P1.21A COMPARISON OF THE CLOUD TOP HEIGHT PRODUCT (CTOP) AND CLOUD-TOP HEIGHTS DERIVED FROM SATELLITE, RAWINSONDE, AND RADAR

Lacey Holland, Agnes Takacs, Barbara Brown, Eric Gilleland, Robert Hueftle, and Jamie Wolff
Research Applications Laboratory
National Center for Atmospheric Research
Boulder, CO 80307

1. INTRODUCTION

The Federal Aviation Administration Aviation Weather Research Program (FAA/AWRP) Oceanic Weather Product Development Team (OW PDT) produces a diagnosis of cloud-top heights (CTOP), which has recently received experimental status through the Aviation Weather Technology Transfer (AWTT) process. The product creates a rapidly-updated view of cloud-top heights. Of particular interest is the occurrence of deep convection related to turbulence, lightning, and icing. However, the CTOP product also indicates upper-level cirrus, anvil clouds, and lower clouds down to 15,000 ft, which may potentially pose a threat in the rare situation of a crippled aircraft.

In this study, the performance of CTOP during two periods, 12 February – 23 April and 15 August – 15 September 2004, is compared to other cloud-top height algorithms available globally, including the NESDIS Cloud-Top Pressure (NCTP) product, NWS radar echo tops (ET), and cloud-top heights estimated from rawinsondes (RCTH). Although each of these data sources infer cloud-top heights, a comparison of the various approaches is useful to evaluate the consistency of the CTOP.

2. DATASETS

This section describes the datasets used to assess the CTOP. The techniques used to infer cloud-top heights from satellite, radar, and rawinsonde observations are described.

In this study, the CTOP was evaluated over data-rich areas such as islands and coastal regions for point locations. This allows for the intercomparison of a variety of datasets for limited locations. The goal of this study is to assess how a variety of inferred cloud-top heights compare with the CTOP Takacs et al (2004a) contains a detailed description of available datasets.

Corresponding author address: Lacey Holland, NCAR/RAL, P.O. Box 3000, Boulder, CO 80307; email: lholland@ucar.edu

2.1 CTOP Diagnostic Product

CTOP uses longwave IR data from the GOES 9, 10, and 12 imagers to diagnose cloud-top heights by combining brightness temperatures across the ~11.0 micron window channel (the IR Window technique). Global Forecast System (GFS) soundings are used to convert the satellite brightness temperatures to altitudes. CTOP is available over three oceanic domains (Gulf of Mexico, Pacific, and North Pacific) as well as a CONUS domain made available only for this evaluation. Issuance times for the product differ for each of the domains due to the varying availability of GOES imager data: CTOP is updated every 30 min for the Gulf of Mexico; 20 min for the Pacific; 3 h for the North Pacific; and every 15 min for the CONUS domain. The nominal resolution for CTOP is 4 km.

2.2 NCTP Product

The NCTP product is based on the GOES sounder. The cloud parameters generated by the NCTP are described more thoroughly in Schreiner et al. (2001). To summarize the algorithm, in cases where the difference between clear and cloud radiances at each field of view is twice that of the instrument noise level, a CO_2-slicing method is used. When this difference is less than twice the instrument noise level (as for very thin, high clouds or low, opaque clouds), the algorithm adopts the IR Window technique, which assumes the cloud to be opaque. In these cases, the NCTP and CTOP use the same technique. These cases are designated by an Effective Cloud Amount (ECA) of 100% and are excluded from the comparisons. Preliminary validation studies have found CO_2-slicing heights to be within 50 hPa RMS of other instruments for most clouds. Madine et al. (2006) describes a detailed grid-to-grid comparison of CTOP and the NCTP.

2.3 RCTP Product

Rawinsonde-derived cloud-top heights were calculated for this comparison. Unlike CTOP, NCTP or ET, this measurement is not gridded weather elements but provides single point

