Response to Community reviewer's comments

Community reviewer's comment:

The manuscript presents a valuable field investigation of UAV-based atmospheric boundary-layer observations and UAV flight disturbances over complex terrain. The combination of UAV–tower intercomparison and vertical sounding observations is interesting and provides useful observational evidence. The manuscript is generally well structured. I have several comments that may help clarify the methodology and interpretation.

Response: We sincerely thank the reviewer for the time and effort spent reviewing our manuscript and for the positive evaluation of our work. We are pleased that the reviewer found the combination of UAV–tower intercomparison and vertical sounding observations interesting, and that the study provides useful observational evidence on boundary-layer structure and UAV flight disturbances over complex terrain. The reviewer's constructive comments have been very helpful in clarifying the methodology and strengthening the interpretation of the results. For clarity purpose, here we have listed the reviewer's comments in bold font, followed by our response in blue plain font, and the modifications to the manuscript are in blue italics.

1.The authors define the attitude turbulence index(T) as and state that it can serve as an indirect indicator of atmospheric turbulence intensity. This is a useful indicator of UAV attitude disturbance. However, the attitude response data obtained may also depend on the characteristics of the UAV platform and its control response. It is recommended that the authors briefly explain the physical meaning and scope of application of this metric. If there are relevant references, listing them would further aid in understanding.

Response: We sincerely thank the commenter for the positive assessment of our work and for this thoughtful comment. We agree that T reflects the closed-loop attitude response of the UAV. It therefore depends not only on the atmospheric forcing but also on the

characteristics of the airframe and its flight-control system. Physically, T is the magnitude of the pitch–roll angular-velocity vector. For a hovering multirotor, it approximates how quickly the rotor thrust axis is being tilted. The mean wind is balanced by a nearly steady tilt, which contributes little to the angular rates. T therefore mainly reflects the attitude response to gusts and turbulent eddies, including the corrective tilting applied by the flight controller.As stated in Section 2.3, T is used as a relative index to compare layers and soundings flown with the same aircraft (DJI Matrice 350 RTK), payload and control settings, and its transfer function is platform-specific. It is not intended as an absolute measure of turbulence intensity. Applying T to other aircraft, or converting it into an absolute quantity such as turbulent kinetic energy or the eddy dissipation rate (EDR), would require calibrating the platform response, for example against sonic-anemometer measurements. Several studies infer wind and turbulence from multirotor attitude and show that this relationship depends on the platform (Palomaki et al., 2017; González-Rocha et al., 2020; Wetz et al., 2021; Shelekhov et al., 2022). Aviation turbulence reporting makes a similar distinction: response measures depend on the aircraft, whereas EDR does not (Sharman et al., 2014).

2. The manuscript identifies a localized region of enhanced attitude turbulence index under moderate vertical wind shear and near-zero to negative Richardson number, and proposes that this may be related to a possible resonance-like coupling between turbulent eddy scales and the dynamic response of the UAV. This is an interesting interpretation and potentially provides an additional perspective on the observed UAV response. At the same time, the current evidence appears to be mainly based on the statistical relationship between atmospheric parameters and UAV attitude response, without direct analysis of the characteristic frequency or spatial/temporal scales of the atmospheric turbulence and UAV dynamics. The authors have already appropriately noted that this interpretation is tentative. Nevertheless, it would be beneficial to explore this perspective further and, where possible, provide relevant references to support this interpretation.

Response: We sincerely thank the commenter for the interest in this interpretation and for the constructive suggestion. We agree that the current evidence is statistical and this interpretation is not yet supported by a direct analysis of the characteristic frequencies and scales of the turbulence and the UAV dynamics. We identified the anomaly from the joint distribution of Ri, vertical wind shear and T (Figure 12). We did not directly analyse the characteristic frequencies or the spatial and temporal scales of the turbulence or of the UAV dynamics, which is why we described the interpretation as tentative. Our interpretation is based on how an aircraft's response to turbulence depends on frequency. The attitude response can be viewed as the turbulence spectrum filtered by the vehicle's own response function. It is therefore strongest where turbulent energy falls within the vehicle's sensitive frequency band (Cornman et al., 1995), and for multirotors this band is limited (Wildmann and Wetz, 2022). Boundary-layer eddies can be comparable in size to small UAVs (Davoudi et al., 2020). Their scale, and hence the frequency at which a hovering UAV encounters them, varies with stability and wind speed (Kaimal et al., 1972). A particular combination of shear and stability could therefore concentrate turbulent energy within the airframe's sensitive band and amplify the attitude response.

