COMPARING THE FAA CLOUD TOP HEIGHT PRODUCT AND THE NESDIS/CIMSS CLOUD TOP PRESSURE PRODUCT IN OCEANIC REGIONS

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1. INTRODUCTION

As part of an effort to assess the quality of the Cloud Top Height (CTOP) product recently developed by the Oceanic Weather Product Development Team (OWPDT) of the Federal Aviation Administration Aviation Weather Research Program (FAA/AWRP), a comparison of CTOP and the NESDIS/CIMSS Cloud Top Pressure (NCTP) product was performed. This study summarizes the comparison of CTOP and NCTP during two periods, 12 February–23 April and 15 August–15 September 2004, for the Pacific, North Pacific, and Gulf of Mexico oceanic domains, as defined by the OWPDT.

The CTOP product, according to the concept of use, employs the IR Window technique to provide a depiction of the current locations of aviation hazards related to convection in remote oceanic regions. NCTP, in contrast, utilizes a hybrid algorithm including both the IR Window as well as the CO_2-slicing approach to determine the heights of clouds with a wide range of transparency. The analysis accounts for these underlying differences by stratifying the results by the transparency of the clouds. In an attempt to delineate the different cloud regimes (i.e., hazardous versus non-hazardous), the comparison utilizes a threshold of the NESDIS/CIMSS effective cloud amount (ECA) as a proxy for the presence of convection.

In addition to the detailed comparison statistics, this paper presents the results of an analysis to justify the overall comparison mechanics, which were designed to account for the temporal and spatial differences between the products. The findings of the satellite product comparison demonstrate very good agreement, with respect to values established by other cloud top height validation studies, between CTOP and NCTP for opaque and thick clouds, particularly at upper levels. The statistics for the thin cloud comparison show significant disagreement, an expected result given the theoretical strengths and weaknesses of the products.

2. TECHNIQUES FOR MEASURING CLOUD-TOP HEIGHT

2.1 *CTOP Diagnostic Product*

The OWPDT utilizes the IR Window technique to create the CTOP product covering three oceanic domains, and for this evaluation only, the CONUS domain (see http://www.rap.ucar.edu/projects/owpdt/realtime_systems.html). This approach combines a brightness temperature, measured by the infrared window channel of the GOES Imager, with a temperature profile from the Global Forecast System (GFS) numerical weather prediction model to estimate the cloud height for a given pixel. An updated version of the procedure described to the OWPDT in a presentation created by Miller et al. (2002) follows:

- The geostationary IR data from GOES 9, 10,12 Imagers is ingested to create a “stitched” image over the domain of interest.
- The closest temporal match between the GOES Imager IR data and the GFS analysis over the same domain is determined.
- The intersection between each IR pixel in the domain of interest, and the GFS is determined by looping downward from the top of the atmosphere until intersection between the IR

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pixel and the GFS profile is achieved or the pressure level exceeds the 850 hPa cutoff.

- If an intersection is found, the GFS geopotential height value is interpolated to the pixel location and an estimate of cloud-top height is produced.
- An image representation of the cloud-top height is then produced.

The authors of the presentation also identified the following qualitative algorithmic cloud-top height detection strengths and weaknesses:

Strengths of the CTOP algorithm include the detection of

- Clouds over the oceans, because the IR technique performs best with a warm stable background
- Clouds that are optically thick
- Cloud regions that are characterized by a well-behaved lapse rate and well-defined tropopause

Weaknesses of the CTOP algorithm include the detection of

- Clouds over land, because of the highly variable temperature background
- Clouds that are optically thin
- Cloud regions that are characterized by a strong mid-level inversion

Due to the varying availability of the GOES Imager coverage over the globe, the issuance times and intervals for the CTOP product differ for each of the domains used in this evaluation. Through OWPDT processing, the product is updated every 20 min for the Pacific domain, every 30 min for the Gulf of Mexico domain, every 15 min for the CONUS domain, and roughly every 3 h for the North Pacific domain. The CTOP product has a nominal resolution of 4 km, the same as the GOES Imager IR window channel scan.

2.2 *NESDIS Cloud-Top Pressure (NCTP) and Effective Cloud Amount (ECA)*

This Section describes the characteristics of the NESDIS cloud products, which include the cloud top pressure (NCTP) and effective cloud amount (ECA) used for the grid-to-grid comparison with CTOP as well as the overall stratification of statistics.

The generation of the GOES Sounder-based derived cloud parameters, cloud top pressure and ECA is described by Schreiner et al. (2001). In this study, of the 77% of cloudy pixels examined, 55% were determined by the CO_2-slicing method and 45% by the IR window technique. The algorithm primarily relies on the CO_2-slicing technique, derived from radiative transfer principles, to determine cloud top pressure and ECA (Menzel et al. 1983; Wylie and Menzel 1989). In cases where the CO_2-slicing calculation fails due to the instrument noise (which typically occurs for very thin, high clouds or low, opaque clouds) the algorithm adopts the IR Window technique to determine the pixel cloud top pressure. A brightness temperature, measured by the GOES Sounder, provides the value for lookup in the GFS temperature profile. In these cases, the value for the effective cloud amount is set to 100%, a value never inferred by the CO_2-slicing technique.

