Climatology of Atmospheric Unstable Layers Revisited – A Corrigendum

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ABSTRACT

We have published a recent paper on differences between temperature fluctuations of various vertical scales in raw and processed US High-Resolution Radiosonde Data (HVRRD). In that paper, we note that the small-scale temperature fluctuations in the raw US HVRRD are significantly larger than those in the processed US HVRRD and that those small-scale temperature fluctuations are much larger during daytime that during nighttime. We believe that this is due to the varying amount of solar radiation falling on the radiosonde temperature sensor as the radiosonde instrument swings and rotates. In light of these new results, we present revisions to some of our conclusions about the climatology of atmospheric unstable layers. When we repeat our calculations of atmospheric unstable layers using the processed US HVRRD, we find the following. 1. The 0000/1200 UTC differences in unstable layer occurrences in the lower stratosphere that were noted in our earlier paper essentially disappear. 2. The "notch" in the deep tropics, where there is a relative deficiency of thin unstable layers and a corresponding excess of thicker layers is still a feature when processed data are analyzed, but the daytime "notch" is less marked when the processed data were used. 3. The discontinuity in unstable layer occurrences, when there was a change in radiosonde instrumentation, is still present when processed data are analyzed, but is diminished from what it was when the raw data were analyzed.

SIGNIFICANCE STATEMENT

In a previous paper deriving the climatology of atmospheric unstable layers, we emphasized several findings. We reexamine three of the main points of that paper when processed US high vertical-resolution radiosonde data are analyzed instead of the raw data used in that previous paper. We find the 0000/1200 UTC differences virtually disappear in the new analysis. We find that the "notch" feature previously noted at Koror still exists, and we find that the discontinuity in unstable layers, when radiosonde instrumentation is changed, is diminished, but is still present in the new analysis.

1. Introduction

Geller et al. (2021) showed some early results of analyses of atmospheric unstable layers, where such layers are defined by $\frac{\partial\theta}{\partial z} < 0$, where θ is potential temperature, and z is altitude. The data set they analyzed was the US 1-second High Vertical-Resolution Radiosonde Data (HVRRD), which had been used previously to derive turbulence information (e. g., Ko et al., 2019), and those data were described in Geller et al. (2021) and Ko et al. (2019). Geller et al. (2021) derived their results using raw data, meteorological parameters derived from the radiosonde measurements while Ko et al. (2019) utilized the processed data, which have been subjected to radiation corrections and smoothing. Radiation corrections have been well documented (e. g., Dirksen et al., 2014), but the details of the smoothing used in deriving the processed data are proprietary to the radiosonde manufacturer and are unavailable to us. This being the case, Wang and Geller (2024) analyzed the temperature fluctuations at various vertical scales in both the raw and processed US HVRRD. Some of their findings were the following.

1. The small-scale temperature fluctuations were larger in the raw HVRRD than in the processed HVRRD.
2. The small-scale temperature fluctuations were much larger in daytime soundings compared to those in nighttime soundings, those day/night differences being smaller, but still present, in the processed data. Small-scale temperature fluctuations were larger in the lower stratosphere than in the troposphere in both the raw and processed data.
3. The discontinuity that was noted in unstable layer occurrences at a radiosonde station when the instrumentation was changed, using raw HVRRD, is also present in the occurrences of small-scale temperature fluctuations. This discontinuity in the occurrences of small-scale temperature fluctuations, when raw HVRRD were used, was larger in daytime soundings than in nighttime soundings. There was also a similar, but smaller, discontinuity when processed HVRRD were used.
4. For larger vertical scale temperature fluctuations (> 1,000 m), the geographical pattern of the root-mean-square (rms) temperature fluctuations very much resemble those that have been previously been reported for gravity waves.

This is a corrigendum to Geller et al. (2021) in that, while the computations in this paper are the same as in our earlier paper, our conclusions about atmospheric unstable layers over the US are significantly altered when processed US HVRRD are used instead of raw HVRRD.

The computational methods used in this paper are the same as those used in Geller et al. (2021) except for the fact that processed US HVRRD are analyzed instead of raw US HVRRD. That is to say, we have used the same algorithm of Wilson et al. (2010) and Wilson et al. (2011) for rejecting spurious overturns existing due to "noise" in the data, and we used the methods of Wilson et al. (2013) to account for the destabilizing effect of moisture.

