Response to Anonymous Referee #2

Reviewer #2: I have reviewed the manuscript titled "A profile-based estimated inversion strength" submitted by Wang et al. to the Atmospheric Chemistry and Physics (ACP). The authors analyzed the radiosondes data at the Southern Great Plains (SGP) station and found the Inversion Strength estimation deviation in the current two variables, the Lower- Troposphere Stability (LTS) and Estimated Inversion Strength (EIS). Two sources of errors are identified, a systematic deviation from the dry adiabat below the lifting condensation level (LCL) and error from the spread of the actual potential temperature around the moist adiabat above the LCL. Based on the findings, the authors proposed a new measure/variable, profiled based inversion strength estimate (EISp) to estimate the inversion strength from the profiles in the reanalysis data. This new measure is defined as the potential temperature difference between the top and bottom of a layer with the maximum potential temperature gradient and with a subtraction of potential temperature changes due to the moist adiabat in this layer. Further analysis shows the EISp explains the low-level cloud significantly better in term of both spatial and temporal variations than the existing variables. The research presented in this manuscript is within the scope of ACP, and appears to significantly improve the understanding of low-level cloud changes by the proposed new measure. The new measure of the inversion strength is likely to be well accepted by the research community and extensively used in future studies. The manuscript is well written and easy to follow. Thus, I recommend the manuscript be accepted with minor revisions.

Response: We thank the anonymous referee for reviewing our manuscript and very helpful comments to modify the manuscript. We have responded to all comments and carefully modified the manuscript accordingly.

My major comments are:

- *It appears the removal of the moist adiabat above the LCL does not benefit a better estimation of inversion strength in EIS based on the radiosonde analysis. Of course, this might be attributed to the spread of the inversion layer. It would be interesting to see if the EISp would actually perform better without the subtraction of the removal of the moist adiabat contribution, i.e. EISp as the potential temperature difference between the top and bottom of a layer with the maximum potential temperature gradient*

Response: Yes, it is interesting to try. By Fig. 2c and 2d (original Fig. 1c and 1d) in the revised manuscript, it is shown that the $\Delta\theta - \Gamma_m \Delta z$ distributions center at zero, which suggests that without removing the moist adiabat the distribution of $\Delta\theta$ likely has a positive shift because Γ_m and Δz are both positive. In addition, a wider spread is expected because of the variability in Γ_m and Δz.

As suggested, the θ difference between the top and bottom of a layer with the maximum gradient ($\Delta\theta_{max}$) without the removal of the moist adiabat has been tested for its performance on constraining LCC based on the SGP observations. The correlation of $\Delta\theta_{max}$ with LCC is 0.11 and the LCC sensitivity to $\Delta\theta_{max}$ is 22%. In contrast, the correlation of EISp with LCC is 0.34 and the LCC sensitivity to EISp is 50%. The correlation of $\Delta\theta_{max}$ with the radiosonde-measured IS is 0.47, which is also smaller than that of EISp (0.74). It seems to be necessary to remove the moist adiabat between the top and bottom of the layer with the maximum gradient to extract the IS from this layer.

- *It appears there are some limitations of the newly proposed variable. Firstly, it is for reanalysis data. For radiosondes with high vertical resolution, it seems the inversion strength can be directly calculated and might perform better than EISp. (Just curious, would the authors suggest the new variable for weather forecasting? It seems the LTS is commonly used in weather forecasting when only reanalysis data are available.). Secondly, all the test data sets are over extratropical regions and it is not clear how the controlling of low-level cloud compare over tropics with over extratropical regions, e.g. Figure 9. As the authors stated in the manuscript, this new variable may have limitations in the polar regions. The author could consider including the limitations this in the abstract.*