Each pixel in the NCTP product has a nominal resolution of 10 km. When inferred by the CO_2-slicing approach, the assigned cloud-top height value, consists of the single pixel value while the assigned ECA consists of a 3x3 pixel averaged value. The maximum cloud top pressure value for the NCTP is either 150 hPa, which is roughly 45,000 ft in the standard atmosphere, or the tropopause, whichever height is lower in the atmosphere. The product covers the domains viewed by the Sounder instrument on GOES-9 (GMS replacement), GOES-10 (West), and GOES–12 (East).

The remote sensing community has generally accepted the CO_2-slicing algorithm as useful for determining cloud top pressure and effective cloud amount for clouds above 600hPa (Zhang and Menzel 2002). The technique, however, is known to have difficulty detecting the following types of clouds:

- Optically thin cirrus clouds (ECA < 10%)
- Multi-layered clouds (e.g., transmissive cloud above a lower opaque cloud)
- Low-level clouds (signal-to-noise problem)
- Clouds existing in an isothermal atmosphere (e.g. polar regions)

The developers of the NCTP have studied the performance of the product as it has matured into operations (Schreiner et al. 2001 and Hawkinson et al. 2001). In addition, the literature provides many validation studies of cloud top height products derived from the CO_2-slicing technique (Frey et al. 1999, Wylie and Menzel 1989, and Menzel et al 1983). The studies do not stratify comparison results based on the technique used by the algorithm (i.e., CO_2-slicing or IR Window techniques) to compute the cloud top pressure pixel. In addition, the algorithm may perform differently in land and ocean domains, a perspective not examined in these reports. The various validation measures, indicating agreement for values within about 3000 ft or 50 hPa, are intended to approximate “acceptable” values for the comparison of CTOP and NCTP.

2.3 *Grid-to-Grid Comparison Mechanics*

The mechanics of the grid-to-grid comparison between the NCTP and CTOP were designed to account for differences in both spatial resolution and measurement time between associated values in CTOP and NCTP, issues that have plagued at least some other cloud-top height validation studies (Wylie and Menzel 1989). All CTOP pixels are marked with the valid time of the product while the scanline time, included in the NCTP product for each pixel, marks the valid time stamp for those pixels. A standard atmosphere calculation is used to convert the NCTP pressure values to height in units of feet. The effective resolution in mid-latitudes of a NCTP pixel is 10-14 km, which varies as a function of latitude due the field of view of the sounding instrument. This resolution roughly corresponds to a 3x3 set of CTOP pixels; the spatial window for a "one-to-one" comparison.

In an attempt to account for cloud movement in the time window by factoring in a mean zonal flow of 30 km/hr (Hansen and Sutera 1987), a 9x9 CTOP spatial window is used to provide a "time corrected" comparison. Two measures are estimated using the pixels within the spatial window; the median and the best match. The median value may not provide a good comparison in regions where the cloud field is discontinuous within the spatial window. For example, if one-third of the pixels contain the intended cloud height while two-thirds contain a cloud at a different height, then the median choice will be penalized by the verification measures. The "best" choice accounts for uncertainties in the cloud field and offers a comparison measure that is too liberal in many circumstances. Together these approaches provide bounds for the grid-to-grid comparisons.

The overall procedure is as follows:

For a given CTOP valid time and domain, select all NCTP pixels within the time window and the appropriate CTOP domain.

1. For each of the NCTP pixels, select the 3x3 and 9x9 CTOP spatial windows centered on the NCTP pixel.

2. Create four NCTP/CTOP comparison pairs by connecting the NCTP value with the CTOP 3x3 median, 3x3 best match, 9x9 median, and 9x9 best match.

In the analysis some of the pairs with the following properties are excluded:

- One or both of the values is set to clear (not cloud present)
- The CTOP value is below 15,000 ft (the algorithm minimum)
- The NCTP value is set to 150 hPa (the algorithm maximum), which is about 45,000 ft.

2.4 *Statistical Measures*

This evaluation of CTOP provides statistics based on a measures-oriented approach for evaluation of forecasts/diagnoses of continuous variables and a distributions-oriented approach (Murphy, 1993). For the grid-to-grid comparisons, the measures-oriented statistics provide values for comparison with validation studies associated with evaluations of the NESDIS cloud-top product and the CO_2-slicing approach. Results include bias scores as well as mean absolute differences (MAD), where

Bias = average CTOP value – average NCTP value

MAD = average absolute difference between the CTOP and the NCTP pixel height values

2.5 *Stratifications*

The statistics for the comparison are stratified using the following criteria:

2.5.a *Cloud Height as determined by CTOP*

The height bins, each covering 5,000 ft, extend from the ground to 70,000 ft. This stratification allows comparison of the products at all levels as well as levels (middle and upper) for which the algorithm development suggests there should be good agreement and where the product is intented to be used.

