The “Notch” in Unstable Layers and the Stability Minimum in the Tropics

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ABSTRACT

In a previous paper, we identified a “notch” in unstable layers at Koror (7.3 ^{0}N, 134.5 ^{0}E), where there was a relative deficiency in thin unstable layers and a corresponding relative excess in thicker layers, at altitudes centered at 12 km. We hypothesized that this feature was associated with the previously identified stability minimum in the tropics at that same altitude. In this paper, we extend our studies of this “notch” and its association with the tropical stability minimum by examining other stations in the deep tropics and also some stations at higher latitudes within the tropics. We find that this “notch” feature is found at all the other radiosonde stations in the deep tropics that we examined. We also find that the annual variations in unstable layer occurrences at stations at higher latitudes within the tropics show variations consistent with our hypothesis that this “notch” is associated with the region of minimum stability in the tropics at altitudes centered around 12 km, in that the annual variation in this “notch” feature is consistent with the annual variation of minimum stability in this region. Two factors contribute to the “notch” feature. One is that the data quality control procedure of the analysis rejects many thin layers due to the small trend-to-noise ratio in the region of minimum stability. The other is that the cloud-top outflow, which was previously identified with the stability minimum, advects thicker unstable layers throughout the deep tropics at the altitudes of the “notch.”

SIGNIFICANCE STATEMENT

Previous papers have separately identified a stability minimum in the tropics and a “notch” feature in the thicknesses of unstable atmospheric layers where there are less thin unstable layers and a corresponding excess of thicker unstable layers, both at altitudes around 12 km. We previously hypothesized that these two features were associated with one another. In this paper, we examine this “notch” feature and the minimum in atmospheric stability at both deep tropical radiosonde stations and stations located at higher latitudes in the tropics, and we find that the annual variation of this “notch” feature is consistent with the latitudinal migration of the latitudes of the stability minimum. Turbulence associated with this “notch” feature might be significant for aircraft operations.

1. Introduction

Geller et al. (2021) reported finding a "notch" feature at Koror (7.3 ^{0}N, 134.5 ^{0}E), where there was a relative deficiency in thin unstable layers at altitudes centered at about 12 km, accompanied by a relative excess in thicker unstable layers at those altitudes. They hypothesized that this "notch" feature was associated with the region of minimum stability found by Grise et al. (2010). Gettelman and Forster (2002) and Fueglistaler et al. (2009) had earlier noted this climatological feature, and they associated it with the region of convective cloud outflow. Geller et al. (2024) have reexamined the atmospheric unstable layer results of Geller et al. (2021) when the processed US High Vertical-Resolution Radiosonde Data (HVRRD) were analyzed instead of the raw data used in Geller et al. (2021), and they noted two factors that contributed to this "notch" feature. With respect to the deficiency of thin unstable layers, Geller et al. (2024) suggested that the data quality methodology of Wilson et al. (2010) and Wilson et al. (2011) played a major role in contributing to this deficiency since at the stability minimum, the trend-to-noise ratio (tnr) in the potential temperature profiles is small, there will be a greater rejection of the thinner overturns. They also noted the advection of cloud-top turbulence would account for the excess of thicker unstable layers in the "notch" region, and the larger eddies of this cloud-top turbulence provide turbulent mixing of the thinner unstable layer environment, forming thicker unstable layers.

Given the results of Geller et al. (2021) and Geller et al. (2024), we expect the following.

1. We expect that the "notch" feature, seen at Koror, is present at all radiosonde stations in the deep tropics.
2. We expect that the annual variations of the "notch" feature at higher latitude tropical radiosonde stations will be consistent with the annual migration of the latitudes of this stability minimum at altitudes around 12 km.

To confirm these expectations, we analyze the distribution of atmospheric unstable layers of various thicknesses using temperature data from the 1-second US HVRRD. This is the same dataset that has been analyzed for turbulence by Ko et al. (2019) and for the climatology of unstable layers by Geller et al. (2021). Details of this dataset were given in both those papers. Geller et al. (2021) used the raw HVRRD for their analysis, while Ko et al. (2019) used the processed HVRRD in their analysis.

The processed HVRRD have been radiation corrected, i.e., the temperature data have been adjusted to take into account how the solar radiation falling on the radiosonde temperature sensor results in temperature readings that differ from the actual atmospheric temperatures. The processed HVRRD have also been smoothed, the details of this smoothing being proprietary to the radiosonde manufacturer. Given this, Wang and Geller (2024) have tried to understand aspects of this smoothing by looking at temperature fluctuations of various vertical scales in raw and processed HVRRD. They found that there were spurious temperature fluctuations at small vertical scales during daytime in both the raw and processed data, and that those spurious temperature fluctuations were greatly diminished, but not eliminated, in the processed data relative to those in the raw data.

Geller et al. (2024) discussed how the use of the raw HVRRD affected the conclusions about the atmospheric unstable layer climatology in Geller et al. (2021). Specific to the present paper, Geller et al. (2024) concluded that the "notch" feature at Koror noted in Geller et al. (2021) was present in both the raw and processed HVRRD, but that this "notch" feature at Koror was more obvious when the daytime raw HVRRD were analyzed than when the processed daytime data were analyzed, and that this "notch" feature looked very similar at Koror in both the nighttime raw and processed data. They noted that there was a smaller deficiency in thin unstable layers in this notch region when the processed data were used than when the raw data were used. They attributed much of the smaller deficiency in thin unstable layers in this "notch" region to the data quality control procedures of Wilson et al. (2010) and Wilson et al. (2011), which leads to the rejection of many of the thin layers in this region due to the small tnr in the region of the stability minimum.

