Total Sky Imager/Whole Sky Imager Cloud Fraction Comparison

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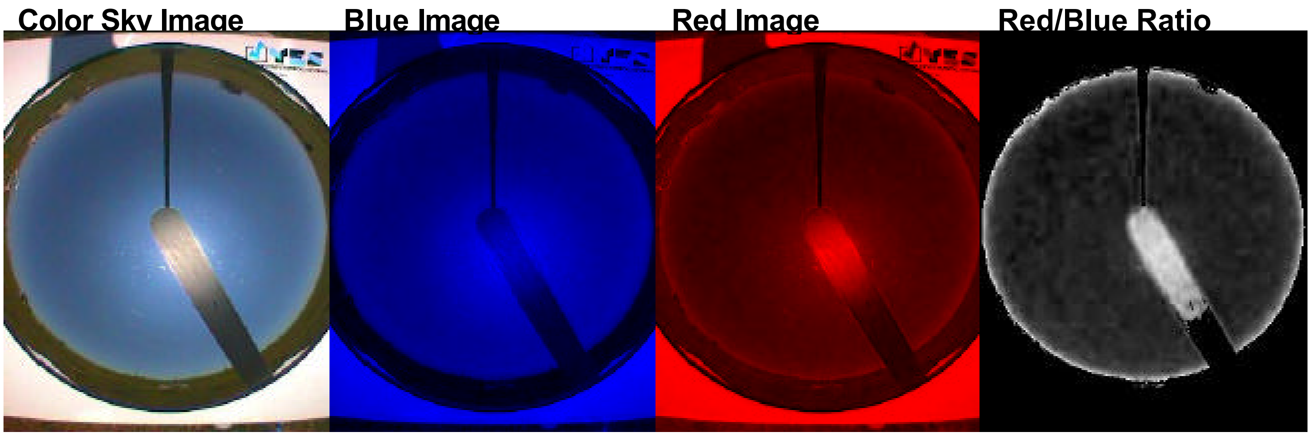
Introduction

During last year's The ARM (Atmospheric Radiation Measurement) Enhanced Shortwave Experiment (ARESE) II Intensive Operational Period (IOP), both the ARM Whole Sky Imager (WSI) and the new Total Sky Imager (TSI) were operated simultaneously in close proximity to one another. Both instruments were located at the Blackwell/Tonkawa Airport for the duration of this IOP. Cloud fraction estimates from these systems during the interval between March 9, 2000, and April 6, 2000, have been compared to evaluate the agreement of these two fully independent estimates. Although the two systems use different algorithms to derive an estimated cloud cover, substantial agreement is evident in the overall results. The primary purpose of the present comparison is to provide a link between the large volume of WSI cloud data gathered within the ARM Program and the increasing usage of TSI instruments by other researchers, as well as ARM (the TSI has recently been accepted as an official ARM instrument). A secondary purpose is to provide assurance of the cloud fraction estimates for the upcoming Island Effect Study expected to take place this year on Nauru Island. During that effort, a TSI will be deployed on the windward side of the island and operated in concert with an additional TSI placed near the WSI at the Denig site to study the effects of the Nauru landmass on measurements at the Denig site.

Brief Description of TSI and WSI Cloud Fraction Estimate Methods

Although both the TSI and the WSI produce cloud fraction estimates as part of their primary products, each proceeds through this task using somewhat different approaches:

TSI. The TSI uses a mounted digital camera looking downwards toward a rotating hemispheric mirror. The digital images are stored in compressed format. Because the images are in color, they contain information on the relative red, green, and blue content that goes into making up a pixel's color. We use a ratio of the red to blue pixel values to distinguish whether a pixel represents a clear or cloudy portion of the sky image. Figure 1 illustrates the use of this ratio while viewing clear skies. Similarly, Figure 2 depicts the effects of clouds on this same ratio, yielding cloud cover estimates for 'opaque' and 'thin' clouds in the portion of the sky that lies above 10 degrees elevation, again dependent of the