2.5.b *Effective Cloud Amount as determined by NCTP*

As explained in Section 3.4, the ECA provides a measure of cloud opacity. Statistics, for the CO_2-slicing derived values only (i.e., ECA < 100%), are stratified into the following ECA categories.

- Opaque — ECA between 95% and 99% inclusive
- Thick — ECA between 51% and 94% inclusive

- Thin ECA between 1% and 50% inclusive

These values were chosen based on general ranges that have been suggested in the remote sensing literature. The opaque range defined for the comparison provides a rough indicator of convective clouds, particularly for levels in the atmosphere above 600 hPa. Remote sensing experts have studied this loose correlation using imagery case studies and ground-based lidar measurements (Personal communication with A. Schreiner). In addition, some numerical weather prediction models, including the operational Rapid Update Cycle (RUC), accept a threshold near 95% as an indicator of the presence of convection. In the case of the RUC convective parameterization, initialization with regions of ECA values great than or equal to 96% is designed to improve convective activity in the early stages of the model forecast (Personal communication with J. Brown, S. Weygandt, and R. Aune). Along with the comparison of the grids for all ECA values, the use of statistics in the opaque and thick ranges allows comparison in a regime where theory predicts agreement.

2.5.c OWPDT Regions

Statistics are presented for both the comparison and the grid-to-grid comparison in each of the domains defined by the CTOP product (GOMEX, N. Pacific, and Pacific; the CONUS domain was used for this comparison study only and will not provided as an experimental product to end users). As noted in Section 2, the GOES Sounder domains provide only partial coverage of the OWPDT regions.

2.5.d *Spatial Window*

Results for the comparison are presented for the two spatial windows, 3x3 and 9x9, as well as the CTOP choice of median or best match.

3. RESULTS

3.1 *CTOP and NCTP - CO_2-slicing Comparison*

All results presented in this Section include only NCTP values inferred by the CO_2-slicing technique. The CTOP and NCTP values are independent in the sense that they are derived from different algorithms, the IR Window versus CO_2-slicing, utilizing data from different instruments, the GOES Imager versus the Sounder. The first pair of height plots presented in this Section (Fig. 22) compares biases, defined as the average CTOP value minus the NCTP value, for the two different CTOP spatial window values, the best match and the median. The best value probably underestimates the bias, while the median overestimates it. Together they bound a reasonable estimate of the measure. The results are stratified by ECA with each curve on the plots representing a different ECA range.

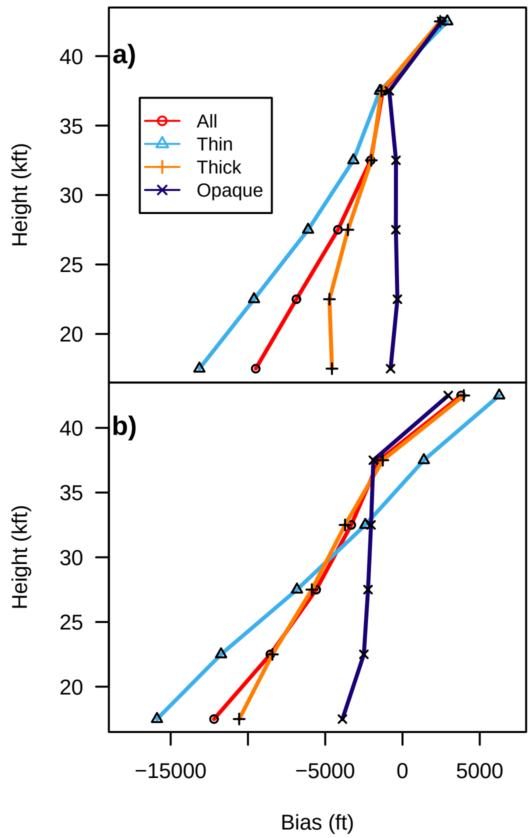

Figure 1. Height series of bias values stratified by effective cloud amount. CTOP comparison values determined (a) by 9x9 best (b) 9x9 median. Data points are plotted in the center of each 5,000 ft vertical bin.

Comparison of the curves in Fig. 1 (a) and (b) reveals that, in general, the best match has a bias lower in absolute value than the bias for the median. The plots show that for opaque clouds, the products agree well throughout the height levels; disagreement at the lower levels increases with decreasing ECA, a result predicted by theory. The following example illustrates the most likely cause for the divergence of the bias curves at lower altitudes. The NCTP CO_2-slicing technique would most likely correctly classify a high cloud with a moderate ECA. The CTOP IR Window technique, however, would “see through” the cloud, measure it as too warm, and misplace the cloud height too low in the atmosphere. The large difference contributing to the bias would then be associated with low clouds, as measured by CTOP.