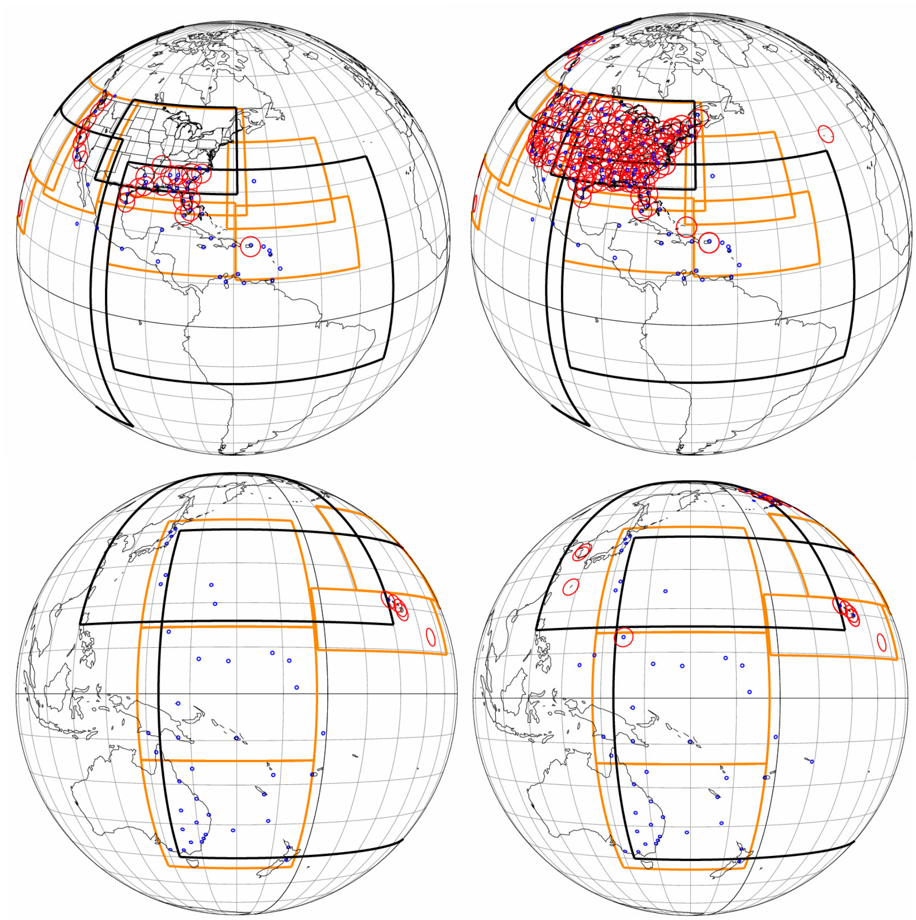

Figure 1. Overlap of CTOP (black), RCTP (blue), ET (red), and NCTP (orange) datasets over the globe. Left hemisphere 12 February-23 April 2004; right hemisphere 15 August-15 September 2004.

values over particular locations. The Wang and Rossow (1995) technique derives cloud-top heights from reported in rawinsondes. The cloud top is set to the lowest pressure where the relative humidity with respect to water (RH_w) or ice (RH_i) either (a) exceeds 87% or (b) exceeds 84% while the level above had RH_w or RH_i that was at least 3% lower than the RH_w or RH_i of the layer in question. In some cases, the technique can overestimate cloud-top pressures. This overestimation occurs most frequently in regions where cloud tops are colder than -40°C, as may occur in deep convective environments. The standard atmosphere was then used to calculate the height of the observation.

Additionally, rawinsonde drift was calculated. An assumed 5.5 m/s ascension rate for the rawinsonde was used for horizontal drift calculations.

2.4 ET Product

The National Weather Service (NWS) radar echo top product (ET) was used in this study. The product, further described in Brown et al. (2000), is based on measurements from WSR-88D radars. It has a 4 km spatial and 6 min temporal resolution. Its range is 230 km and vertical resolution, 5,000 ft. The lowest detectable tops are at 5,000 ft, while the highest are at 70,000 ft. The vertical accuracy of the echo top heights decreases with range due to beam broadening. The highest top at 1 km resolution reflectivity is mapped to a 4x4 km box.

2.5 Other Datasets

Other datasets commonly used for evaluating cloud-top heights such as PIREPs and AIREPs were also considered for use in this evaluation. However, because of the paucity of AIREPs and PIREPs reporting cloud tops during the evaluation period they were excluded from this study. The use of surface observations and observer estimates of cloud heights were also considered, and may be more appropriate in future studies of products under development by the OW PDT.

3. METHODOLOGY

This section describes the methods used to match and intercompare the CTOP to inferred cloud-top heights. The CTOP, NCTP, ET, and RCTP were intercompared over CTOP domains - the Gulf of Mexico (GOMEX), Pacific (PAC), and North Pacific (NPAC) domains, and over the continental U.S. domain (CONUS), which was included only for comparison purposes. Figure 1 shows the overlap of datasets over each hemisphere. These methods are based on Takacs et al. (2004b).

3.1 Matching Methods

For this intercomparison, CTOP, NCTP, and ET heights are matched to RCTP observations. Initially, CTOP, NCTP, and ET grid points surrounding the RCTP height within 6, 12, and 24 km radii were considered. Table 1 shows the average number of gridpoints for each gridded product included within each radius around the reported RCTP height. Quantities such as the median value of these points were calculated, as was a "peak" value – the maximum cloud-top height found within each radius. The "best" value represents the cloud-top height closest in value to the RCTP. The "best" also represents the smallest deviation of the gridded products from the RCTP-inferred height. Both the "peak" and "best" are strongly functions of the resolution of the grid. In contrast, the median is relatively resistant to changes in radius size. Although the "peak" and "best" were examined and give additional information about the characteristics of each dataset, results using the median over a 6 km radius are the focus of this study.

	CTOP	**NCTP**	**ET**
6 km	7	1	7
12 km	28	2	28
24 km	112	9	112

Table 1. Average number of gridpoints contained within each radius.

3.2 Statistical Measures

For this intercomparison, robust statistics such as the Interquartile Range (IQR, the difference between the 25th and 75th quantiles) and median are applied to differences between the RCTP and other cloud-top height values are considered in most cases. In addition, the mean is computed for some comparisons. Actual (rather than absolute) differences are used for this analysis to provide indications of skewness and bias. Note that because the median is the midpoint of a distribution, a distribution is symmetric if the mean and median are equal. These differences are examined more closely in exploratory data analyses including histograms, scatterplots, height series, and spatial maps.

4. RESULTS

The results of the cloud-top height intercomparison are summarized in this section.

4.1 Overall Results from the Intercomparison

Since the CTOP product is aimed at diagnosing cloud-top heights at upper flight levels, the figures presented in this section show results for CTOP over 15,000 ft. Because of the height limitations of NCTP, clouds above 45,000 ft are excluded. These overall results include all regions and time periods and all cloud types.

A histogram of the differences between the cloud-top heights measured by the CTOP and the NCTP is shown in Fig. 2. For these figures, the abscissas are "binned" into 5,000 ft classes. The ordinate axis represents the number of values for each bin.

In Fig. 2, the results indicate that the NCTP usually reports higher heights than the CTOP when compared at station locations. However, the magnitudes of these differences are most commonly less than 5,000 ft.