One of the principal conclusions of Geller et al. (2021) was that unstable layer occurrences of vertical scale 10-400 m were greater at 0000 UTC in the western United States and were greater at 1200 UTC in the eastern United States. Geller et al. (2021) also noted the existence of a "notch" in unstable layer occurrences at Koror (7.3 ^{0}N, 134.5 ^{0}E) at altitudes near 12 km, where there was a relative deficiency in thin unstable layers and an accompanying excess of thicker unstable layers. Finally, Geller et al. (2021) noted a discontinuity in the occurrences of unstable layers of thicknesses 10-400 m at Jacksonville, FL when the radiosonde instrumentation at that station was changed. In the following we will see how each of these three conclusions are changed when processed US HVRRD are used instead of raw US HVRRD.

2. 0000/1200 UTC Differences

The top panel in figure 2 of Geller et al. (2021) showed the aggregate frequencies of occurrence of unstable layers of thickness 10-400 m, occurring at altitudes 15-25 km at 0000 and 1200 UTC, at Riverton, Wyoming (43.06 ^{0}N, 108.47 ^{0}W), and the top panel of figure 4 of Geller et al. (2021) shows the same for Greensboro, North Carolina. Geller et al. (2021) pointed out that those aggregate frequencies were greater at 0000 UTC than at 1200 UTC at Riverton, while the opposite was true for Greensboro. Figure 5 of Geller et al (2021) showed that, in general, these aggregate frequencies for altitudes 15-25 km were larger at 1200 UTC than at 0000 UTC for radiosonde stations in the eastern United States, while the opposite was true for radiosonde stations in the western United States. The locations of Riverton, WY and Greensboro were shown in that figure 5, so Geller et al. (2021) concluded that the

Riverton and Greensboro results shown in their figures 2 and 4 were a manifestation of the general picture shown in their figure 5.

Figure 1 shows the aggregate frequencies for the occurrence of unstable layers of thickness 10-400 m for altitudes 15-25 km for Riverton (top panel) and for Greensboro (bottom panel) at 0000 and 1200 UTC when those calculations used raw US HVRRD (thin lines) and also when those calculations used the processed US HVRRD (thick lines). It is clear that the 0000/1200 UTC differences that were apparent when the raw data were analyzed virtually disappear when the processed data were analyzed. Note that the aggregate frequencies of unstable layers are often larger when the processed data were used than when the raw data were used. We believe that this is due to our applying the methodology of Wilson et al. (2010) and Wilson et al. (2011) to reject spurious unstable layers that arise from noise in the data. Wang and Geller (2024) have shown that, in general, the trend-to-noise ratio (tnr) for small-scale vertical temperature gradients is larger in the processed HVRRD than in the raw HVRRD. This smaller tnr in the raw data leads to greater rejection of small-scale overturnings when the raw data are used than when the processed data are used. The greater rejections of small-scale overturnings less than 100 m when the raw data are analyzed sometimes result in smaller aggegate frequencies for unstable thicknesses less than 100 m when the raw data are used than when the processed data are used.

We show that this is the case in the following two figures. Figure 2 shows that UTC differences are greatly diminished when the processed HVRRD are analyzed relative to when the raw HVRRD are analyzed, and the number of occurrences are greatly diminished for unstable layer thicknesses 100-400 m relative to the situation for the 10-400 m thickesses. Two other interesting features are also seen. Contrary to what was seen in figure 1, the aggregate frequencies at both 0000 and 1200 UTC are always less when the processed data are used than when the raw data are used. The fact that the aggregate frequencies were sometimes seen to be greater when the processed HVRRD were used than when the raw HVRRD were used must have been due to a greater aggregate frequency of unstable layers of thicness 10-100 m, and this was due to a greater number of the thin layers being discarded in the raw data when the Wilson et al. (2010) and Wilson et al. (2011) methodology was used. Also, although the 0000/1200 UTC differences are much smaller in figure 2 relative to what is seen in figure 1, the 0000/1200 UTC difference in occurrences are in the same sense regardless of whether the raw or processed HVRRD are analyzed; that is to say, the 0000

UTC occurrences are systematically greater for Riverton, and the 1200 UTC occurrences are systematically greater for Greensboro.