The abrupt increase in differences at the highest level is mainly due to variation in the highest allowable cloud level of the NCTP product. For cases where the NCTP processing determines that the height of the tropopause is lower in the atmosphere than 150 hPa (~ 45,000 ft), the algorithm chooses the height of the tropopause, rather than 150 hPa as the maximum height value. No comparison is done for NCTP pixels set to the algorithm's maximum value of 150 hPa. Therefore, these differences do not contribute to the overall statistics in the uppermost height bin. The analysis approach does however include comparisons for which the NCTP pixel is set to the height of the tropopause. The NCTP dataset does not contain any additional information that may be used to determine whether the tropopause height at a given location is utilized. In situations where the algorithm chooses the tropopause height as its maximum value, boundary differences can contribute significantly to the overall statistics. For example, if CTOP determines a cloud height of 45,000 ft and NCTP agrees by determining the maximum cloud height equal to the tropopause height at 41,000 ft, then a difference of 4,000 ft is added to the statistics in the upper bin. Additionally, most of the NCTP values from 40,000-45,000 ft are determined by the IR Window technique and are not included in this analysis. This yields a much smaller sample size in the uppermost bin that may lead to greater variability in the values being compared.

Integrating the height curves provides the following overall values. For cloud heights of all ECA values, the best match bias is –5,470 ft while the median bias is –8,480 ft. With only opaque clouds included in the measure, the best match bias is –550 ft and the median bias is –2,270 ft. These bias values, when compared to the results of studies used to validate the NESDIS cloud-top product and the CO_2-slicing method, show very good agreement between the products for opaque clouds and marginal agreement for non-opaque clouds. It is notable that for cloud tops above 30,000 ft, as measured by CTOP, the products qualitatively agree for all ECA values.

The next pair of height series plots presented in this section (Fig. 2 (a) and (b)) compares MAD, for the two different CTOP spatial windows with values for the best match and median.

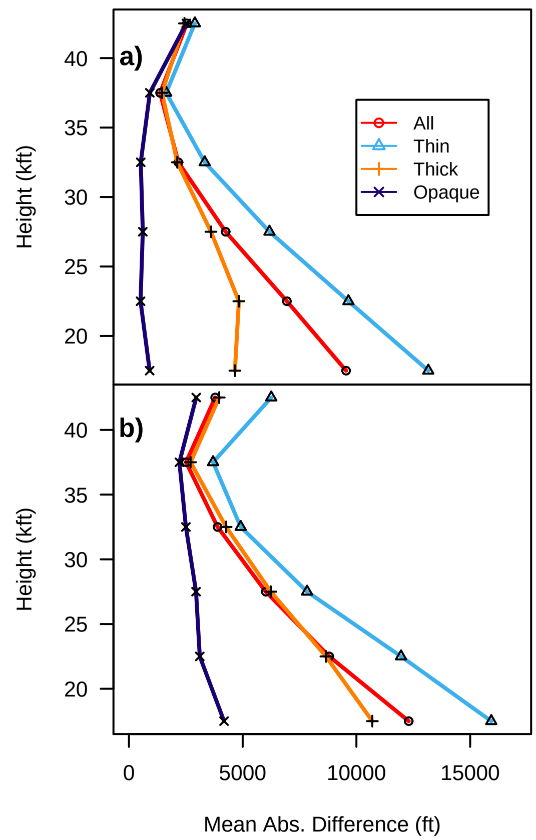

Figure 2. Height series of MAD values stratified by effective cloud amount. CTOP comparison values determined (a) by 9x9 best (b) 9x9 median.

Comparison of the curves in Fig. 2 (a) and (b) reveals that the best values have lower MADs than the medians, as would be expected. These plots of MAD exhibit characteristics similar to those in the bias plots of Fig. 1. According to the MAD, the products agree for opaque clouds throughout the height levels. Disagreement, as described and explained for the bias plots, is evident for the thin cloud categories. Integrating the values over the 15,000-45,000 ft layer provides the following overall values. For cloud heights of all ECA values, the overall MAD for the best match is 5,550 ft while the MAD for the median is 8,790 ft. With only opaque clouds included in the measure, the overall MAD for the best match is 670 ft and the overall MAD for the median is 2,810 ft. As with the bias measures, these MAD values show very good agreement with the results of validation studies for the NESDIS and CO_2-slicing cloud-top measurement approaches.

The next set of height series plots presented in this section compares the bias stratified by CTOP region for both opaque and non-opaque clouds (Fig. 3), which is the aggregate of thick and thin clouds.