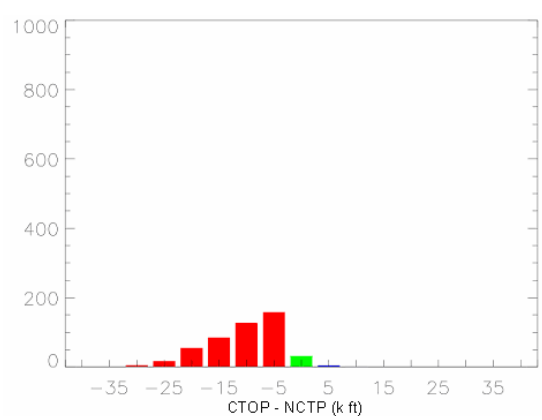

Figure 2. Histogram showing differences between CTOP and NCTP from 15,000 ft to 45,000 ft in 5,000 ft bins for the median CTOP height within a 6-km radius around the RCTP location. Red bars denote RCTP heights exceeding CTOP heights by more than 2,500 ft. Blue bars denote CTOP exceeding RCTP by more than 2,500 ft. The green bar indicates differences between -2,500 to 2,500 ft (ECAs of 100% are excluded).

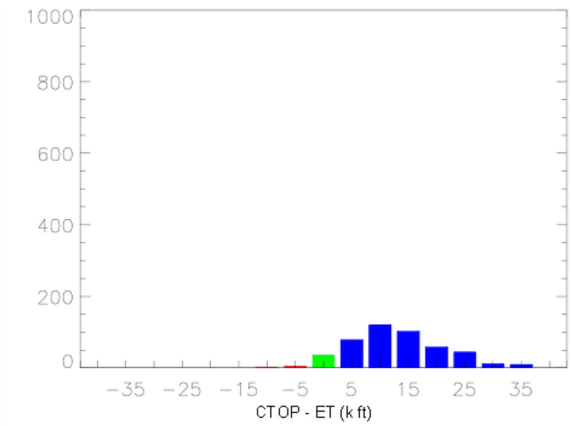

Figure 3. Same as Fig. 2, except for CTOP and ET.

Figure 3 shows differences between CTOP and ET heights. In most cases, the cloud-top heights diagnosed by the CTOP are typically higher by nearly 10,000-15,000 ft. In a very small number of cases, the ET reports heights exceeding those observed by the CTOP. These cases possibly occur because the ETs are not based on optimal elevation angle at some sites; in addition, topography may sometimes affect the radar observations (Brown et al. 2000). The results of this comparison are consistent with the well-known relationship between radar echo tops and cloud-top heights.

As shown in Fig. 4, for most cases the RCTP reports a lower height than the CTOP for clouds between 15,000 and 45,000 ft. Because the RCTP generally tends to underestimate cloud-top heights, the results show that the CTOP values are nearly consistent with the RCTP values, with errors that are typically $\pm$ 5,000 ft.

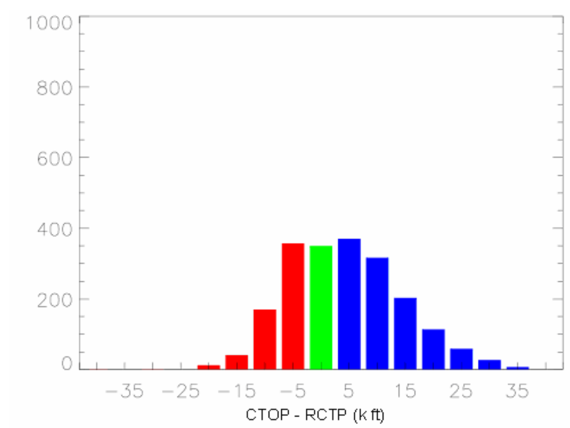

Figure 4. Same as Fig. 2, except for CTOP and RCTP.

However, in a number of cases, the CTOP is quite a bit higher than the RCTP, as shown by the blue bars. In fact, the shape of the histogram indicates that the distribution is somewhat skewed toward positive values and higher CTOP heights.

Figures 5-8 show differences between CTOP and RCTP as a function of CTOP height. At given heights between 15,000 to 45,000 ft, the number of CTOP/RCTP pairs, the median and mean difference between the derived cloud-top heights, and the 25th and 75th percentiles are shown.

Differences between the CTOP and NCTP for all cloud types decrease with height (Fig. 5). NCTP usually reports higher heights than the CTOP, particularly below 30,000 ft. The differences between CTOP and NCTP heights are largest below 20,000 ft where the NCTP may detect optically thin clouds at upper levels, but those clouds may be undetected by CTOP.

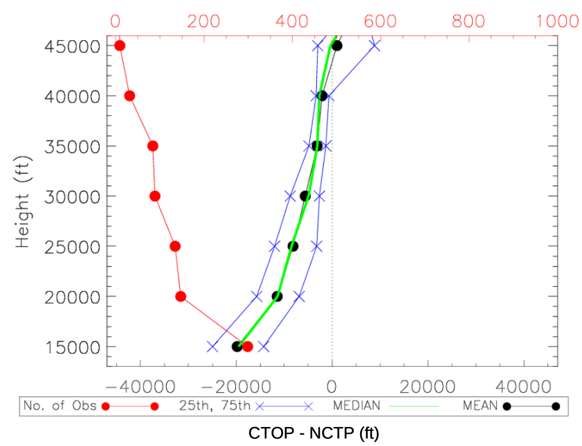

Figure 5. Differences between CTOP and NCTP heights stratified by CTOP height are shown in 5,000 ft intervals. Number of observations (red; circle, see upper scale), mean difference (black; circles to the right of zero), median difference (green; solid line), and 25th and 75th percentiles (blue;'x') are shown. The 15,000 ft interval includes all below it. (ECA = 100% excluded)

Figure 6 shows the comparison between the CTOP and ET derived cloud-top heights. Similarly to Fig. 3, differences in the cloud-top height values computed between the CTOP and ET increase from a difference of nearly 0 at 15,000 ft to a difference of nearly 20,000 ft at a height of 45,000 ft (Fig. 6). This result may be partially due to the decrease in sample size from 200 at 15,000 ft to nearly 0 at 45,000 ft. As expected, the CTOP is higher than the ET throughout all height ranges.