2. The "notch" in the deep tropics

Figure 1 shows the distribution of the $\log_{10}$ frequency of occurrence per sounding of unstable layers of various thicknesses as a function of altitude at Koror, Palau (7.3 ^{0}N, 134.5 ^{0}E), as computed using the processed data at 1200 UTC for the months January, April, July, and October using all the data that were available to us at the time, namely, 2012-2018 for January, 2011-2018 for April and July, and 2011-2017 for October. The methodology to derive the unstable layer statistics from the 1-second US HVRRD follows closely Geller et al. (2021) except that the processed data are analyzed here. Basically, we perform Thorpe analysis (Thorpe, 1977), which has been adapted for the analysis of atmospheric turbulence. Specifically, we follow Wilson et al. (2010) and Wilson et al. (2011) to detect turbulence overturning events that can be distinguished from measurement noise. We also apply the techniques of Wilson et al. (2013) to account for the destabilizing effect of water vapor, which is particularly important in the troposphere.

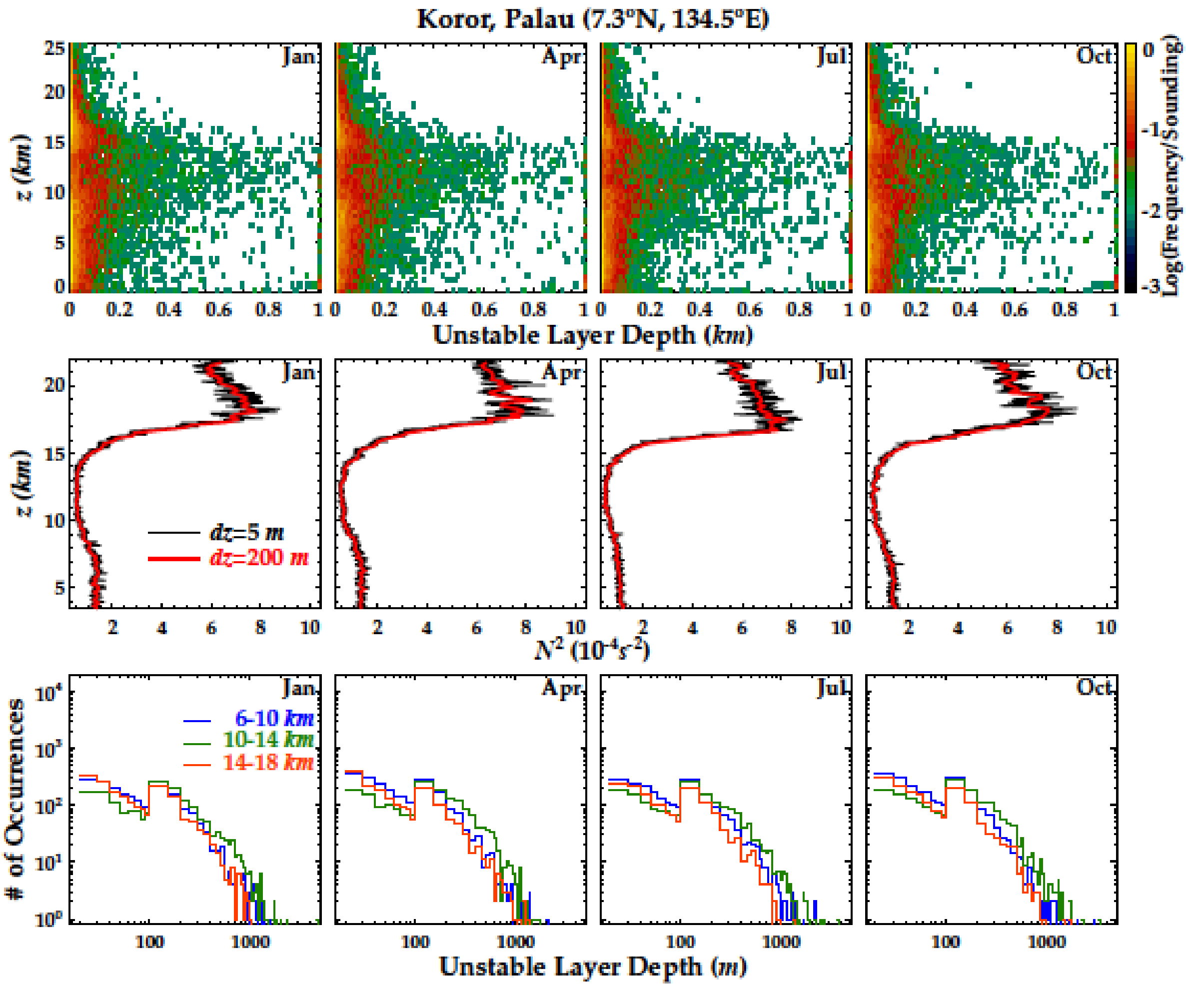

Figure 1. Top Row – Distribution of the thicknesses of unstable layers at Koror in January, April, July, and October calculated from processed HVRRD at 1200 UTC. Middle Row – Monthly mean N^2 profiles for Koror for January, April, July, and October. Black curves are results using the native 5 m resolution data, and the red curves show the results using 300 m resolution smoothed data. Bottom Row – Histograms for the thicknesses of unstable layers for the altitude regions 6-10 km (blue), 10-14 km (green), and 14-18 km (red).

We show the 1200 UTC results since Wang and Geller (2024) have shown that the nighttime HVRRD are less "noisy" than are the daytime data. Furthermore, Geller and Wang (2024) have shown that the 1200 UTC (nighttime) view of the "notch" at Koror using the raw HVRRD is very similar to that calculated using the 1200 UTC processed HVRRD. Figure 1 also shows the corresponding monthly mean N^2 profiles for those same months, and also "notch" histograms, similar to what was shown in figure 11 in Geller et al. (2021) for the same months. Note that there is a stability minimum at altitudes centered at about 12 km in the N^2 profiles in all months, with this minimum being slightly deeper in July. This is consistent with the stability minimum results of Grise et al. (2010). Examining the histograms, we see that there are clear deficiencies in the thinnest layers and enhancements in thicker unstable layers for all months in the 10-14 km region, the “notch” region, relative to the 4 km thick regions directly above and below the “notch” region. Also, note that similar results are shown in the supplementary figures for the other deep tropical stations we have analyzed – Ponape, Micronesia (7.0 ^{0}N, 158.2 ^{0}E), Chuuk, Micronesia (7.5 ^{0}N, 151.8 ^{0}E), Majuro, Marshall Islands (7.1 ^{0}N, 171.3 ^{0}E), and Yap, Micronesia (9.5 ^{0}N, 138.1 ^{0}E); that is to say, a clear “notch” is seen in all months, as is the clear minimum in N^2 at altitudes centered at about 12 km, and also enhancements in the thicker unstable layers in the 10-14 km region of the “notch” relative to the 6-10 and 14-18 km altitude regions.