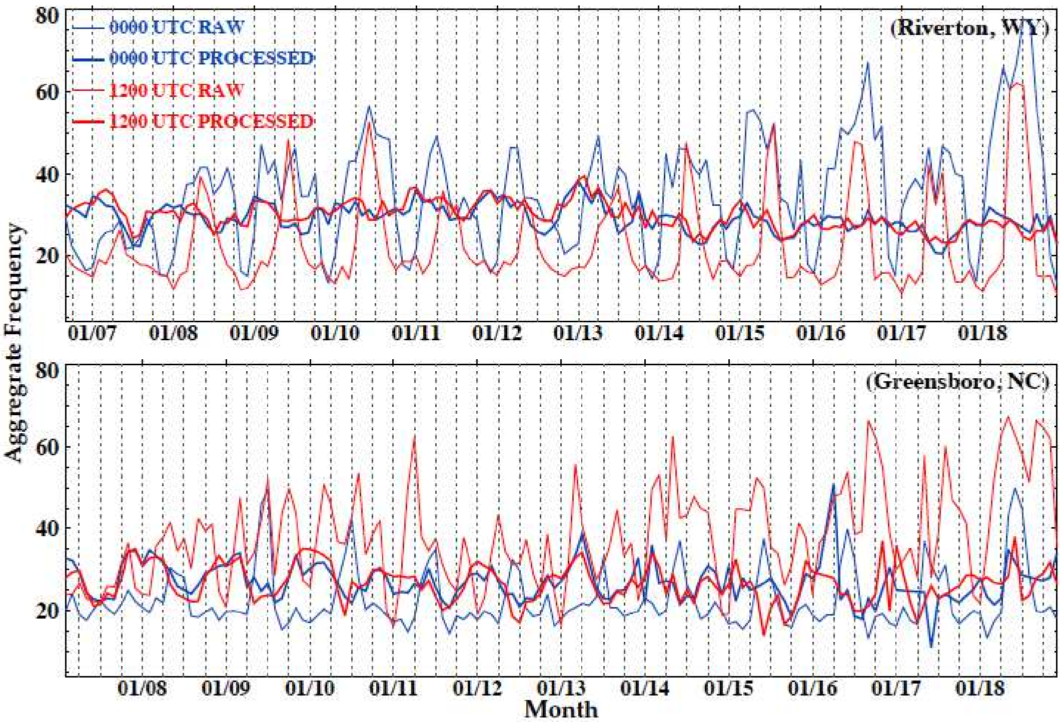

Figure 1. Time series for the aggregate frequencies of occurrence of unstable layers of thicknesses 10-400 m at altitudes of 15-25 km at Riverton, WY (43.06 ^{0}N, 108.47 ^{0}W) for months since September, 2006 (top) and Greensboro, NC (36.08 ^{0}N, 79.95 ^{0}W) since February, 2007 (bottom) calculated with raw US HVRRD (thin lines) and processed US HVRRD (thick lines) at 0000 UTC (blue) and 1200 UTC (red). Vertical dashed lines indicate Januaries (at the year indicators), Aprils, Julys, and Octobers.

A more quantitative way to examine the differences in the occurrences of unstable layers of different thicknesses is to look at the histograms showing the numbers of occurrences per sounding of unstable layers for various vertical layer thicknesses.[1] This is shown in figure 3 for July and December at Riverton and April and December at Greensboro for the altitude range 15-25 km for 0000 and 1200 UTC. We show results for this altitude range since Wang and Geller (2024) have shown that the differences between temperature fluctuations in raw and processed HVRRD profiles are largest in the stratosphere. Note that at Riverton the July histograms show larger occurrences of unstable layers of all thicknesses when the raw data were used. This is consistent with the larger aggregate frequencies seen during the summer months in figure 1 at that station. In December at Riverton, however, a different situation is seen. At both 0000 and 1200 UTC, larger occurrences are seen for layers 20-50 m, with similar occurrences seen for larger unstable layer depths. This is consistent with the results of figure 1 where the aggregate frequencies are less for the raw data than for the processed data in the winter months. The July histogram results are also consistent with the results of figure 2 where the aggregate frequencies for thicknesses 100-400 m are much larger in summer when the raw data at 0000 UTC are used than when processed data are used with the 1200 UTC differences being smaller. In winter, the differences in aggregate frequencies when raw versus processed data are used are much smaller for thickness 100-400 m, consistent with what is seen in the histograms. At Greensboro, again the histogram results are consistent with what was seen in the aggregate frequency time series shown in figures 1 and 2.