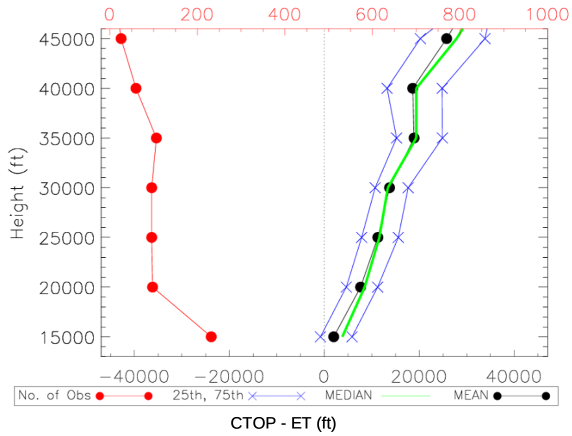

Figure 6. Same as Fig. 5, except for CTOP and ET.

Figure 7 shows that at levels below 25,000 ft and for all cloud types, the differences between the cloud-top heights produced by CTOP and RCTP are typically less than 5,000 ft. However, above 25,000 ft, these differences steadily increase. At CTOP heights of less than 40,000 ft, the differences between CTOP and RCTP remain less than 12,000 ft. However, at heights above 40,000 ft, the differences reach nearly 20,000 ft. However, the variability as represented by the width of the IQR (i.e., the difference between the 25^{th} and 75^{th} quantiles) is relatively constant with height.

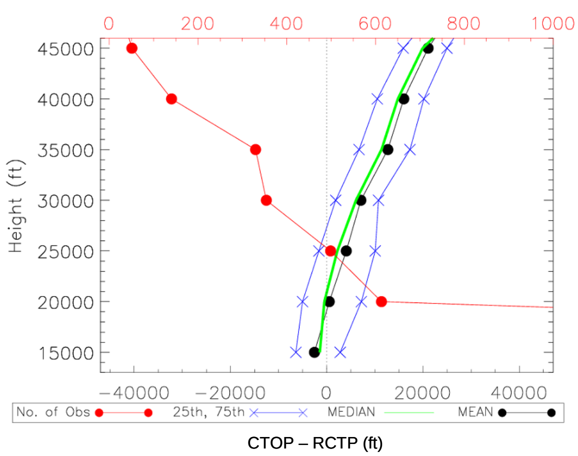

Figure 7. Same as Fig. 5, except for CTOP and RCTP.

The frequencies of cloud occurrence between CTOP and NCTP and ET for all cloud types were also compared. If a cloud was detected by the RCTP, then the existence or absence of cloud produced by the CTOP, NCTP, and ET was recorded. The results for CTOP vs. NCTP and CTOP vs. ET are presented in Tables 2 and 3, respectively.

	NCTP = 0	**NCTP ≠ 0**
CTOP = 0	2,081 (37.2%)	225 (4.0%)
CTOP ≠ 0	1,254 (22.4%)	2,037 (36.4%)

Table 2. Contingency table showing, where CTOP and NCTP detect (≠ 0) or miss (= 0) a cloud, if a cloud was detected by the RCTP. These results are based on the single closest point to the rawinsonde location.

Based on the information in Table 2, when RCTP detects a cloud, the CTOP was likely to diagnose a cloud 59% of the time, while the NCTP diagnosed a cloud 40% of the time. Also, 36% of the time the CTOP product detected a cloud when both the NCTP and RCTP also detected clouds. However, 37% of the time no clouds were diagnosed by the NCTP or CTOP when clouds were detected by the RCTP product.

The cloud vs. no-cloud results for ET and CTOP are summarized in Table 3. The results in Table 3 indicate that when RCTP detects a cloud, the CTOP detects almost twice as many clouds as the ET. However, the CTOP misses clouds detected by ET 21% of the time.

	ET = 0	**ET ≠ 0**
CTOP = 0	1,735 (30.0%)	265 (4.6%)
CTOP ≠ 0	2,782 (48.1%)	1,003 (17.3%)

Table 3. Same as Table 2, except for ET and CTOP.

4.2 Regional Results

This section presents comparisons of CTOP and the other measures of cloud-top height for the CTOP regions. Comparisons of the cloud-top measures over each CTOP domain are shown in scatterplots in Figs. 7 and 8.

The RCTP and CTOP are compared in Fig. 7. Each diagram shows a general cluster of points, especially at heights less than 20,000 ft, around the 1:1 line. For the Pacific, the February-April period shows more scatter than the August-September period. Noting that the Pacific region contains significantly more data in the Southern Hemisphere, this result suggests that this region displays more variability during its convective season. The plots also indicate that there is little systematic difference between the RCTP and CTOP.