Having seen that the existence of this “notch” in unstable layers and the stability minimum at altitudes centered around 12 km are present in all the deep tropical stations that we have examined, we now look at the annual behavior of this “notch” and the stability minimum at higher latitudes in the tropics.

3. The “notch” at higher latitude tropical stations

Looking at figure 3 of Grise et al. (2010), we see that the region of deepest stability minimum extends from about 18 ^{0}S to about 16 ^{0}N in the DJF season, extends from about 15 ^{0}S to about 15 ^{0}N in the MAM season, extends from about 16 ^{0}S to about 20 ^{0}N in the JJA season, and extends from about 16 ^{0}S to about 19 ^{0}N in the SON season. Thus, the southern edge of this region of the deepest stability minimum migrates by about 3 ^{0} while the northern edge of this region of stability minimum migrates by about 5 ^{0} throughout the year. Given this, we examine tropical stations at the northern and southern edges of the deep tropics to see if the “notch” feature evolution throughout the year is consistent with the seasonal migration of the stability minimum. The stations we examine are Pago Pago, American Samoa (14.3 ^{0}S, 170.7 ^{0}W), Agana, Guam (13.5 ^{0}N, 144.8 ^{0}E), and San Juan, Puerto Rico (18.4 ^{0}N, 66.0 ^{0}W). Figure 2 shows results at Pago Pago. At Pago Pago, we see that there is a “notch” feature, i. e., a deficiency of thin unstable layers at altitudes centered about 12 km, and there are also many thicker unstable layers at altitudes centered at about 12 km in all four months. Looking at the stability profiles next, we see the deep minima in N^2 in all four months at about 12 km altitude, with the deepest minimum in January. The histograms for Pago Pago are consistent with this in that the there are excesses in thicker unstable layers in all four months, but the shape of the histograms in January and April most resemble those in the deep tropics. This is consistent with Figure 4 in Grise et al. (2010), in that Pago Pago is within the region of minimum stability in all four months. The “notch” feature at Pago Pago is not as marked as at Koror though in terms of the deficiency of thin unstable layers, the excess in thicker layers, and the depth of the minimum stability at an altitude of about 12 km. This is consistent with Pago Pago being near the edge of the minimum stability region, where the stability minimum is not as marked as in the deep tropics.