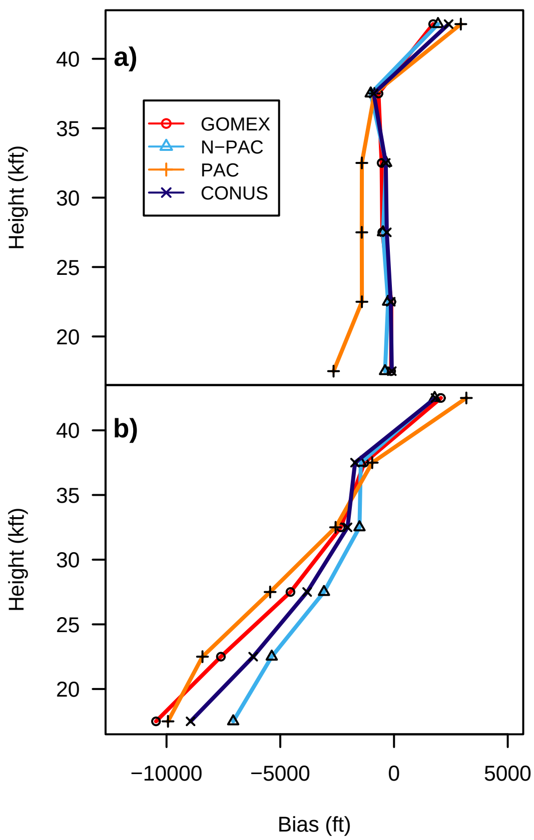

Figure 3. Height series of bias values stratified by CTOP region. Results are presented for (a) opaque (ECA >= 95%) and (b) non-opaque (ECA < 95%).

Figure 3 (a) demonstrates very good agreement between CTOP and NCTP for opaque cloud-top height values in all of the CTOP domains. The bias for the Pacific domain is notably different than the measures for the other domains. There are many possible explanations for the difference of the Pacific domain values. One of the NCTP product developers suggested that the algorithm quality control, geared to the domains in and around CONUS, might not be performing as well for the GOES-9 Sounder data. He also noted that the Sounder instrument on GOES-9, older than those on the other GOES satellites, appears to be noisier (Personal communication, A. Schreiner). Climatological differences between the Pacific domain and the others may also be contributing to the variation.

The bias difference for the non-opaque clouds, previously described for Figure 1, is evident in Figure 3 (b) for all of the CTOP regions. The two tropical regions, the Pacific and GOMEX domains, appear to have slightly higher overall biases. This result may be due to climatological differences. This plot also demonstrates marginal agreement between the products for upper level non-opaque clouds in all CTOP domains.

Comprehensive statistics for the CO_2-slicing comparison are presented in Tables 1 and 2. Values are included for all four of the comparison values as defined by the grid-to-grid mechanics. As described in Section 3.4.2, bias and MAD measures with absolute value less than ~3000 feet indicate very good agreement.

The negative overall bias associated with all comparison mechanics and all ECA stratifications indicates that, in general, cloud-top heights from CTOP are lower in the atmosphere than those from NCTP. Both tables demonstrate that CTOP and NCTP strongly agree for opaque clouds when any of the four comparison values is used. There is also good agreement for thick clouds for the 9x9 best match comparison approach. The products strongly disagree with differences ranging from over 9,000 ft to nearly 15,000 ft, according to all comparison mechanics, for clouds in the thin ECA stratification.

3.2 NCTP IR Window Comparison

All results in this Section include only NCTP values inferred by the IR Window technique (i.e. NCTP pixels with an assumed ECA of 100%). The comparison values are not independent with respect to the algorithm used to identify the clouds, but they are independent with respect to the data source. This analysis provides a comparison in a regime where the products should strongly agree. Figure 4 presents the bias and the MAD for the IR Window technique NCTP pixels only, with CTOP comparison values determined by a 9x9 spatial window. Statistics for both the median and best match mechanics are shown.

Figure 4 demonstrates very good agreement with a bias less than ~1000 feet when the two products infer cloud-top height values with the same technique. The MAD values for the 9x9 best match show very good agreement while the MAD values for the 9x9 median diverge slightly, although still showing marginal agreement at the lower levels. Differences in time and pixel resolution could account for the larger MAD values. Based on the comparisons shown in Table 1, the results for the 3x3 best and median values for the IR Window technique, not presented here, are expected to fall within the bounds presented in Fig. 4.

Table 1. Overall bias values (ft) for the various comparisons and ECA ranges.

Effective Cloud Amount	9x9 Best	9x9 Median	3x3 Best	3x3 Median
All	-5,470	-8,480	-7,110	-8,080
Opaque	-550	-2,270	-1,280	-2,020
Thick	-3,380	-7,800	-5,620	-7,410
Thin	-9,550	-14,300	-12,460	-14,080

Table 2. Mean absolute difference values (ft) for the various comparisons and ECA ranges.