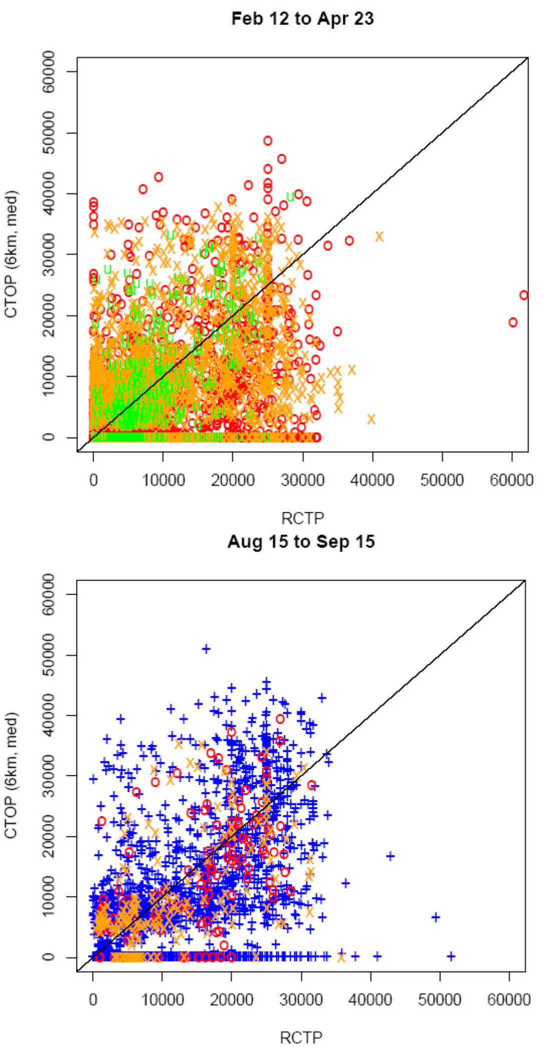

Figure 8. Scatterplot comparison of CTOP and RCTP for 12 February–23 April (top) and 15 August – 15 September (bottom) is shown. Different regions are shown using different symbols and colors; Pacific, 'o'; CONUS, '+'; Gulf of Mexico, 'x'; and North Pacific, 'u'.

When comparing the CTOP and ET (not shown), the CTOP is consistently higher than the ET, showing more consistent differences over the Gulf of Mexico and less over the CONUS.

In Fig. 8, ECA values of less than 100% appear as scattered points between binned values of NCTP (since the NCTP values based on the CO_2-slicing method are binned; those based on the IR window technique are not). Symbols are as in Fig. 7.

In comparing the NCTP and CTOP (Fig. 8), in cases where the NCTP and CTOP detected clouds, the NCTP usually reported a higher height. The two products were most closely matched over the CONUS. There is less of a relationship between CTOP and NCTP over the Pacific. The 12 February–23 April period also shows less of a relationship between NCTP and CTOP than the 15 August–15 September period. The differences also appear more systematic, with very few instances where CTOP heights are lower than NCTP heights.

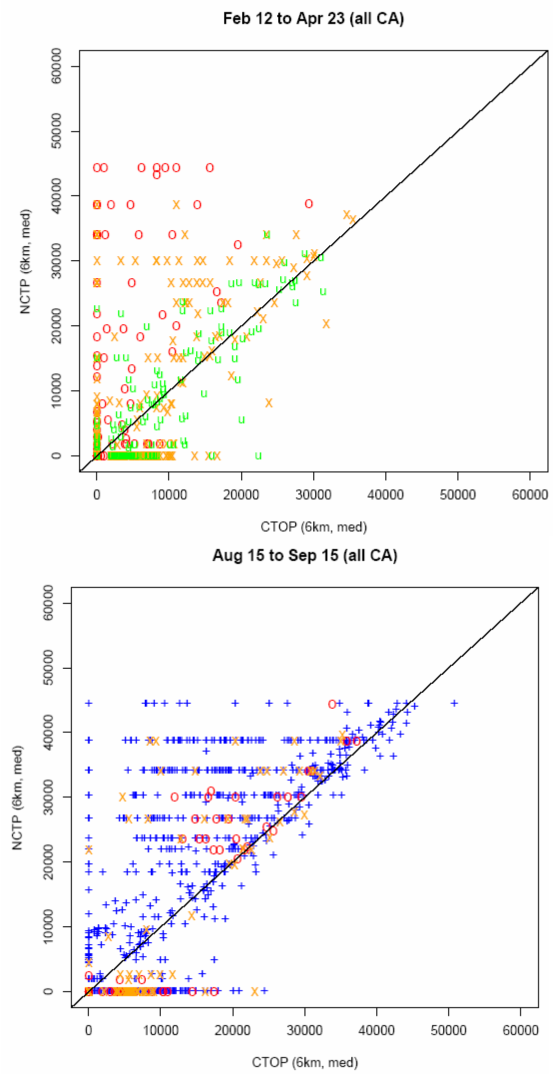

Figure 9. As in Fig. 8, for CTOP and NCTP. ECAs of 100% are included. Points with ECA values of less than 100% appear as scattered points between binned values of NCTP (since the NCTP values based on the CO_2-slicing method are binned; those based on the IR window technique are not).