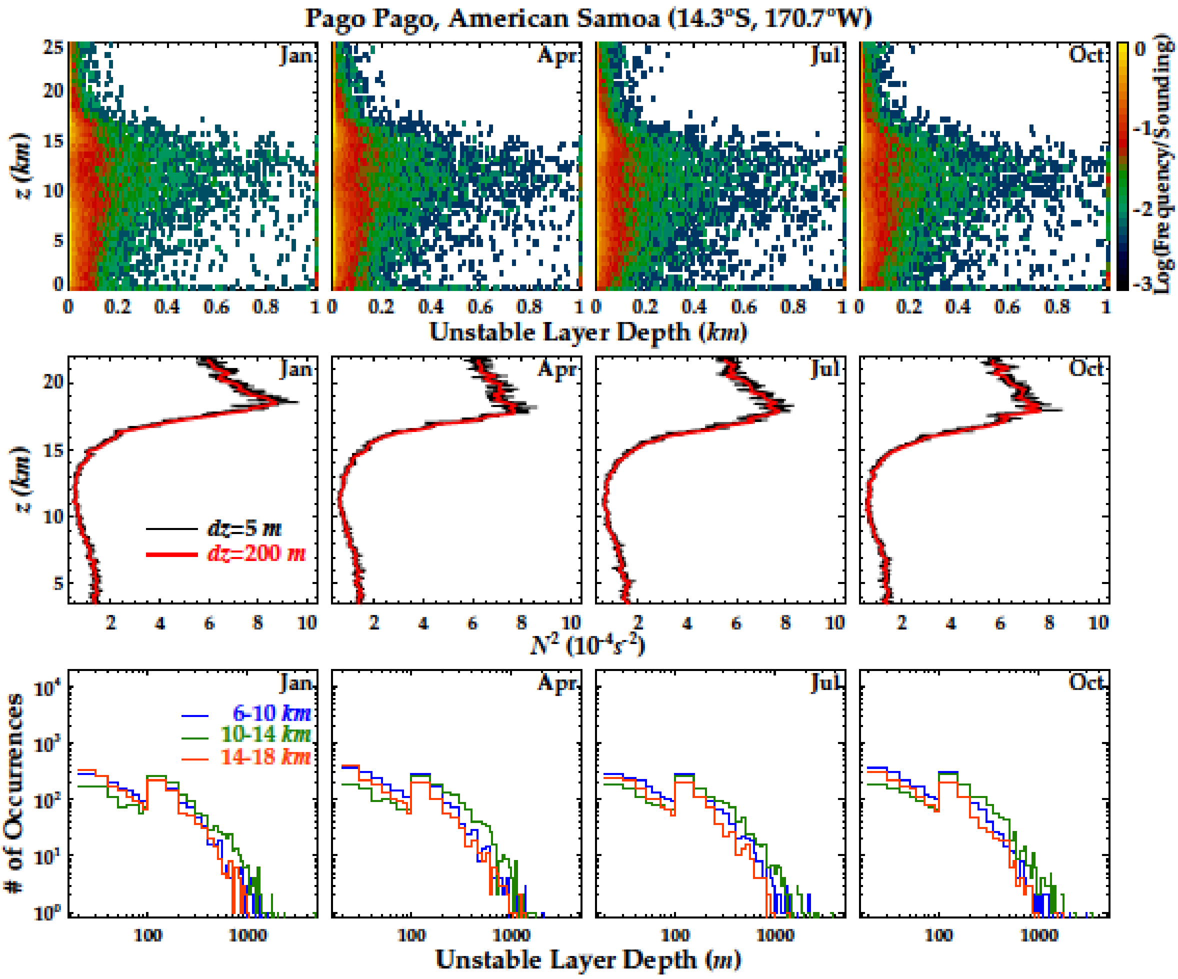

Figure 2. Same as figure 1, but for Pago Pago. The data used for Pago Pago in Started in February of 2011 and ended in August of 2019.

Results for Agana are shown in figure 3. At Agana, we see a more prominent “notch” feature in than at Pago Pago even though Agana is only 0.8 ^{0} closer to the Equator, but in the

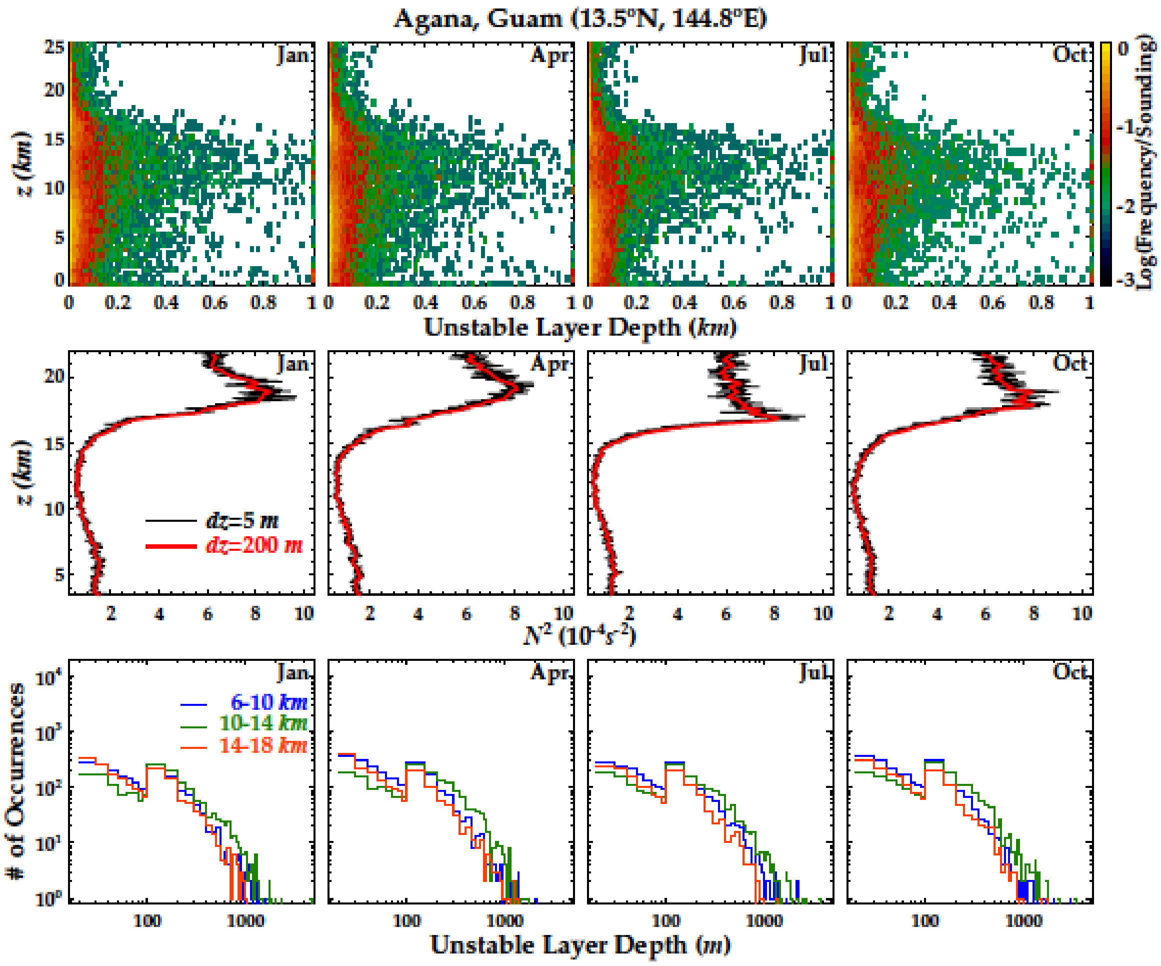

Figure 3: Same as figures 1 and 2, but at Agana. The data used for Agana began in April of 2011 and ended in August of 2019.

Northern Hemisphere. This is consistent with the Northern Hemisphere bias in the latitudes of minimum stability, which was noted earlier in this section.[1] We also see deeper stability minima at Agana than at Pago Pago, particularly in July and October. In addition, the

[1] Note that there is a much larger Northern Hemisphere bias in the annual migration of the ICTZ (Inter-Tropical Convergence Zone) than in the annual migration of the stratospheric stability minimum.

histograms at Agana show greater excesses in thick unstable layers than were seen at Pago Pago.

