 m s <sup>-1</sup>             |                                      |
| Mean RMS (Strong)                                                                                                            | 0.2841 m s <sup>-1</sup>             |                                      | 0.3110 m s <sup>-1</sup>             |                                      |
| RMS difference                                                                                                               | 0.009 m s <sup>-1</sup>              |                                      | 0.036 m s <sup>-1</sup>              |                                      |
| Effect size (r)                                                                                                              | 0.0782                               |                                      | 0.1108                               |                                      |
| Test-5: Is the absolute vertical velocity at the wind maximum larger during jet conditions than during weak-flow conditions? |                                      |                                      |                                      |                                      |
| Parameters                                                                                                                   | Strong Westerly vs Weak              |                                      | Strong Easterly vs Weak              |                                      |
| p-value                                                                                                                      | 0.2896                               |                                      | 0.6370                               |                                      |
| Median  w  (Weak)                                                                                                            | 0.1957 m s <sup>-1</sup>             |                                      | 0.1957 m s <sup>-1</sup>             |                                      |
| Median  w  (Strong)                                                                                                          | 0.2052 m s <sup>-1</sup>             |                                      | 0.2038 m s <sup>-1</sup>             |                                      |
| Effect size (r)                                                                                                              | 0.026                                |                                      | 0.015                                |                                      |
| Test-6: Does the RMS magnitude of vertical velocity increase above or below the wind maximum under jet conditions?           |                                      |                                      |                                      |                                      |
| Parameters                                                                                                                   | Strong Westerly vs Weak (Above)      | Strong Westerly vs Weak (Below)      | Strong Easterly vs Weak (Above)      | Strong Easterly vs Weak (Below)      |
| p-value                                                                                                                      | 0.0001                               | 0.4115                               | 0.0275                               | 0.0074                               |
| Mean RMS (Strong)                                                                                                            | 0.2892 m s <sup>-1</sup>             | 0.2578 m s <sup>-1</sup>             | 0.2919 m s <sup>-1</sup>             | 0.3055 m s <sup>-1</sup>             |
| Mean RMS (Weak)                                                                                                              | 0.2662 m s <sup>-1</sup>             | 0.2620 m s <sup>-1</sup>             | 0.2662 m s <sup>-1</sup>             | 0.2620 m s <sup>-1</sup>             |
| Effect size (r)                                                                                                              | 0.099                                | 0.020                                | 0.072                                | 0.088                                |