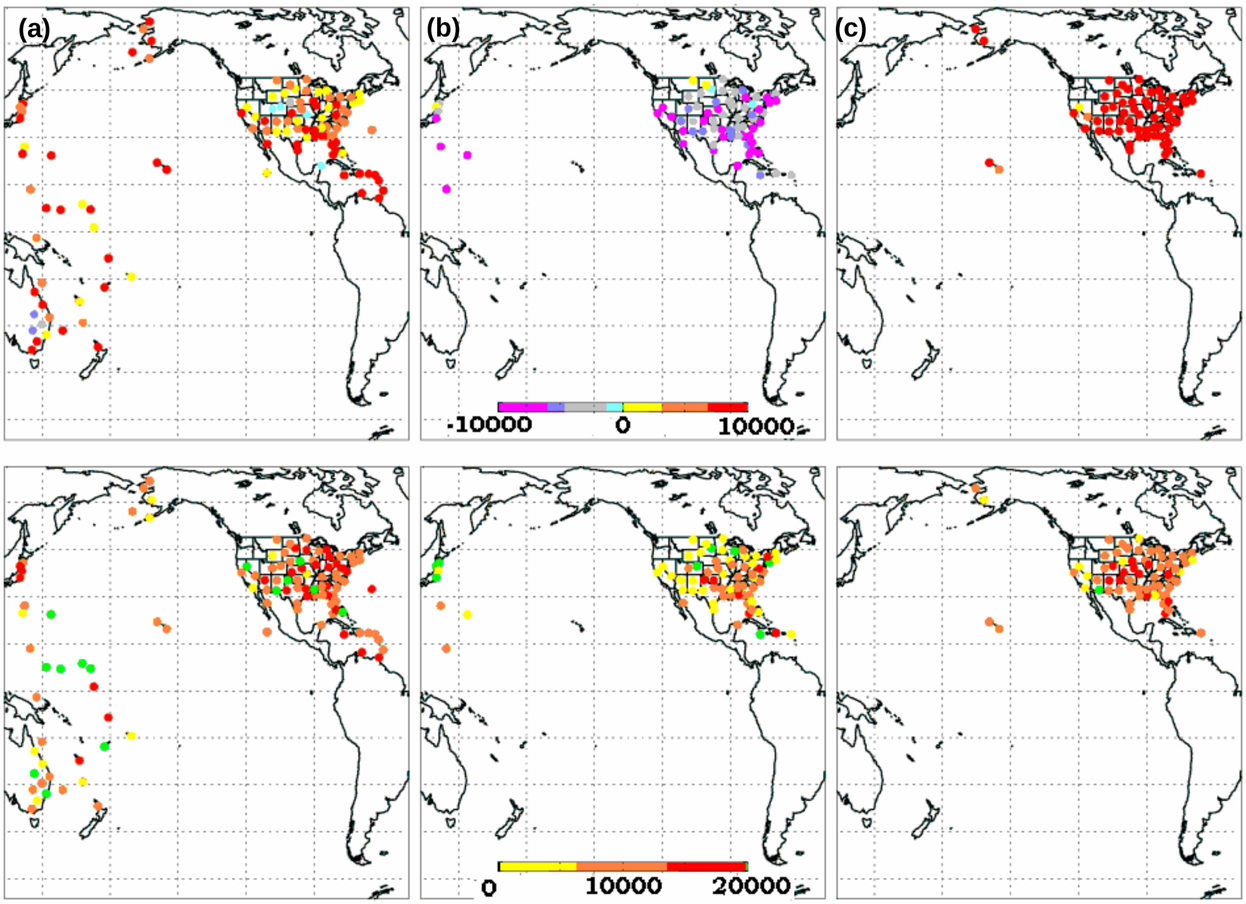

Figure 10. Maps showing median differences for comparisons with CTOP over 15,000 for (a) CTOP vs. RCTP, (b) CTOP vs. NCTP, and (c) CTOP vs. ET (top row). Green denotes areas where the median differences are near zero. Maps showing IQR for same differences (bottom row). Green in bottom row denotes areas where the IQR exceeds 20,000 ft.

4.3 Spatial Results

Figure 10 shows a map of the medians of differences between CTOP and RCTP, and NCTP, and ET for CTOP heights greater than 15,000 ft. Variability is shown through the IQR in the second row of maps. In comparing RCTP and CTOP, CTOP is usually higher than RCTP, especially over the Gulf of Mexico, which suggests that RCTP underestimates cloud-top heights in areas of deep convection. Additionally, in areas with high low-level humidity, such as the Gulf of Mexico, a cloud may also be detected by RCTP, though none may be found (Wang and Rossow 1995). The relatively large IQR values in the Gulf of Mexico region indicate relatively large variability and may result from these factors.

This map shows that over most areas the RCTP heights are lower than the CTOP, especially over the Gulf of Mexico and similar low-latitude regions. Also, particularly over CONUS, the NCTP is usually higher than the CTOP. This difference is likely due to the detection of high, thin clouds by NCTP. The differences are more variable over the Great Plains, Gulf of Mexico and surrounding areas, but less so over the southwestern U.S. The differences between CTOP and ET show that for nearly all stations, the CTOP height exceeds that of the ET. However, some arid mountainous regions or regions with climatologically lower relative humidity show smaller differences between the two.

4.4 Results by NCTP Effective Cloud Amount

The results in this section include only NCTP pixels with ECA values between 90 and 99% which are derived from the CO_2-slicing technique. The results for all regions and seasons combined for the NCTP and CTOP comparison are shown in Fig.11.

Most frequently, the CTOP and NCTP are within 5,000 ft of each other. This result is most likely because the high, thin clouds diagnosed by NCTP and undiagnosed by CTOP were removed from the dataset.

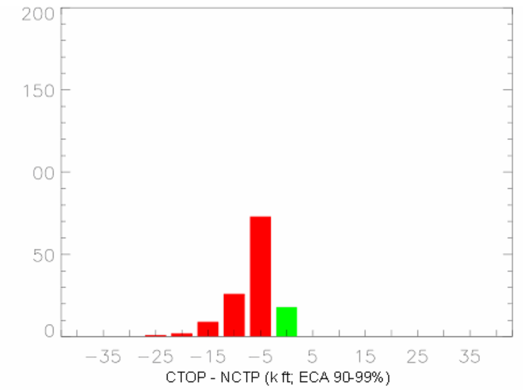

Figure 11. Histogram showing differences between CTOP and NCTP above 15,000 ft in 5,000 ft bins for the median CTOP height within a 6-km radius of the RCTP with ECA values between 90 and 99%.

Examination of the differences between CTOP and RCTP when ECAs are 90-99%, as shown in Fig. 12, indicates there are fewer instances where the RCTP exceeds the CTOP. More commonly, the CTOP exceeds the RCTP by 5,000 ft.

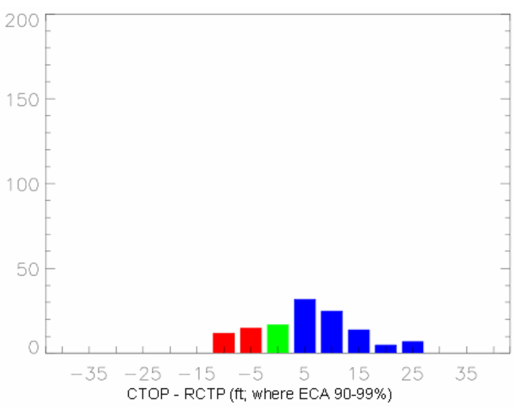

Figure 12. As in Fig. 11, except for CTOP and RCTP.