Next, we look at the results at San Juan in figure 4. This is the highest latitude station at which the “notch” feature is examined in this paper. At San Juan, we do not see a clear “notch,” where there is a marked deficiency in thin unstable layers such as was seen at the lower latitude stations, but we do see a clear excess of thick unstable layers that is centered at altitudes near 12 km, and most peaked, in October. Looking at the stability profiles, this “notch” picture seems quite consistent with the stability where the stability minimum in October is highest and

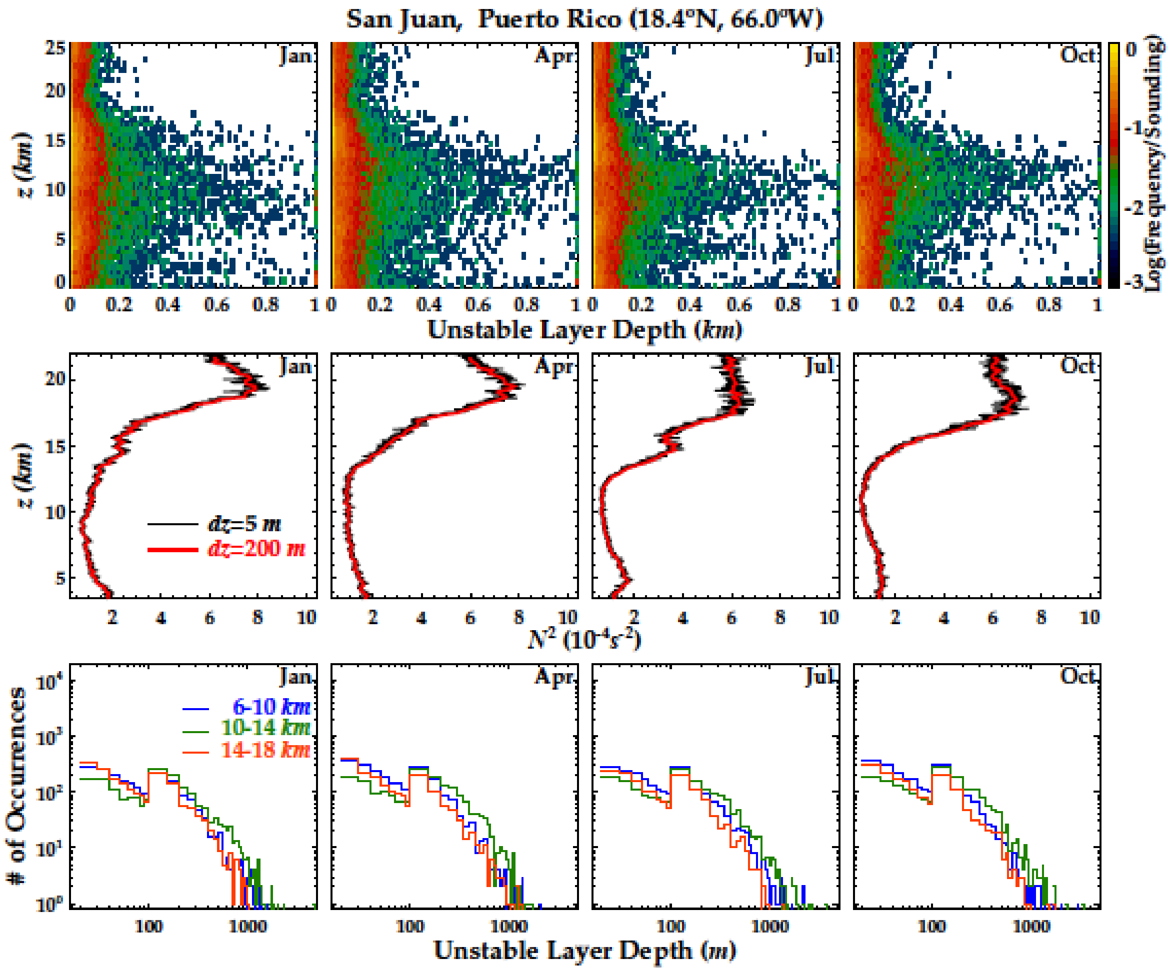

Figure 4. Same as figures 1, 2, and 3, but for San Juan, Puerto Rico. The data used for San Juan started in March of 2010 and ended in August of 2019.

deepest. The stability minima are most marked in July and October. In January, the minimum stability is at much lower altitudes, centered at about 9 km, and is not as deep as in July and October. In April, again the stability minimum is not as deep as in July and October and is broader in altitude. This is consistent with San Juan being outside the stability minimum latitude range during January and April. The histograms show excesses in thick unstable layers in all four months, but these excesses are not as marked as in the deep tropics. This picture is broadly consistent with figure 4 of Grise et al. (2010).

4. Summary and Conclusions

In a previous paper, Geller et al. (2021) identified a "notch" feature at Koror (7.3 ^{0}N, 134.5 ^{0}E), where this "notch" feature was characterized by a relative deficiency in thin atmospheric layers at altitudes centered at about 12 km, and a relative excess of thick atmospheric unstable layers at those altitudes. We also hypothesized that this "notch" feature was associated with the stability minimum in the tropics that was identified by Grise et al. (2010). This paper further investigates these topics by analyzing the unstable layer distribution

at four additional stations in the deep tropics, within 10 ^{0} of the Equator, where US HVRRD are available. Those stations vary in their longitude from about 171 to 138 ^{0}E. We found "notch" features very similar to what we found at Koror at all those stations.

To test our hypothesis that this "notch" feature is associated with the stability minimum in the tropics that was identified by Grise et al. (2010), we analyzed the US HVRRD at stations that were located slightly poleward of the deep tropics: Agana, Guam at 13.5 ^{0}N and Pago Pago, American Samoa at 14.3 ^{0}N. We also examined one US HVRRD station located further poleward, San Juan, Puerto Rico at 18.4 ^{0}N. We then examined whether the seasonal variations of this "notch" feature were consistent with the migration of the stability minimum, identified by Grise et al. (2010), annually into the summer hemisphere. We found that the annual variation of the "notch" feature at those stations was broadly consistent with the annual migration of the stability minimum feature. To identify the annual migration of the stability minimum, we examined the stability profiles at those stations for the same months when the "notch" was examined. We also looked at the histograms for the thicknesses of atmospheric unstable layers. The annual variations of those histograms were consistent with the overall picture of the "notch" region and with the stability minimum in the tropics and its annual migration in latitude.