Response: For the first limitation, when the high-resolution radiosondes are available, the exact inversion top and base can be obtained fairly straightforward (Mohrmann et al., 2019). And in fact, the computation of EISp is adapted from the algorithm of obtaining the IS from high-resolution radiosondes, but is suitable for coarser resolution atmospheric profiles whether it is from the soundings or reanalysis. Because high-resolution soundings are rare, an applicable metric derived from reanalysis would be much more beneficial. It has been demonstrated in section 3 that the EISp can provide a more accurate estimate for the IS from the ERA5 profiles as compared to the LTS and EIS at the locations of subtropics and midlatitude with available radiosondes. Results in section 4 also demonstrate that the EISp is a better LCC controlling factor than LTS and EIS over subtropical eastern oceans. It has been explained in the main text:
Line 251-254 in the revised manuscript, "When high-resolution radiosondes are available, the exact IS can be obtained fairly straightforward (section 2.5, Eq. 6). The computation of EISp is in fact adapted from the algorithm of obtaining the IS from high-resolution radiosondes, but is adjusted to suit coarse-resolution atmospheric profiles in reanalysis. Because high-resolution soundings are rare, an applicable metric derived from reanalysis would be much more beneficial.".

For the second limitation, subtropics and midlatitude are most dominated by low clouds with the strongest cooling radiative effects on the earth (Klein and Hartmann, 1993) and thereby are the main focus for relationships between LCC and IS (e.g., Myers and Norris (2013), Qu et al. (2014), Mccoy et al. (2017) and Mohrmann et al. (2019)). Thus, these regions are the main focus of this work to provide a physically more reasonable and better cloud-controlling factor, which can be used to help evaluate the LCC responses to climate changes or aerosols. However, over tropics with less stratiform low clouds, the relationship between LCC and IS is not as important as those over subtropics and how the IS controls low clouds over tropics is also less important. Only a negative correlation between the LCC and IS is found and consistent with Szoeke et al. (2016) and the mechanism is still not clear. Since it is not an important focus of investigating the relationship of LCC with IS, it is barely discussed in this work.

If the use of LTS in weather forecasting is intended to measure the IS, EISp might be a better choice since the EISp does capture the IS more accurately than the LTS especially on short time scales of 1-7 days according to our results. However, because LTS measures the bulk lower-tropospheric stability, whether EISp can be used to replace LTS for weather forecasting requires further investigation.

- *The structure of the manuscript seems fine. The EISp definition can appear earlier in the manuscript. The authors could consider either moving section 3.1 to section 2, or making section 3.1 a separate section.*

Response: The EISp definition has been moved to section 3.1 to introduce the EISp at the beginning of the section 3:

Line 226-255 in the revised manuscript, "The EISp is designed to capture the IS information from the thinnest layer encompassing the inversion in low-resolution (hundreds of meters) atmospheric profiles. For these coarse-resolution profiles (e.g., ERA5), it is difficult to accurately locate the exact place of the inversion because usually the thickness of the inversion is much smaller than the distance between two adjacent vertical levels. Thus only one or two adjacent layers that could encompass the inversion are located. The latter is for the consideration that an inversion layer may be across two adjacent layers of the ERA5. Specifically, the EISp is computed as follows:

(1) Locating the layer of the maximum θ vertical gradient $(d\theta/dz)_{max}$:

For each hourly ERA5 profile, the layer of $(d\theta/dz)_{max}$ is firstly located between the LCL and 5km AGL (the red zone in Fig.1), since the inversion just features strong gradients in thermodynamical properties.

(2) Finding the layers encompassing the full inversion:

The layer of $(d\theta/dz)_{max}$ may not encompass the full inversion if the inversion crosses two adjacent layers of the ERA5. Thus, the layer of $(d\theta/dz)_{max}$ is combined with an adjacent layer just above or below it respectively, to constitute other two candidate layers that could encompass the full inversion (the blue and green zone in Fig.1).

(3) Calculating the EISp:

The EISp is calculated for the three possible layers identified in second stage, respectively:

$EIS_p = \theta_{top} - \theta_{base} - \Gamma_m(z_{top} - z_{base})$, (8)

where subscripts "top" and "base" represent the top and base levels of a candidate layer. Γ_m is computed using Eq. (5) at the base level. The θ increase of the moist adiabat is removed to extract the strength of the inversion between the top and base levels, which is consistent with the EIS framework in Wood and Bretherton (2006). The final EISp is determined by which layer in Fig.1 encompasses stronger inversion computed from Eq. (8) and thus refers to the largest value among the three candidates EISp1-3.