[1] It should be noted that the histogram in figure 3 is plotted differently than in Geller et al. (2021) in that different intervals are used for thicknesses less than and greater than 100 m to emphasize the differences between results using raw and processed data for the thinner layers. This gives rise to a different slope of the histogram results for thicknesses less than and greater than 100 m.

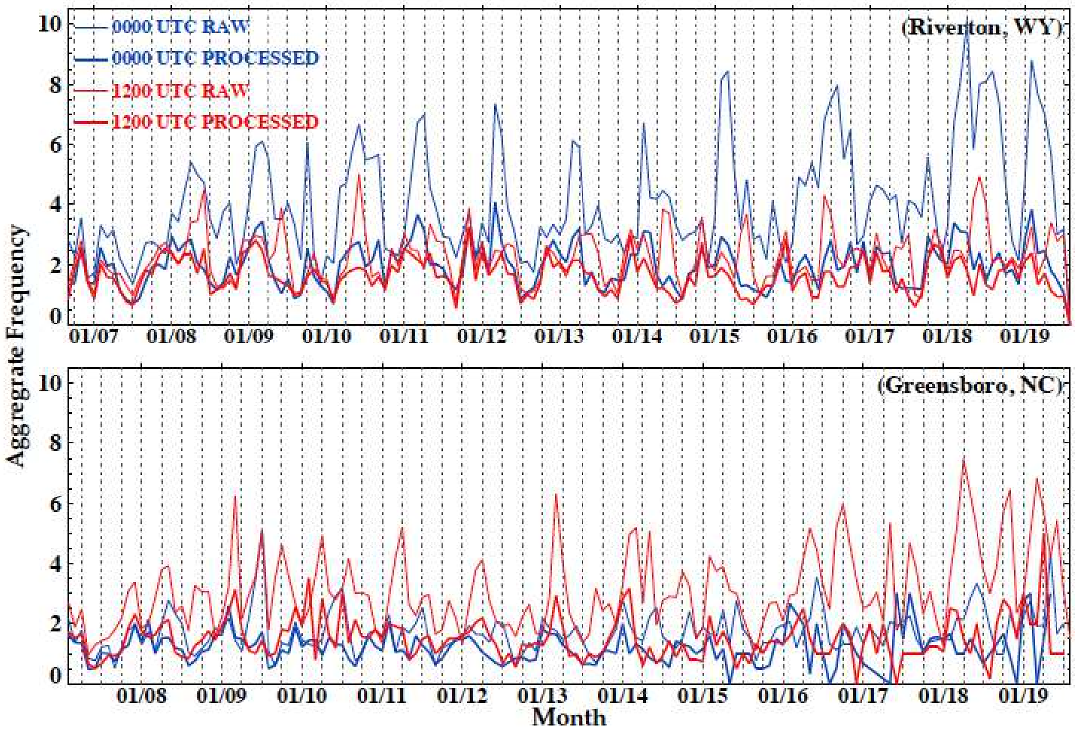

Figure 2. Same as figure 1, but for unstable layers of thicknesses 100-400 m.