Grise et al. (2010) indicated that the deep tropical stability minimum region centered at about 12 km altitude had been noted in previous papers by Gettelman and Forster (2002) and Fueglistaler et al. (2009), and that those previous authors associated this stability minimum with convective cloud outflow. This study suggests that the “notch” feature might be the signature of large eddies associated with turbulence at convective cloud tops being advected throughout the tropics at altitudes around 12 km, resulting in the advection of low stability air and the mixing of small unstable regions, resulting in less thin layers and more thick unstable layers at those altitudes. There is another important factor accounting for the depletion of thin unstable layers in the “notch” region, and that is the elimination of many of the thin layers through the use of the Wilson et al. (2010) and Wilson et al. (2011) methodology. In this methodology, small overturns are rejected as likely being a result of “noise” in the sounding. The identification procedure uses the tnr (trend-to-noise ratio) as a criterion, and in the region of the stability minimum the tnr is smallest, so there is greatest rejection of thin overturns.

We do not know how many of the soundings analyzed in this paper were taken in convective cloud regions and how many were in cloud-free regions. In principle, we can use the humidity measurements from the soundings to see if a sounding traveled through a cloud region, but humidity measurements in the upper troposphere at altitudes near 12 km are unreliable. Satellite measurements could be used to look if the various soundings traveled through clouds, but that is beyond the scope of this paper. Of course, one expects turbulence inside clouds, but the fact that the excess in thick unstable layers is confined to altitudes around 12 km suggests that we are “seeing” unstable layers associated with the advection of turbulent eddies from cloud-top turbulence.

It should be noted that 12 km corresponds to an altitude of 39,370 feet, which is not an uncommon altitude for aircraft flying long distance routes crossing the Equator. It would be interesting to see what, if any, effect this change in unstable layer thicknesses in the “notch” region might have on aviation turbulence.

Acknowledgments.

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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/.

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Supplementary Figures

The following are figures, in the same format as figures 1, 2, 3, and 4, for the additional stations in the deep tropics that we have analyzed: Ponape (7.0 ^{0}N, 158.2 ^{0}E), Majuro (7.1 ^{0}N, 171.3 ^{0}E), Chuuk (7.5 ^{0}N, 151.8 ^{0}E), and Yap (9.5 ^{0}N, 138.0 ^{0}E). Note that the nature of the "notch" in unstable layers seen at altitudes centered at about 12 km, the stability profiles, and the histograms look very similar to what is seen in figure 1 at Koror (7.3 ^{0}N, 134.5 ^{0}E).

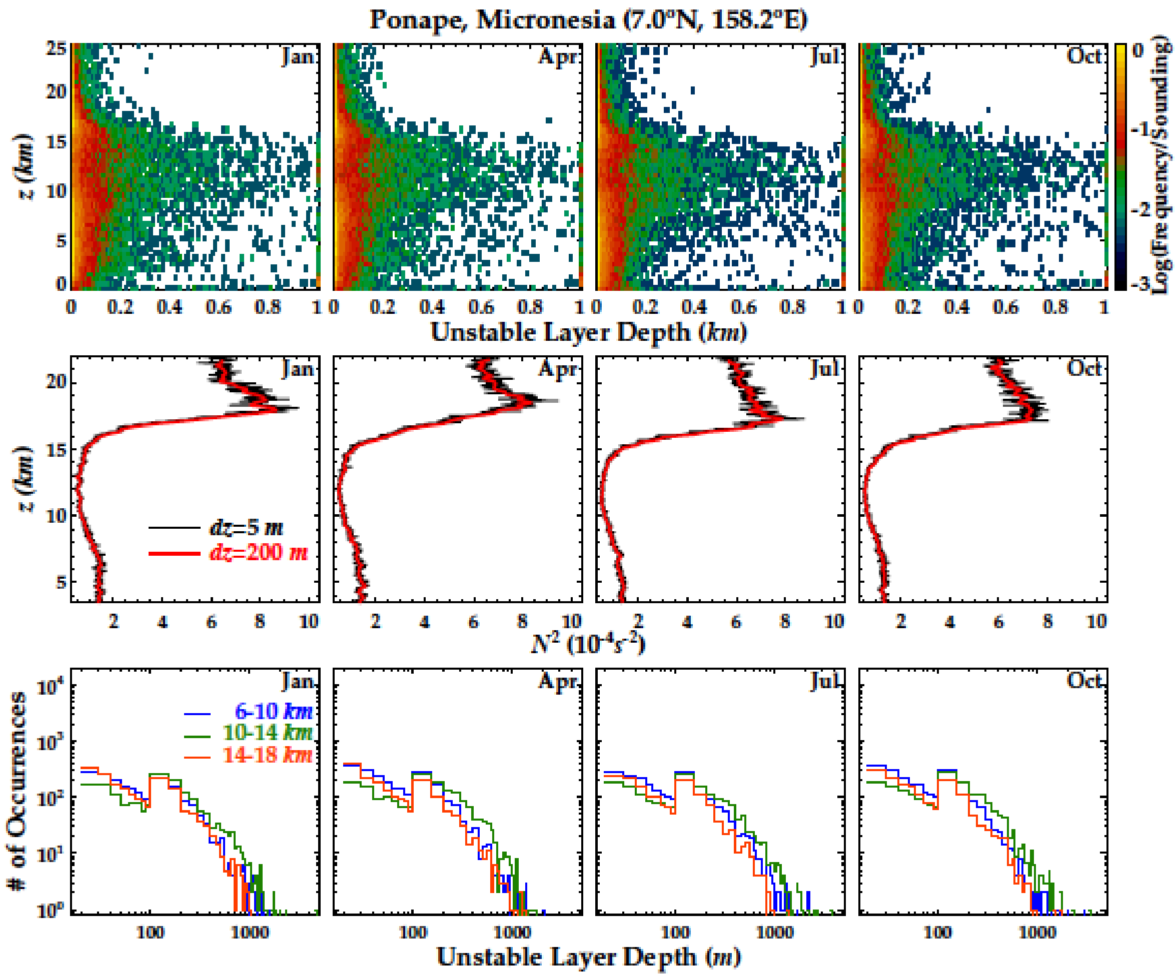

Figure S1. Top – Distribution of the thicknesses of unstable layers at Ponape in January, April, July, and October calculated from processed HVRRD at 1200 UTC. Middle – Monthly mean N^2 profiles for Ponape for January, April, July, and October. Black curves are results using the native 5 m data, and the red curves show the results using 300 m smoothed data. Bottom – Histograms for the thicknesses of unstable regions for the altitude regions 6-10 km, 10-14 km (the "notch" region, and 14-18 km. The data used for Ponape began in May of 2011 and ended in August of 2019.