The EIS (Wood and Bretherton, 2006) assumes that the PBL is well mixed (dry adiabat below the LCL and moist adiabat above the LCL) for estimating the IS. If that is the case, EISp would give the same results as EIS. However, it will be shown in the following sections that the actual PBL often deviates from the well mixed conditions, where the EISp provides

a physically more reasonable estimate for the IS than the EIS and thus a stronger cloud-controlling factor.
When high-resolution radiosondes are available, the exact IS can be obtained fairly straightforward (section 2.5, Eq. 6). The computation of EISp is in fact adapted from the algorithm of obtaining the IS from high-resolution radiosondes, but is adjusted to suit coarse-resolution atmospheric profiles in reanalysis. Because high-resolution soundings are rare, an applicable metric derived from reanalysis would be much more beneficial. Because the IGRA soundings have similar vertical resolutions as ERA5 in lower troposphere, the IS of these soundings (used in section 3.3) is derived exactly by the same way as the EISp.".

Minor comments:

- *Please spell out SGP (Southern Great Plains)*

Response: It has been corrected:
Line 82 in the revised manuscript, "Southern Great Plains".

- *L178, change "or" to "and"?*

Response: It has been changed:
Line 237 in the revised manuscript, "above and below it".

- *L215, this sentence only considers land case, please add the part for ocean case. L222, can you add explantion why the heigh difference can be used to differentiate the coupled and decoupled PBLs?*

Response: It has been added as:
Line 276 in the revised manuscript, "If over oceans, the levels of 3km and 150m can be replaced with 700hPa and 1000hPa.".

An explanation has been added as:
Line 120-122 in the revised manuscript, "When the PBL is well mixed, Δz_b is close to zero, but in the decoupled PBLs the cloud and subcloud layers would be separated by a stable layer and the LCL may diverge from the cloud base hundreds of meters with large Δz_b (Nicholls, 1984; Jones et al., 2011).".

- *L257, by eye check, it appears it is as sensitive as LTS.*

Response: This sentence has been changed as:
Line 320 in the revised manuscript, "the composites of LCC are slightly/significantly more sensitive to the changes of IS than the LTS/EIS.".

- *L261, I was just wondering whether the strong IS is the result of the cloud formation and then maintain the low level cloud?*

Response: Mauger and Norris (2010) found that stronger capping inversion at the PBL top precedes the increase in cloud cover. The stronger inversion reduces entrainment and decreases the rate at which dry air from above the inversion is incorporated into the boundary layer, thus allowing the PBL to moisten and cloud cover to increase (Mauger and Norris, 2010). As soon as clouds form, the longwave radiation cools the cloud top and sharpens the inversion (Paluch and Lenschow, 1991).

- *L288-L292, this part is really confusing and hard to understand.*

Response: It has been rewritten as**:**

Line 346-359 in the revised manuscript, "To understand why this happens, the LTS and EIS in Eq. (9) both have been separated into three terms to discuss. For the LTS, the two terms $\theta_{LCL} - \theta_0$ and $\Delta\theta$ of Eq. (9a) usually offset each other with a negative correlation of -0.56 and a slope of the least-squares fit -0.5K/K (Fig. 4a). In contrast, the slope of the least-squares fit between $\Delta\theta - \Gamma_m \Delta z$ and $\theta_{LCL} - \theta_0$ is only -0.05K/K (not shown). Furthermore, the LTS and EIS equation can be transformed into:

$$\mathrm{LTS} = \left(1 + \frac{\Delta\theta}{\theta_{LCL}-\theta_0}\right)(\theta_{LCL} - \theta_0) + \mathrm{IS}, \text{ (10a)}$$

$$\mathrm{EIS} = \left(1 + \frac{\Delta\theta-\Gamma_m\Delta z}{\theta_{LCL}-\theta_0}\right)(\theta_{LCL} - \theta_0) + \mathrm{IS}. \text{ (10b)}$$