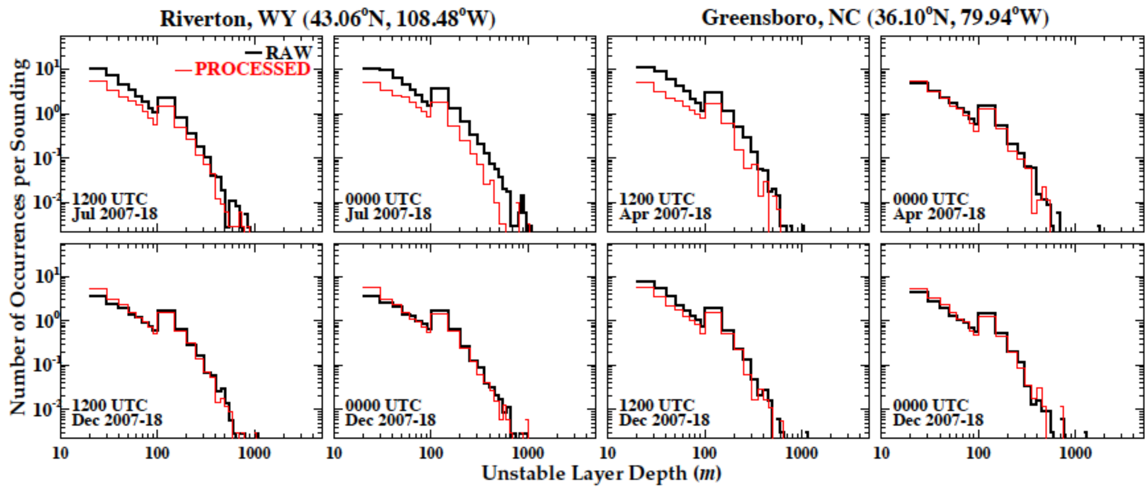

Figure 3. Histograms, showing numbers of occurrences per sounding of unstable layers of various depths for July and December at Riverton, WY (left) and April and December at Greensboro, NC (right) using raw data (black) and processed data (red) at 00 and 12 UT. Note that different intervals have been used for unstable layer thicknesses less than 100 m than for thicknesses greater than 100 m.

3. The “notch” at Koror

Figure 4 shows plots of $\log_{10}$ of the frequency of the occurrences of unstable layers of various depths as a function of altitude using raw HVRRD (left panels) and processed HVRRD (right panels) for April and July for 0000 and 1200 UTC at Koror (7.34 ^{0}N, 134.48 ^{0}E). Geller et al. (2021) pointed out the existence of a “notch” at altitudes around 12 km at Koror, where this “notch” was characterized by a deficiency of thin unstable layers and a corresponding excess of thicker layers at those altitudes. It should be noted that 1200 UTC is nighttime, and 0000 UTC is daytime at Koror. It is clear that this “notch” is more obvious at 0000 UTC (daytime) when the raw HVRRD were used than when the processed HVRRD were used, particularly in the relative deficiency of thin layers, while the 1200 UTC (nighttime) pictures of the notch using raw HVRRD looked relatively more similar to the results using the processed HVRRD. Interestingly, the excess in thicker unstable layers concentrated at altitudes near 12 km was more obvious when the processed HVRRD were used, both at 0000 and 1200 UTC. Thus, this “notch” feature was present when either the raw or processed HVRRD were used. We believe that two influences on the thicknesses of unstable layers are seen in figure 4. Grise et al. (2010) have pointed out the existence of a minimum in atmospheric stability in the deep tropics. Furthermore, Gettelman and Forster (2002) and Fueglistaler et al. (2009) had earlier associated this stability minimum with