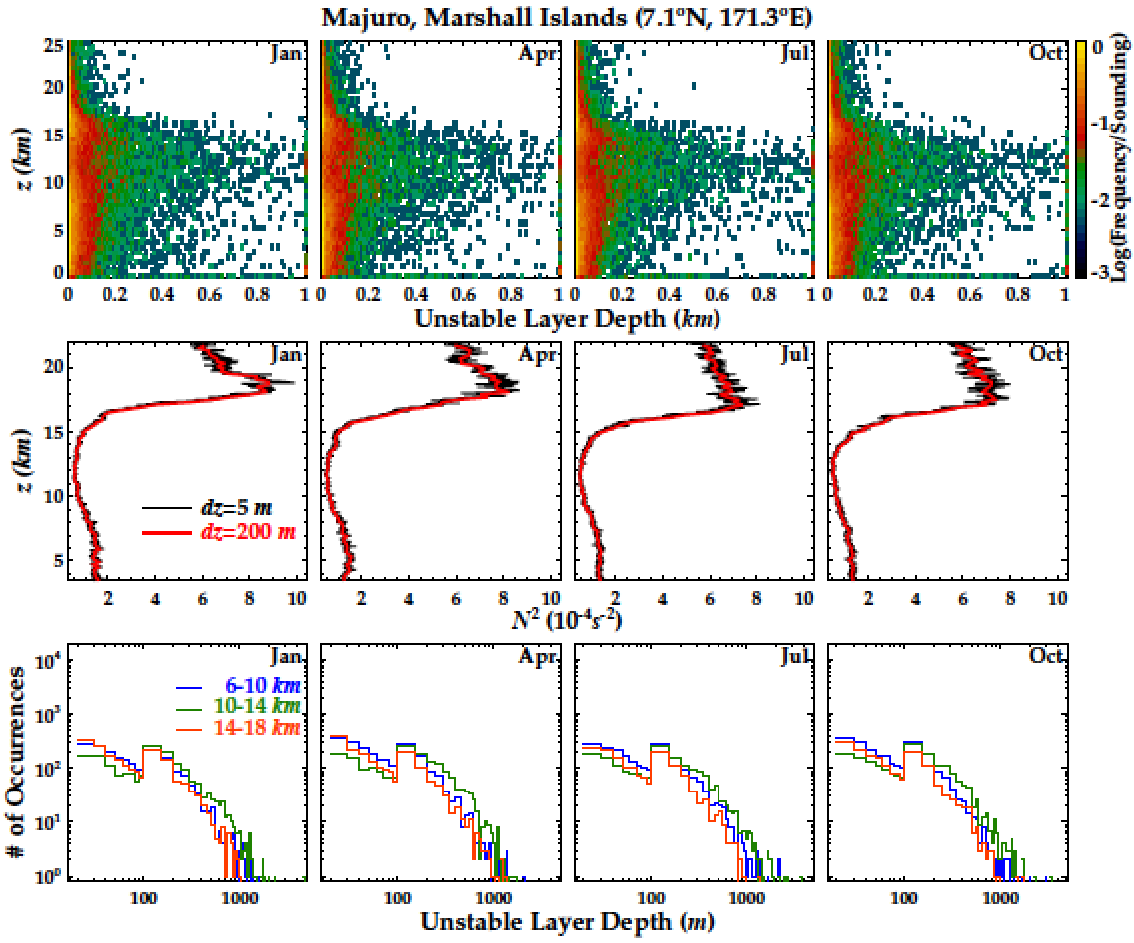

Figure S2. Same as figure S1, but for Majuro. The data used for Majuro began in May of 2011 and ended in August of 2019.