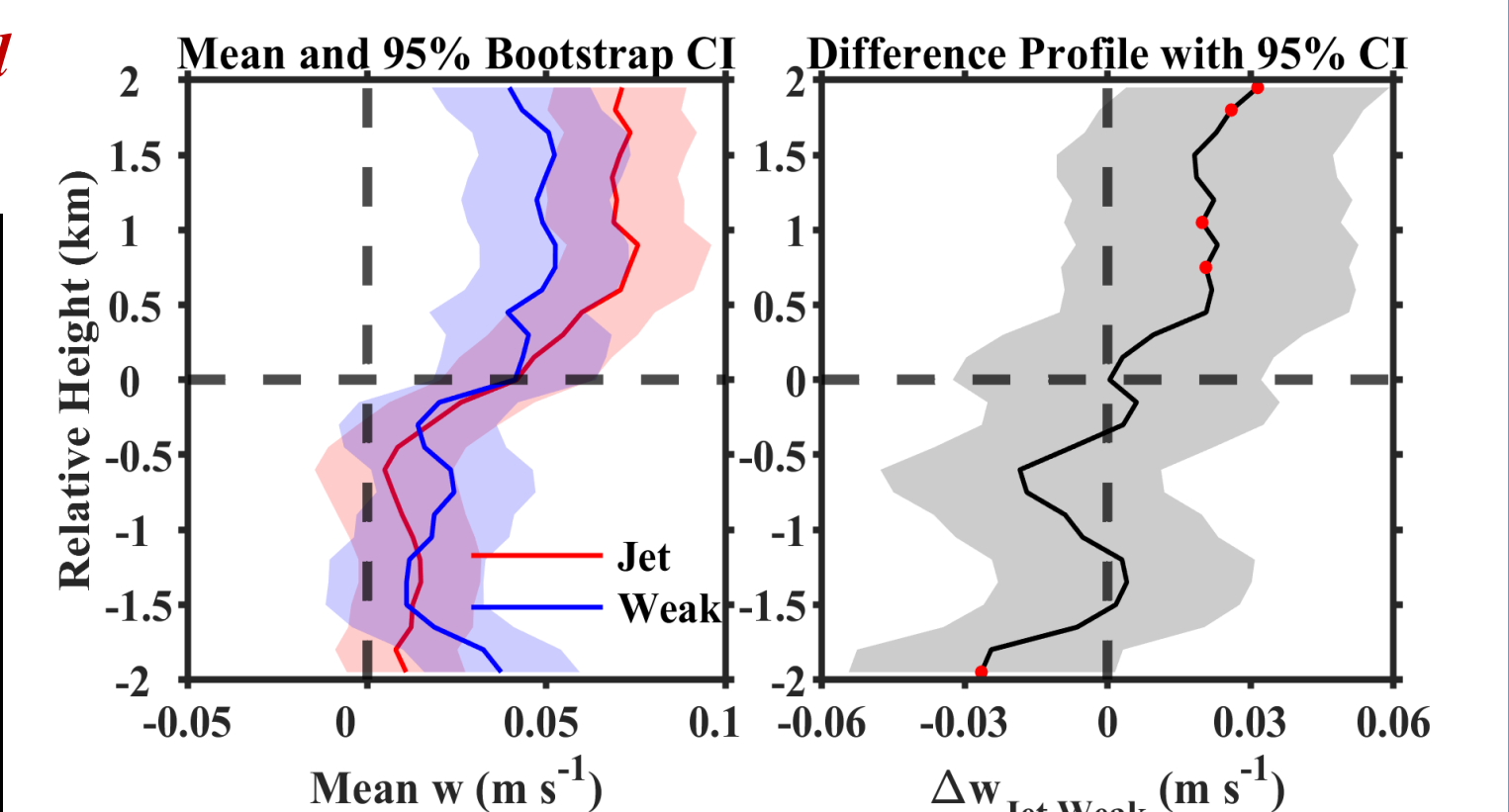


Fig.7 Mean and 95% bootstrap confidence interval (shaded area) (left) for vertical velocity structure in a 4 km deep slab relative to wind maxima during and weak flow and the difference (right) between the two with the 95% bootstrap confidence interval (shaded grey)

- Collectively, all the tests show no systematic occurrence of downdraft–updraft structure across strong jet maxima.
- Strong jets enhance vertical motion variability and upward motion above the jet core.
- Jet–vertical-motion coupling reflects changes in magnitude and vertical distribution, not jet-induced bias structures.
- Bootstrap confidence intervals support that strong jets show enhanced upward motion above the jet core relative to weak flow.
- Statistically significant positive differences are confined mainly above the core.
- Enhanced upward motion above the jet core, suggests enhanced upward transport, but a direct causality or specific transport pathway cannot be established from this.

## Concluding Remarks

- This study highlights the first all-season analysis of characteristics of the mean vertical air motion in the IGP delta region, affected by the seasonal transition from influence of STJ to ASMA.
- Monthly mean profiles of vertical air motion show enhanced upper-tropospheric updrafts in all months excepting the summer monsoon.
- Evaluation of the established jet-induced bias model does not provide any significant evidence to attribute the observed mean profiles are primarily attributable to jet-induced bias
- Detailed profile-wise statistical tests and bootstrap sampling indicate that strong jets enhance upward vertical-motion variability primarily above the jet core, independent of jet direction, with no comparable enhancement below.
- No statistically significant increase of coherent downdraft–updraft reversal is observed across the jet, while enhanced upper-level ascent may favor upward transport of airmass across the tropopause.

## Acknowledgment

The authors would like to sincerely thank all the technical and scientific staff of Institute of Radio Physics and Electronics, University of Calcutta, at the Haringhata ST radar for conducting and providing the ST radar data used in this study. Nabarun Poddar thanks the Indian Space Research Organisation (ISRO) for providing the research fellowship during the study period.

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