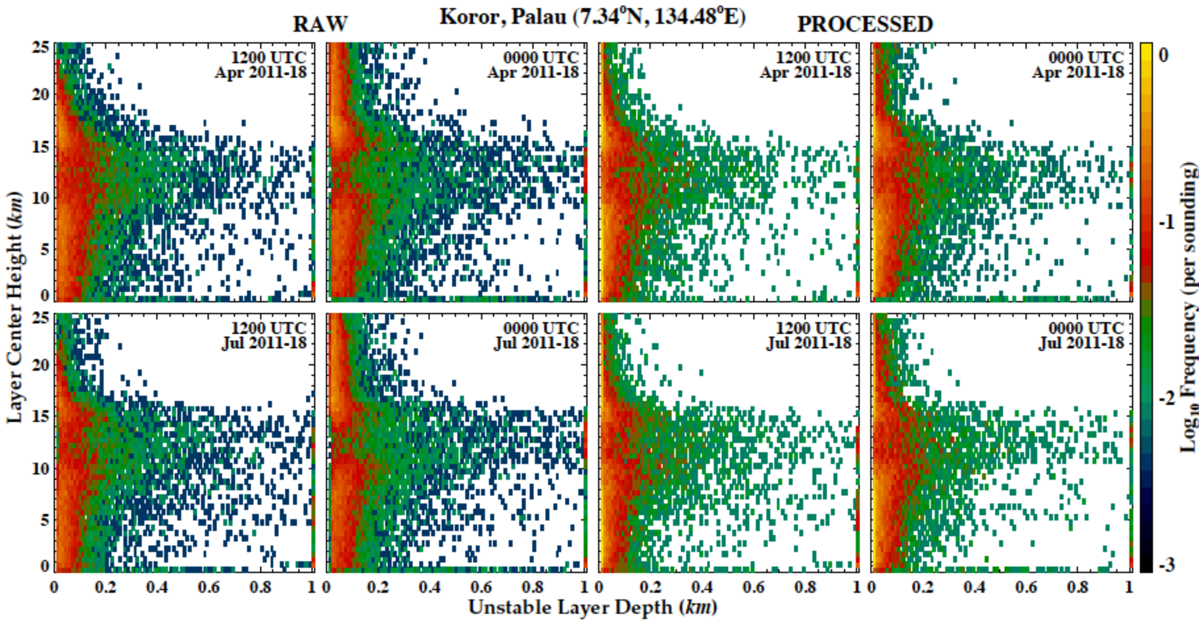

Figure 4. Plots showing $\log_{10}$ frequency of frequency of occurrence per sounding of the depth of unstable layers with altitude at Koror (7.3 ^{0}N, 134.5 ^{0}E) for April and July where 1200 UTC is at night and 0000 UTC is daytime. Left – results using raw HVRRD. Right – results using processed HVRRD.

convective cloud outflow. This convective cloud outflow likely advects cloud top turbulence, which accounts for the greater number of thick unstable layers at Koror at altitudes around 12 km. This turbulence may act to entrain the thinner unstable layers at those latitudes, but we believe that another influence is leading to the apparent depletion of thin unstable layers at those altitudes, and that is the application of the Wilson et al. (2010) and Wilson et al. (2011) methodology to discard spurious overturnings that arise from noise in the data. The Wilson et al. (2010) and Wilson et al. (2011) methodology acts to discard more of the thinner unstable layers when there is a smaller tnr. Clearly in the region of the stability minimum, the gradient in potential temperature is smallest, leading to more discarding of thin unstable layers. This is consistent with what is seen in figure 4, Wang and Geller (2024) have shown that spurious small-scale temperature fluctuations are greater in daylight than at night. This is consistent with a less distinct "notch" being seen at Koror at 1200 UTC (nighttime) than at 0000 UTC (daytime) when the raw data are used.

In figure 4, more frequent thicker unstable layers (thicknesses greater than about 400 m) appear present in the 10-14 km altitude region (i. e., the "notch" region) when the processed HVRRD are used, as manifested by the preponderance of green pixels in the processed plots in that altitude region. We note that Wilson et al.'s (2011) figure 7 showed a greater frequency of thicker overturns in low-resolution (6-7 m) standard radiosonde data than in high-resolution (10-20 cm) balloon data. This is likely due to small-scale overturnings disrupting the thicker unstable layers, thereby breaking those thicker overturns into a number of smaller overturns. This is also consistent with the results in Wilson et al. (2010).

Geller et al.'s (2021) figure 9 showed time series of the aggregate frequencies of unstable layers of thicknesses 10-400 m occurring between 15-25 km at Koror. They noted that there were more unstable layers of those thicknesses at 0000 UTC than at 1200 UTC and also that there appeared to be a secular increase in layers of those thicknesses after 2014. Figure 5 shows those results both when the raw HVRRD were used as in Geller et al. (2021)

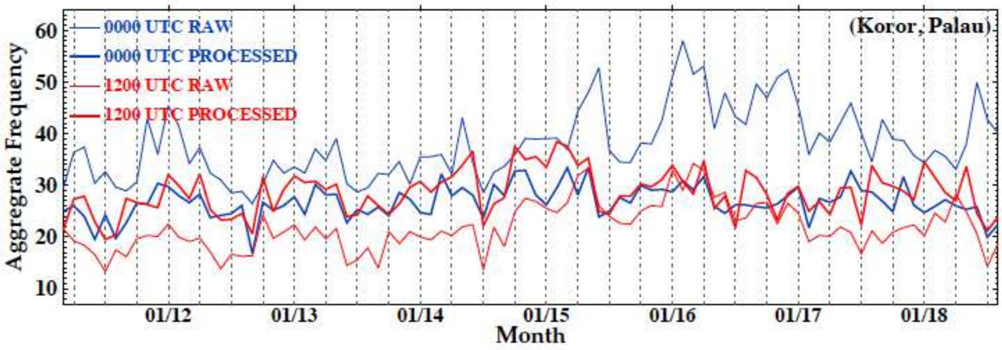

Figure 5. Time series of monthly aggregate frequencies of unstable layers of thicknesses 10-400 m at Koror at 0000 UTC and 1200 UTC, where the starting month is March, 2011. As before, 0000 UTC results are in blue, 1200 UTC results are in red, thin lines show results from raw data, and thick lines are from processed data.