Effective Cloud Amount	9x9 Best	9x9 Median	3x3 Best	3x3 Median
All	5,550	8,790	7,300	8,470
Opaque	670	2,810	1,640	2,680
Thick	3,480	8,120	5,840	7,800
Thin	9,605	14,480	12,550	14,320

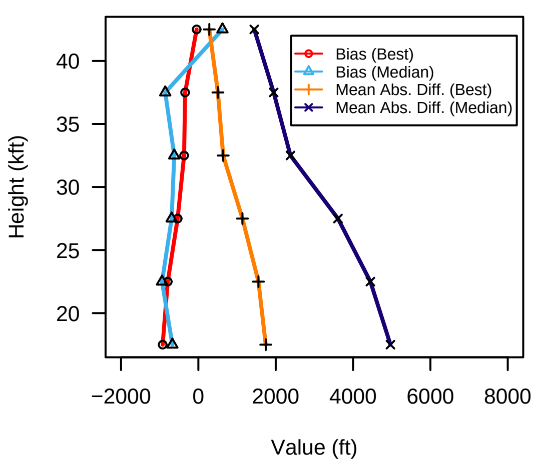

Figure 4. Height series of bias and MAD for IR Window technique NCTP pixels only, with CTOP comparison values determined by a 9x9 spatial window.

Figure 4 demonstrates very good agreement with a bias less than ~1000 feet when the two products infer cloud-top height values with the same technique. The MAD values for the 9x9 best match show very good agreement while the MAD values for the 9x9 median diverge slightly, although still showing marginal agreement at the lower levels. Differences in time and pixel resolution could account for the larger MAD values. Based on the comparisons shown in Table 1, the results for the 3x3 best and median values for the IR Window technique, not presented here, are expected to fall within the bounds presented in Fig. 4.

3.3 Distributions-Oriented Comparison

The overall grid-to-grid analysis relies on the measures-oriented comparison to provide the quantitative statistics for the assessment of CTOP. The matching mechanics excluded many comparison pairs from the overall statistics, mainly to account for differences in the valid height ranges of the products. In order to assess the qualitative impact of the exclusion rules, joint and conditional probability distributions are presented in this section.

Figure 5 presents joint probability distributions for CTOP and NCTP stratified for (a) opaque (ECA >= 95%) and (b) non-opaque (ECA < 95%) clouds. The area inside the bold internal bounding box represents statistics that were included in the measures-oriented results while values outside of the bounding box were excluded. Similarly, the ellipses labeled ‘B’ in figures 5 (a) and (b) designate the comparisons excluded because the NCTP value was set to the maximum value for the algorithm. The values, constrained to an area around the diagonal, are reasonable for the opaque clouds. Again, for the non-opaque cloud stratification, the values “smear” away from the diagonal. These results indicate that the measures-oriented statistics are probably good measures for the opaque cloud stratification – the mechanics seem sound. The statistics are, however, probably low estimates – they show better agreement than they should - for the cloud heights in the non-opaque clouds stratified by CTOP height. Overall, the qualitative clustering of probability along the diagonal for opaque clouds in figure 5 (a) shows good agreement between the products. The example of a cloud with a moderate ECA, described in the measures-oriented analysis, explains the smearing of the pattern in the non-opaque distribution.