When focusing on ECAs of 90-99%, the differences between CTOP and ET (Fig. 13) change little from the case when all ECAs (excluding 100%) are included (Fig. 4). In this case, the sample size is greatly reduced.

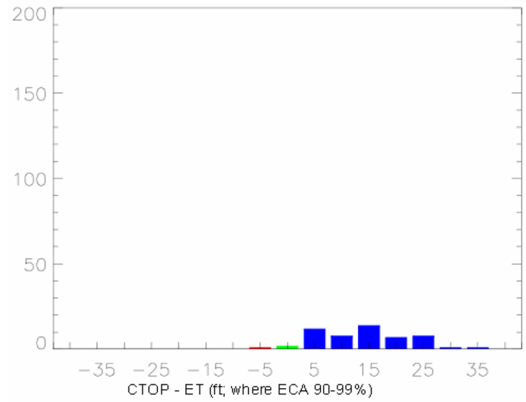

Figure 13. As in Fig.11, except for CTOP and ET.

Figure 13 shows differences between the CTOP and the NCTP for each 5,000-ft level between 15,000 and 45,000 ft. When ECAs less than 90% and equal to 100% are excluded, NCTP and CTOP show mean and median differences of less than 5,000 ft at levels above 25,000 ft. Differences at the lower levels (below 25,000 ft) decrease from those presented for all cloud types (Fig. 7). However, the sample size also decreases, which also may affect the results.

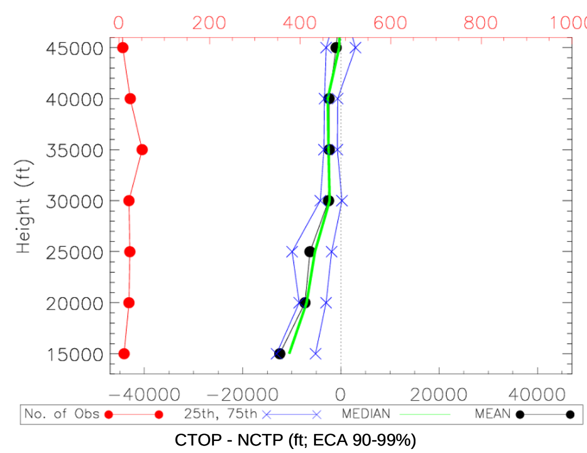

Figure 14. Differences between CTOP and NCTP heights, where the NCTP ECA is between 90-99%, stratified by CTOP height are shown in 5,000 ft intervals, valid below their plotted height. Number of matched pairs (red, see upper scale), mean difference (black), median difference (green), and 25th and 75th percentiles (blue) are shown. Each interval includes observations within 5,000 ft below it.

By limiting the analysis to ECAs between 90-99% (Fig. 15), the differences between RCTP and CTOP become more exaggerated below 15,000 ft than compared to those presented for all cloud types (Fig. 7). The differences between 20,000 ft and 30,000 ft decreased, while those above 30,000 ft change little. At low levels, the RCTP heights are higher than those diagnosed by CTOP, while at mid-levels, they become more similar.

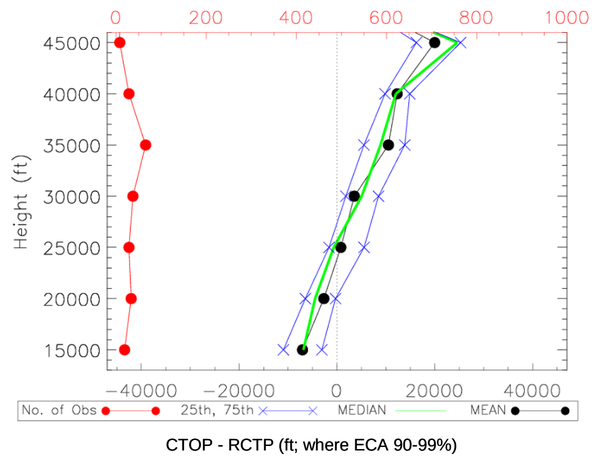

Figure 15. As in Fig. 18, except for CTOP and RCTP.

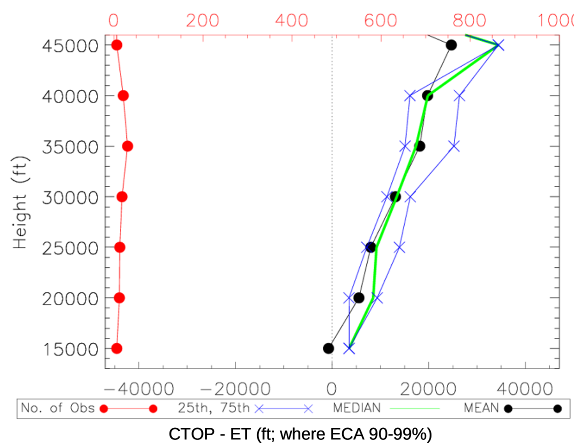

Figure 16. As in Fig. 13, except for CTOP and ET.

The results in Fig. 16 indicate that when the ECA values are restricted to 90-99%, the differences between ET and CTOP change little with height than compared to those presented for when all cloud types, although the sample size decreased greatly. (Note that below 15,000 ft, less than five observations meeting these criteria were included).