and when the processed HVRRD were used. Note that the 0000/1200 UTC differences are greatly diminished when the processed data were analyzed, and the secular increases in the occurrences of those layers are no longer present when the processed HVRRD are used. Also, it is interesting to note that the 0000 UTC plots show that while the aggregate frequencies of unstable layers of thickness 10-400 m in the stratosphere are often larger when the raw HVRRD are used, the calculations with the processed HVRRD often show larger aggregate frequencies of unstable layers of thickness 10-400 m in the stratosphere at 1200 UTC. Histograms for the numbers of unstable layers of various thicknesses per sounding (not shown) are consistent with this.

4. Discontinuity when radiosonde instrumentation was changed

Figure 6 shows the time series for the aggregate frequencies of the occurrences of unstable layers of thicknesses 10-400 m in the stratosphere (15-25 km) at Jacksonville, Florida. A clear discontinuity is seen in early 2013 in the raw data results, when there was a

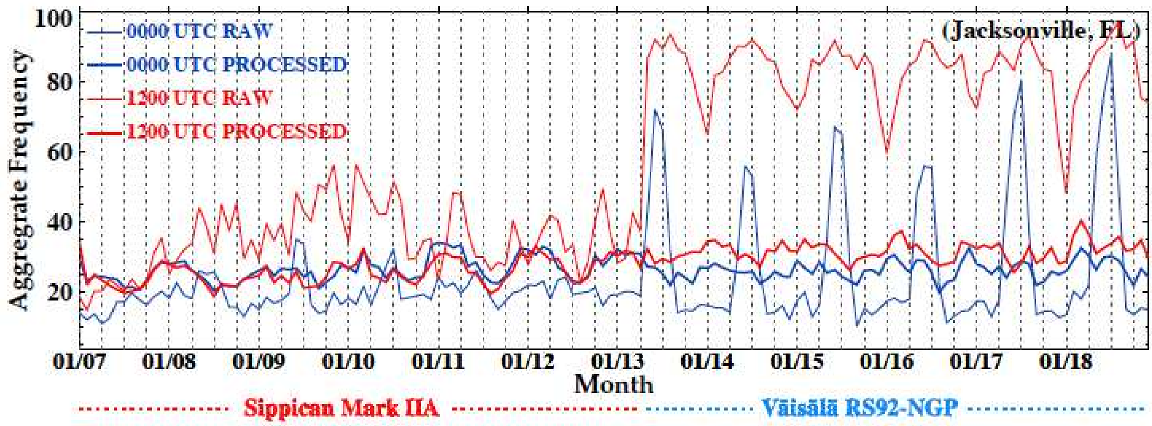

Figure 6. Time series of monthly aggregate frequencies of unstable layer thicknesses 10-400 m in the 15-25 km altitude region at Jacksonville, FL at 0000 UTC and 1200 UTC, where the starting month is January, 2007. Blue lines show results at 0000 UTC, and red lines show results at 1200 UTC. Thin lines show results using raw data, and thick lines show results using processed data.