On average, the coefficient before $\theta_{LCL} - \theta_0$ for the LTS in Eq. (10a) is 0.5 while that for EIS in Eq. (10b) is 0.95. The variation of LTS and EIS result from both the changes of IS (positively correlated with LCC as shown in Fig. 3c) and the changes of $\theta_{LCL} - \theta_0$ (negatively correlated with LCC as shown in Fig. 4b). According to Eqs. (10a) and (10b), the LTS actually only involves half of the bias caused by $\theta_{LCL} - \theta_0$ and thus not as strongly influenced by $\theta_{LCL} - \theta_0$ as the EIS. As a result, only removing the moist adiabat ($\Gamma_m \Delta z$) does not make the EIS a better estimate for the IS at the SGP but make the EIS more influenced by $\theta_{LCL} - \theta_0$. This explains why the LTS is better correlated with LCC and RH (Figs. 3a and 3d) than the EIS (Figs. 3b and 3e) at the SGP. However, the physical reason that why the PBL stratification changes in this way is unclear to us and it is beyond the scope of this study.".

- *L293, this paragraph is confusing and hard to understand.*

Response: It has been rewritten as:

Line 362-367 in the revised manuscript, "Figs. 4c and 4d suggest that the spread of $|\Delta\theta - \Gamma_m \Delta z|$ increases with the layer thickness either between the LCL and the inversion base or between the inversion top and 3km AGL (with a correlation of 0.59 or 0.58, respectively). Thus, the thicker the layer encompassing inversion involved in the EIS calculation is, the larger the uncertainty is. Including more layers around the inversion layer in estimating the IS likely results in more uncertainty. This suggests a possible way of better estimating the IS if we can reduce the layer thickness (Δz) associated with the second term on the rhs of Eq. (9b), which also makes the IS estimate less dependent on the moist adiabatic assumption.".

- *L312, for extreme case, e.g. radiosonde with very high vertical resolution, the EISp is the Inversion Strength? If this is the case, the authors might want to state this in the manuscript.*

Response: Yes, if using the high-resolution radiosondes with the exact inversion top and base, the EISp is just the IS. This has been stated in the manuscript:

Line 252 in the revised manuscript, "The computation of EISp is in fact adapted from the algorithm of obtaining the IS from high-resolution radiosondes, but is suitable for coarser atmospheric profiles of either soundings or reanalysis.".

- *Fig 9, why these is negative values for R-square? This figure shows correlation rather than R-square?*

Response: R-square is used with a minus/plus sign to indicate negative/positive correlations. It has been stated in section 2.6 and also mentioned in the caption of Fig.9: **Line 511 in the revised manuscript,** "The minus/plus sign of R-square indicates negative/positive correlations.".

- *Fig 9, The quality of text in this figure seems low compared to other figures.*

Response: The discussion about Fig.9 has been separated into three parts: (1) subtropical eastern oceans; (2) midlatitude oceans; (3) land regions.

The text has been rewritten as:
Line 513-545 in the revised manuscript, "In Fig.9, the dependence of LCC on the LTS, EIS and EISp is further examined globally for the full daily time series (i.e., all time scales) and for the daily, 7-day window-averaged anomalies and monthly means (i.e., daily, 7-day and monthly time scales). It is noted that the dependence of LCC on the three ERA5-based metrics are variant across different regions. LCC is best correlated with the three metrics over the subtropical eastern oceans and some land regions that are most dominated by low clouds. Over midlatitude oceans and inner tropical convergence zone, the LCC is weakly or negatively correlated with the three metrics. Thus, it is discussed separately for the most LCC-dominated regions over subtropical oceans, midlatitude oceans and land.
(1) Over the subtropical eastern oceans with more than 60% of LCC, on all time scales (Figs. 9a-c), the EISp explains 36% of the variance in LCC on average, larger than that explained by the LTS (21%) and the EIS (20%). The fact that EIS does not provide a stronger correlation with LCC than LTS was also recognized by Park and Shin (2019) and Cutler et al. (2022). In contrast, the explained variance of the linear fitting between LCC and EISp is 1.8 times of that with LTS and EIS. Besides, the mean LCC sensitivity (defined in Eq. (11) and not shown in the figure) to the EISp on all time scales is 48% over these regions, significantly higher than that to the LTS (37%) and the EIS (36%). Although radiosondes are rare and the ERA5 profiles are mostly from the model output over these regions, the EISp still provides a much stronger constraint on LCC than LTS and EIS. As shown in Figs. 9d-i through daily to monthly time scales, the EISp robustly explains larger LCC variance than the LTS and EIS especially on short time scales.
(2) Over midlatitude oceans, weak and not significant correlations between LCC and the three metrics exist through all of time scales in Fig.9. This poor relationship is also found at the ENA site (Table 2) even using the radiosonde to derive the IS, and thus it is not caused by using the ERA5 to estimate the IS. This suggests that the IS-LCC relationship is indeed not uniform but varies with regions. Klein et al. (2017) also indicated that the LCC relationship with cloud controlling factors (e.g., the IS and sea surface temperature) is systematically different between the subtropical stratocumulus region and other regions (e.g., trade cumulus and midlatitude regions). Thus, when the IS is used to constrain the environmental influence on LCC variations, it should be noted that LCC is not all uniformly constrained by the IS for