3. The calculations of Ri and vertical wind shear are based on discrete UAV vertical profile data. Although the calculation process has been described in great detail, it would be valuable to examine whether the derived gradients are sensitive to the observed vertical resolution. Therefore, we recommend that the authors briefly discuss the feasibility of the current vertical resolution and cite relevant studies that have used discrete radiosonde or UAV profile data.

Response: In this study, Ri and vertical wind shear were computed by finite differences between adjacent hovering levels. These levels were 8–16 m apart in the tower comparison and 200 m apart in the attitude-disturbance soundings, so the results represent layer-averaged gradients. At the 8–16 m spacing, the UAV-derived Ri agrees well with the tower values at the same levels (Figure 4b). Previous studies have shown that both shear and Ri are sensitive to vertical resolution (Balsley et al., 2008; Houchi et al., 2010; Shao et al., 2023). Richardson numbers derived from discrete profiles are nonetheless widely used,

for example to estimate boundary-layer height from radiosondes (Guo et al., 2016) and turbulence from multicopter profiles (Greene et al., 2022).

We fully agree with the commenter that the derived gradients may be sensitive to vertical resolution. We acknowledge that this sensitivity was not evaluated in the present work, and that the 200 m spacing of the attitude-disturbance soundings is a limitation. Ri and shear in these layers should be regarded as bulk-layer values, and the Ri thresholds should be interpreted with caution.

4.The manuscript uses three successive evening sounding cases to examine the transition from convective/weakly unstable to stable boundary-layer conditions. The results show clear differences in UAV attitude response among the different stability conditions. Since several of the conclusions are based on these three representative cases, I suggest that the authors briefly explain the criteria for selecting these cases and discuss their representativeness and the applicability of the conclusions to other atmospheric conditions.

Response: We sincerely thank this constructive suggestion. The cases were selected primarily from observations during the transition from a convective to a stable boundary layer. We acknowledge the following limitations of the present work:

All three cases come from a single summer evening at one site in the eastern Taihang piedmont, under cloudy conditions with weak synoptic forcing. Other conditions are not covered, such as a fully developed daytime convective boundary layer, strong-wind or frontal situations, nocturnal low-level jets, other seasons and other terrain types. The specific thresholds and magnitudes, as well as case-specific features such as the ascent–descent asymmetry and the cloud-base disturbances, should therefore not be generalized directly.

5.The UAV was operated approximately 50 m upwind of the gradient tower to minimize mutual interference. A brief explanation or reference supporting the choice of this distance would improve the description of the experimental design.

Response: The 50 m distance was chosen mainly to avoid mutual interference. Placing the UAV upwind gives it free inflow that is not disturbed by the tower structure. At this distance, the rotor-induced flow of the UAV is also expected to have decayed before

reaching the tower sensors. The distance also provides a safety margin for operating the aircraft near the tower. A similar upwind arrangement was used by Wetz et al. (2021), who hovered quadrotors about 20 m upwind of a 99 m tower to ensure undisturbed inflow. Our larger separation is more conservative with respect to interference and flight safety for the larger M350 RTK.

6.The authors are encouraged to further discuss how atmospheric stability modulates the relationship between vertical wind shear and UAV flight disturbances, particularly in the interpretation of Figure 12.

Response: Atmospheric stability does not act on UAV flight disturbance directly. Instead, it modulates the relationship between vertical wind shear and flight disturbance through the turbulent kinetic energy budget. Shear produces turbulence, while buoyancy enhances it under unstable stratification and suppresses it under stable stratification. However, how stability modulates the relationship between shear and turbulence is closely linked to local weather and thermal conditions, such as surface heating, cloud cover and the evolution of the boundary layer. The present study is considerably limited in this respect, because it is based on a small number of soundings at a single site under one weather situation. This question is therefore beyond what the present study can resolve.

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