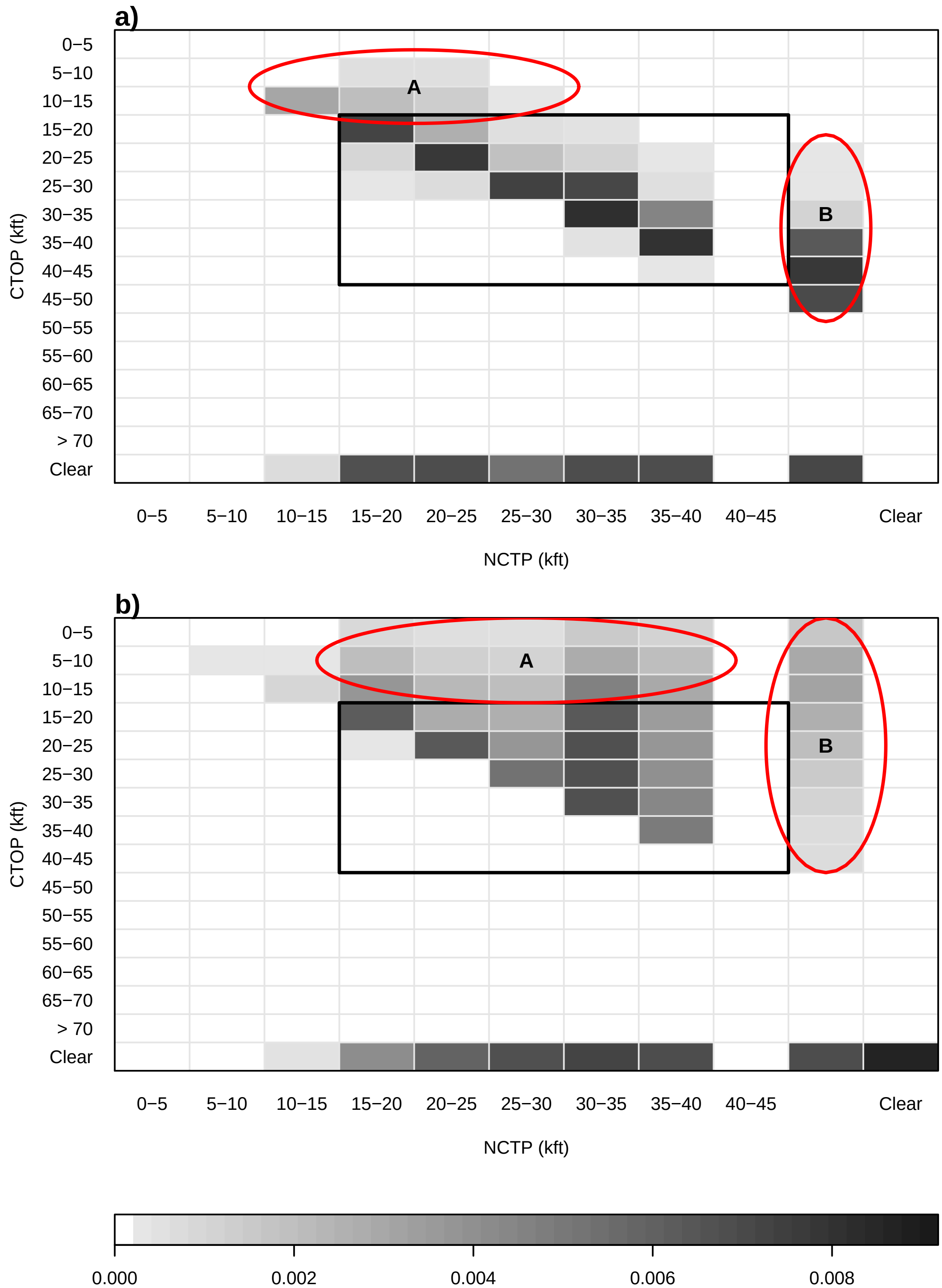

Figure 5. Joint Probability Distributions for CTOP and NCTP. Results are presented for (a) opaque (ECA >= 95%) and (b) non-opaque (ECA < 95%) clouds. The ellipses labeled 'A' in figures 5.5 (a) and (b) roughly designate the comparisons excluded by the measures-oriented statistics because the CTOP value was below the valid range of the algorithm.