different regions. For some regions such as midlatitude oceans, the IS might not be a good constraint on LCC. But by more accurately estimating the IS, the EISp is more correlated with LCC than the LTS and EIS over midlatitude oceans such as North Pacific and North Atlantic on all time scales in Figs. 9a-c.
(3) Over land regions of relatively more LCC (about 15%-25% at south America, China and Europe), the correlation between EISp and LCC is comparable to the subtropical oceanic regions through all of time scales in Fig.9. This suggests the EISp is also an important controlling factor for continental LCC over these regions. Besides, the EISp is more correlated with LCC than the LTS and EIS over most land regions, except over China where the LTS explains larger LCC variance than the EIS and EISp. The higher correlation of LTS with LCC over China might not be only attributed to the IS (LTS is not a direct measure of inversion but static stability). But more comprehensive and in-depth investigations on the LTS-LCC dependence are needed to understand the exact reason of this phenomenon.**”**.

- *L448, please explain how you calculate the values for different time scales, in section 2?*

Response: The method of separating different time scales has been explained in the section 2.6:
Line 208-212 in the revised manuscript, “for isolating the correlation and the regression slope on different time scales, window anomalies are defined as consistent with that in Szoeke et al. (2016): $x^{\Delta_i} = [x]^{\Delta_i} - [x]^{\Delta_{i+1}}$. The brackets represent mean of x over the window of length Δ. The superscripts Δ_i and Δ_{i+1} are the i-th window length and the next longer window length.”.

This sentence has been changed as:
Line 513-514 in the revised manuscript, “the dependence of LCC on the LTS, EIS and EISp is further examined globally for the full daily time series (i.e., all time scales) and for the daily, 7-day window-averaged anomalies and monthly means (i.e., daily, 7-day and monthly time scales).”.

- *L454, it appears the values are negative over tropical oceans.*

Response: This sentence has been changed as:
Line 516-517 in the revised manuscript, “LCC is best correlated with three metrics over the subtropical eastern oceans and some land regions that are most dominated by low clouds. Over midlatitude oceans and inner tropical convergence zone, the LCC is weakly or negatively correlated with the three metrics.”.

- *Figure 10, curious why use for example “Californian” than “California” or “Californian region”?*

Response: These have been changed as “Peru”, “Namibia”, “California”, “Australia”, “Canaria” in Figure 7 and Figure 10.

- *L482, should be explained variance rather than “variance”? also L516.*

Response: The “variance” has been changed as “window-averaged LCC anomalies”. The sentence has been changed as:
Line 558-560 in the revised manuscript, “As shown in Fig. 10 (the dash line in the left panel), over the five key tropical and subtropical eastern oceans, the daily and seasonal window-averaged LCC anomalies accounts for a larger portion of the total LCC variance, indicating the LCC variation mainly happens at the daily and seasonal time scales.”.

The sentence at L516 has been changed as:
Line 593 in the revised manuscript, “67% of the LCC variance is from the daily time scale”.