Figure 17 shows that the medians of the differences between CTOP and NCTP are smaller over the Gulf of Mexico as well as over CONUS when the gridpoints are restricted to those with ECAs between 90 and 99%. These differences are smaller than the differences computed for all cloud types. In addition, the IQR is smaller, than for all cloud types, indicating the differences are less variable. The median differences between NCTP and CTOP are reduced when ECAs of 90-99% are examined. The IQR is also smaller for RCTP and ET when examining values associated with the 90-99% range of ECA than when all cloud types are included, but the sign of the differences does not change. Overall, when we restrict the analysis to areas where the NCTP ECA is between 90-99% (most likely opaque clouds), the differences between the cloud-top height values produced by RCTP and CTOP change little, as do the differences between ET and CTOP, possibly suggesting that the ECA has little effect in these comparisons on the RCTP and ET. However, the cloud-top height differences between NCTP and CTOP are reduced when the comparison is restricted to opaque clouds

5. SUMMARY

To summarize, the results from the intercomparisons using the 6-km radius and median value of CTOP with RCTP, ET, and NCTP, several relationships were identified:

Overall results for all cloud types and heights from 15,000 to 45,000 ft combined:

- CTOP typically had higher heights than RCTP, with differences typically larger than 5,000 ft.
- CTOP heights were consistently higher than ET, which was expected.
- CTOP heights were typically lower than the NCTP heights with differences ranging between 5,000 and 10,000 ft.

Overall results for all cloud types stratified by height:

- RCTP and CTOP showed good agreement below 25,000 ft. Differences above 25,000 ft increased to nearly 20,000 ft.
- ET and CTOP differences were less than 5,000 ft at a height of 15,000 ft, but increased to nearly 20,000 ft at a height of 45,000 ft.

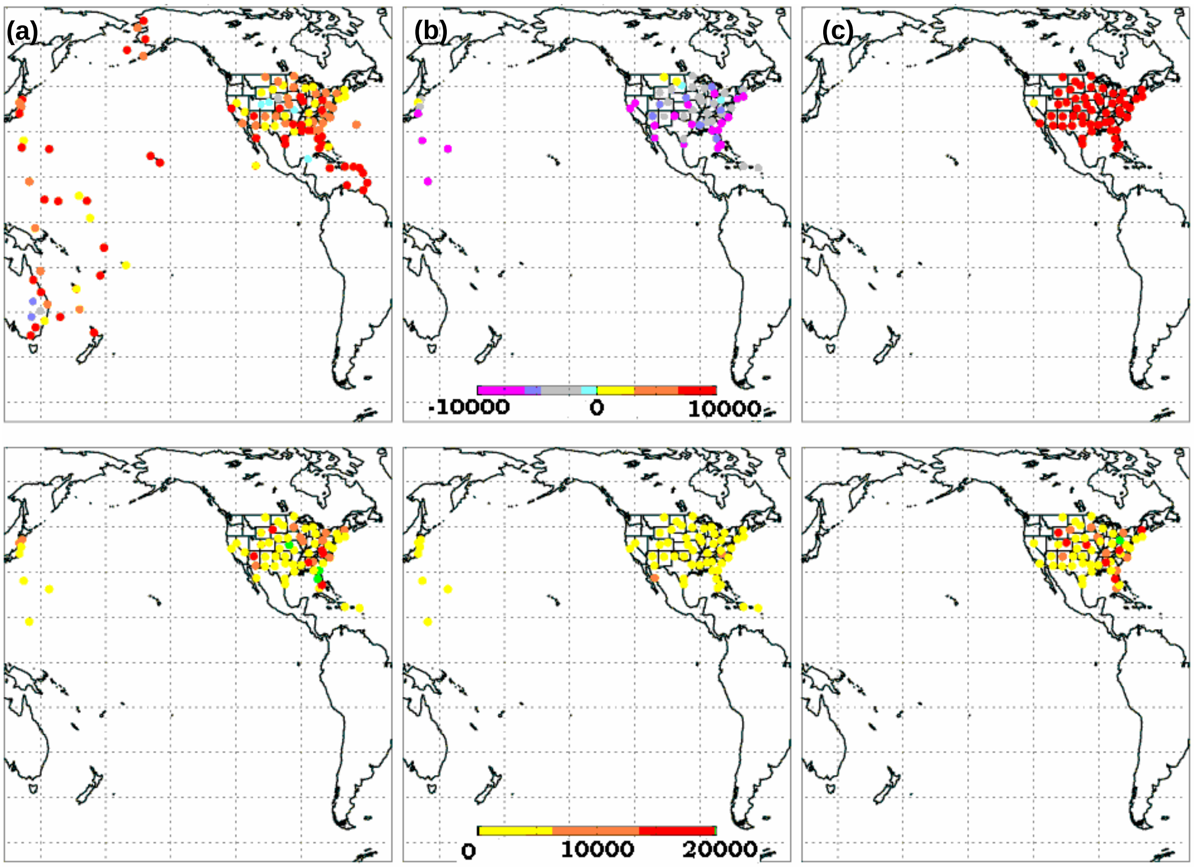

Figure 17. As in Fig.9, except for ECAs of 90-99%.

- NCTP and CTOP differences were typically 10,000 to 20,000 ft at heights below 30,000 ft. Above 30,000 ft, the differences decrease to less than 5,000 ft, which are within the instrument error.

Overall results for ECA values between 90-99% stratified by height:

- NCTP and CTOP differences decrease when compared to all cloud amounts
- RCTP and CTOP and ET and CTOP differences were similar to those when all cloud types were included.

Other results to consider:

- CTOP and RCTP are more likely to agree than disagree on the existence of clouds

6. CONCLUSIONS

This report has summarized results of a comparison of cloud-top heights produced by the OW PDT CTOP product and derived cloud-top heights from other measuring instruments to determine the relative quality of the CTOP product. The study used a point-to-point intercomparison approach to determine relative differences between four cloud-top height techniques. The investigation included the periods 12 February-23 April and 15 August-15 September, 2004. The results of the study indicate that CTOP appears to have approximately the same or improved capabilities compared to other methods for determining cloud-top heights over the oceans that were considered in this study.

In particular, the intercomparison revealed that when all cloud types are considered from 15,000-45,000 ft the CTOP heights are typically higher than the radar-derived and echo top height products, but typically the differences were within the instrument error.

7. ACKNOWLEDGMENTS

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