change in radiosonde instrumentation from the Sippican Mark IIa to the Väisälä RS92-NGP. Geller et al. (2021), while noting this discontinuity, did not give any explanation for its cause. In light of the Wang and Geller (2024) paper, we believe that this is a result of the differing amount of spurious small-scale temperature fluctuations when different radiosonde instruments are used. These results are consistent with the findings of Wang and Geller (2024) who showed that small-scale temperature fluctuations are larger in raw HVRRD than in processed HVRRD. Wang and Geller (2024) also showed that the day/night differences in those small-scale temperature fluctuations are smaller when processed HVRRD are used than when raw HVRRD are used. Also as mentioned in the previous section, Wilson et al. (2010) showed that spurious small-scale temperature fluctuations can affect the calculated statistics for larger-scale unstable overturnings, or unstable layers. Wang and Geller (2024) hypothesized that the varying sunlight falling on radiosonde temperature sensors are likely the cause of much of these small-scale temperature fluctuations as the temperature sensors experience different sunlight exposure as the instrument rotates and swings, so it is reasonable to assume that the different temperature sensors used by different radiosonde manufacturers might have different responses to this. This discontinuity is diminished when the processed HVRRD are used, but it is not eliminated. It appears that the data processing was much more effective during the period when the Sippican Mark IIa instrument was being used in that the 0000/1200 UTC differences are diminished, but not eliminated. Also, note that the number of unstable layers occurrences at 1200 UTC is much less when the processed data were used. Explaining the causes behind the greater differences in the aggregate frequencies of the unstable layers found when the Sippican Mark IIa instrument was used relative to those when the Väisälä RS92-NGP was used instrument was used will likely require understanding both the responses of those temperature sensors to varying radiation and the smoothing used in deriving the processed data.[2]

5. Summary and Conclusions

Geller et al. (2021) presented several results on atmospheric unstable layers, where their calculations were performed using raw US HVRRD. Wang and Geller (2024) have shown that spurious temperature fluctuations at small vertical scales are present in raw US HVRRD, particularly during daytime. They argue that much of those spurious small-scale temperature fluctuations are due to the varying solar radiation falling on the radiosonde temperature sensor so they expect that those spurious small-scale vertical temperature fluctuations will be different for different radiosonde instruments. Wang and Geller (2024) show that the small-scale temperature variations are smaller by about a factor of two in the processed HVRRD relative to the raw HVRRD and that the 0000/1200 UTC differences in those temperature fluctuations are also much smaller in the processed HVRRD, but are still present. Therefore, we conclude that the smoothing employed in the processed HVRRD diminishes, but does not eliminate the spurious temperature fluctuations. Given this situation, we examine how the conclusions in Geller et al. (2021) are changed when their calculations are done using processed instead of raw HVRRD.

Our principal findings were the following.

[2] We note that there was a change in instrumentation from the Sippican Mark IIA to the Lockheed Martin LMS-6 on 05 April 2015 0000 UTC at Koror. This likely accounts for the discontinuity seen in figure 5 around mid-2015.

1. The 0000/1200 UTC differences in unstable layer occurrences that were seen over the contiguous United States in Geller et al. (2021) were largely a consequence of the day-night differences in spurious small-scale temperature fluctuations in the raw US HVRRD, and those day-night differences largely disappeared when the processed US HVRRD were used.
2. The “notch” in unstable layer occurrences that was seen at Koror, in the deep tropics, where there are less thin unstable layers and more thicker unstable layers at altitudes around 12 km is less prominent, but still present, when the daytime processed HVRRD are analyzed compared to what was seen when the raw data were used. This “notch” feature is similar in nighttime soundings when either the raw or processed US HVRRD were used.
3. The discontinuity in unstable layer occurrences noted in Geller et al. (2021), accompanying a change in radiosonde instrumentation, when the raw HVRRD were analyzed is diminished, but not eliminated, when the processed HVRRD were analyzed. One cause of this discontinuity appears to be the different responses to the varying solar radiation experienced when the different temperature sensors swing and/or rotate during radiosonde ascent.

The results of this paper illustrate some of the cautions that should be exercised when analyzing raw US HVRRD, and to a lesser extent processed US HVRRD. More specifically, the results of this paper indicate that the spurious temperature fluctuations in HVRRD, and their day/night differences can affect determinations of unstable layers, or the turbulent overturnings with which Thorpe analysis of turbulence begins. This is particularly the case when raw HVRRD, and to a lesser extent processed HVRRD, are used. Thus, caution should be exercised when comparing Thorpe analysis of turbulence from the HVRRD obtained with different radiosonde instruments.

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Data Availability Statement.

Radiosonde data analyzed in this study were obtained from the U.S. National Oceanic and Atmospheric Administration National Centers for Environmental Information: ftp://ftp.ncdc.noaa.gov/pub/data/ua/. Copies of the diagnostic software used for the analysis of this paper can be obtained by contacting Dr. Ling Wang at lwang@gats-inc.com.

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