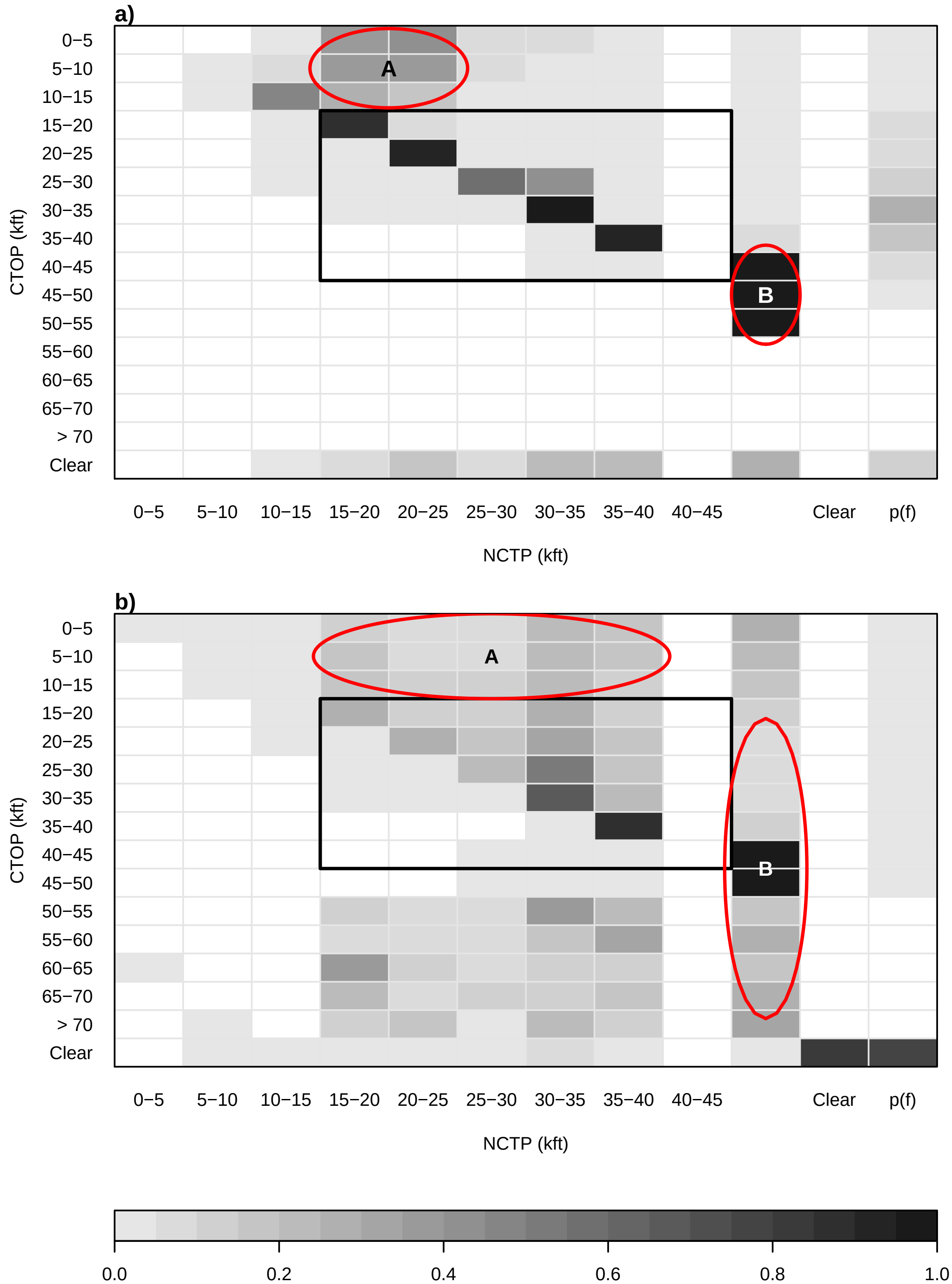

Figure 6. Conditional Probability Distributions for the probability of NCTP given CTOP. Results are presented for (a) opaque (ECA >= 95%) and (b) non-opaque (ECA < 95%).

Figure 6 presents conditioned probability distributions for the probability of NCTP given CTOP stratified for (a) opaque (ECA >= 95%) and (b) non-opaque (ECA < 95%) clouds. The values in the distribution should be interpreted by row from left to right. The area inside the bold internal bounding box represents statistics that were included in the measures-oriented results while values outside of the bounding box were excluded. These conditioned distributions highlight and confirm the observations in the discussion of figure 5.

4. CONCLUSIONS

This paper has summarized results of a comparison of cloud-top heights produced by the OWPDT CTOP product and NCTP to determine the relative quality of the CTOP product. Results from the grid-to-grid comparison indicated very good agreement between the CTOP and the satellite-derived heights for opaque and thick cloud from 25,000-40,000 ft (as measured by CTOP) with overall differences approximately 3,000 ft. The statistics for the thin cloud comparison showed significant disagreement for all heights below 40,000 ft, an expected result given the theoretical strengths and weaknesses of the two products. The CTOP and NCTP algorithms strongly agree when estimating the heights of deep convective clouds that may be a hazard to aviation.

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6. REFERENCES

Frey, R. A., B. A. Baum, W. P. Menzel, S. A. Ackerman, C. C. Moeller, and J. D. Spinhime, 1999: A comparison of cloud-top heights computed from airborne LIDAR and MAS radiance data using CO_2 slicing. *J. Geophys. Res.*, **104**, 24,547-24,555.

Hansen, Anthony R., A. Sutera, 1987: The probability density distribution of the speed and horizontal and vertical shear of the zonal-mean flow. *J. Atmos. Sci.*, **44,** No. 11, 1525-1533.

Hawkinson, J. A., W. Feltz, T. J. Schmit, A. J. Schreiner, and S. A. Acherman, 2001: A validation study of the GOES sounder cloud top pressure product. *Preprints of 11th Conference on Satellite Meteorology and Oceanography, Madison, WI, October 2001*. Amer. Meteor. Soc., Boston, MA, 348-350.

Menzel, W.P., W. L. Smith, and T. R. Stewart, 1983: Improved cloud motion wind vector and altitude assignment using VAS. *J. Cli. and Appl. Meteor.*, **22,** 377-384.

Miller, S, J. Hawkins, T. Lee, 2002: Cloud-top heights for aviation near-real time application. Available from URL: http://www.rap.ucar.edu/projects/owpdt/documents/cloudtops2.html.

Murphy, A.H., 1993: What is a good forecast: An essay on the nature of goodness in weather forecasting. *Wea. Forecasting.* **8,** 281-293.

Schreiner, A.J., T. J. Schmit, and W. P. Menzel, 2001: Observations and trends of clouds based on GOES sounder data. *J. Geophys. Res*., **106**, 20,349-20, and 363.

Warren, S. G., C. J. Hahn, J. London, R. M. Chervin and R. L. Jenne, 1986: Global distribution of total cloud cover and cloud type amounts over land. NCAR Tech. Note NCAR/TN-273+STR, 228 pp.

Wielicki, B. A., and J. A. Coakley Jr., 1981: Cloud retrieval using infrared sounder data: Error analysis. *J. Appl. Meteor.*, **20**, 157-169.

Wylie, D.P. and W. P. Menzel, 1989: Two years of cloud cover statistics using VAS. *J. Climate*, **2**, 380-392.

Zhang, H., and W. P. Menzel, 2002: Improvement in thin cirrus retrievals using an emissivity-adjusted CO_2-slicing algorithm. *J. Geophys. Res.*, **107**, 4235.