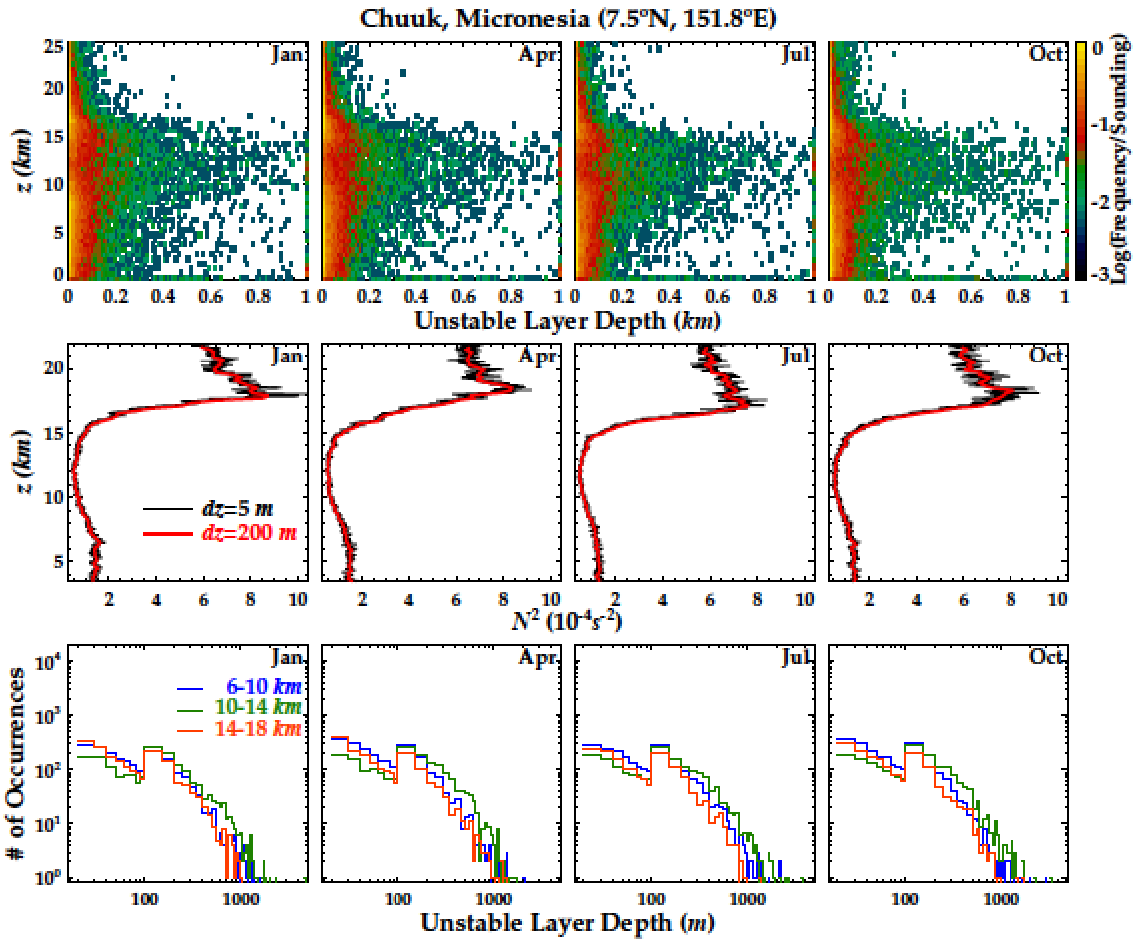

Figure S3. Same as figures S1 and S2, but for Chuuk. The data used for Chuuk began in May of 2011 and ended in August of 2019.

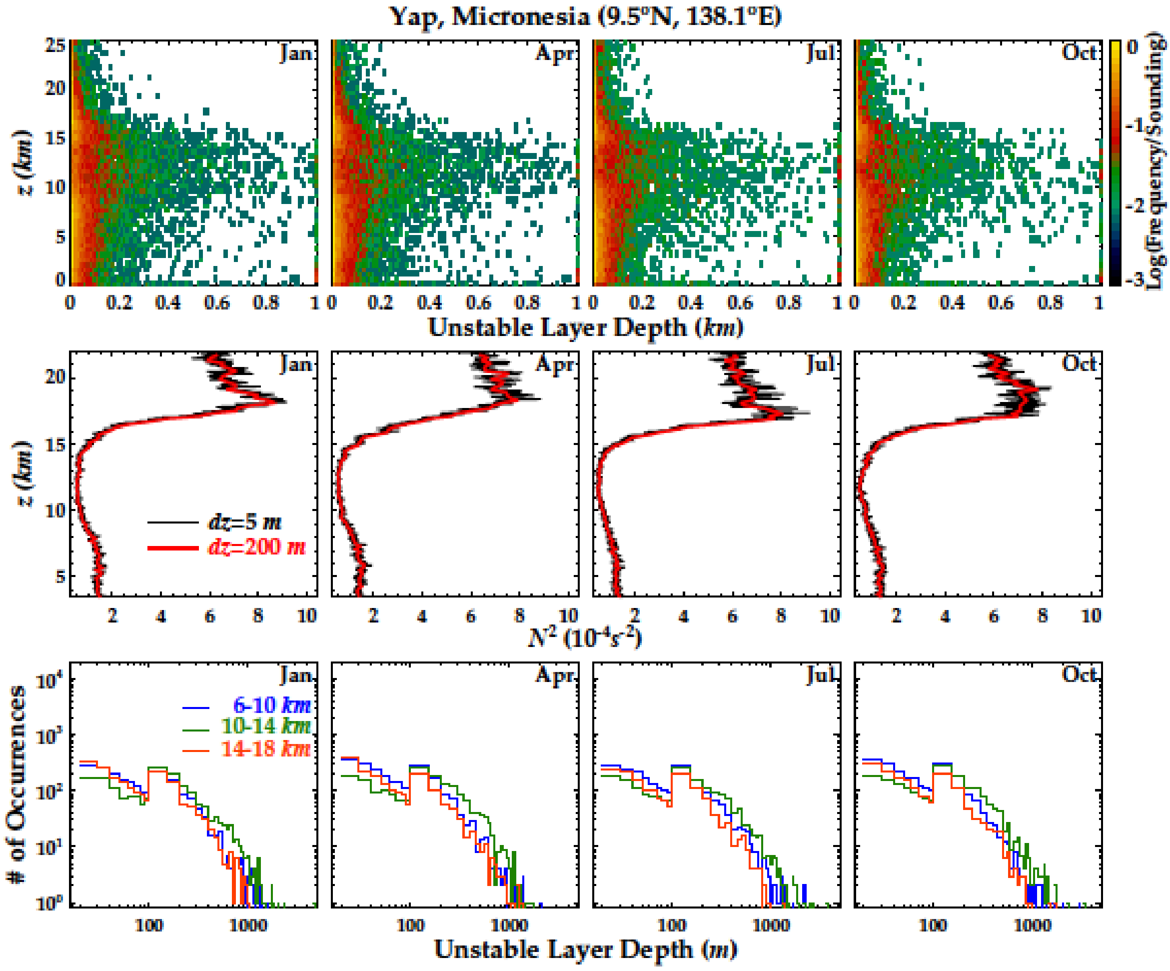

Figure S4. Same as figures S1, S2, and S3, but for Yap. The data used for Yap began in March of 2011 and ended in August of 2019.