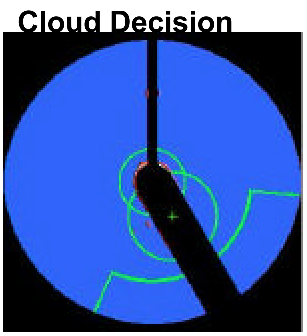


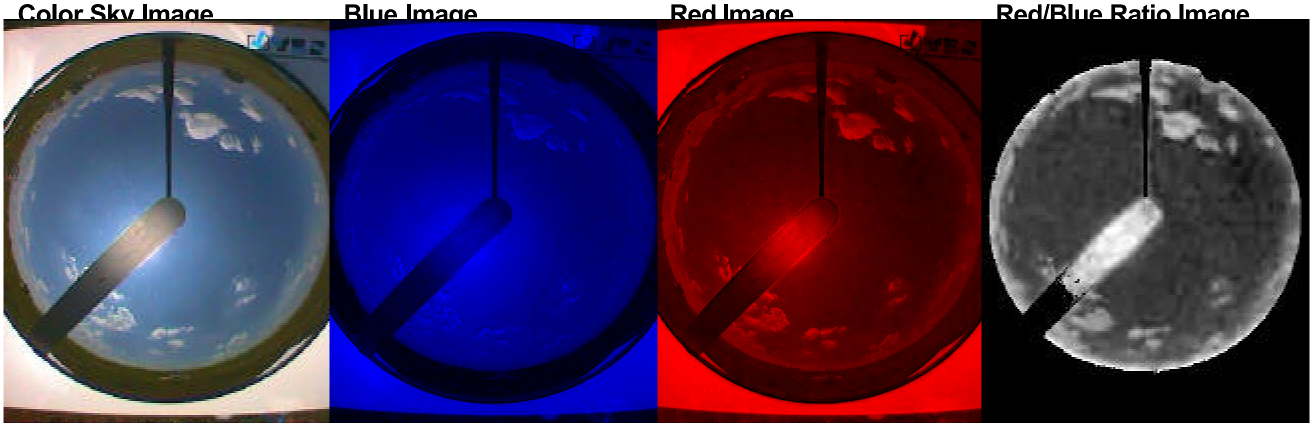
Figure 1. Clear Sky: For molecular scattering (clear skies), more blue is scattered than red. A sample image of clear sky is shown in the upper left. To the right are two images that show the corresponding extracted blue and red pixel values that make up the sample image. As is shown, the red pixel values are relatively small (dark) in the sky portion of the image compared to the corresponding blue pixel values, except near the horizon where the increased atmospheric path length makes the original sky image appear white to our eyes. The relative red/blue ratio values are shown in the far right image above. Below the color sky image is the corresponding "cloud decision image," a graphical depiction of the results of the sky cover retrieval processing. In this image, the camera arm and sun-blocking strip are masked out with black, and the blue color in the rest of the circle denotes that all the processed pixels (for a 160 degree FOV) have been determined to be "clear."

relative values of this ratio. The particular ratios defining 'opaque' and 'thin' from clear are user-defined quantities. The fully independent choice of these thresholds helps to explain some of the minor differences in cloud fraction reported by the TSI and WSI.

WSI. The WSI cloud retrieval classifies sky elements as belonging to one of ten defined categories. For daytime retrievals each spatial element is about 35 microsteradians in size. The eight categories that define daytime estimates are listed and defined below. For the day retrieval cases, X is the ratio of measured 450-nm radiance to that expected for the same element in an exceptionally clear (pristine) sky. Y is similarly the ratio of measured 650-nm radiance to that for a pristine sky and Z is the same ratio for 800 nm.

1. *Clear*. This category is for all elements that have radiance values very close to those expected for pristine clear skies, i.e., all sky elements whose X, Y, and Z ratios are essentially 1.0. The specific daytime limits are $Z < 2.111*X - 0.528$, $Z < 1.3$, $Z > 0.7$, and $X < 1.3$.

Color Sky Image **Blue Image** **Red Image** **Red/Blue Ratio Image**



Cloud Decision Image

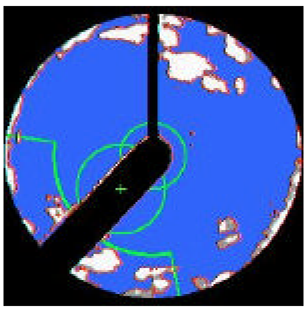


Figure 2. Cloudy Sky: Clouds, unlike the clear-sky, generally scatter both the blue and red visible light more equally. A sample of a partly cloudy sky is shown in the upper left image. To the right of this sample image again are two images that show the corresponding extracted blue and red pixel values that make up the sample image. In this case, where there are clouds present, the red pixel values are much greater than where there are not clouds. The blue pixel image shows far less contrast in pixel values. The relative ratio of red/blue pixel values (far right) clearly shows that the ratio is greater for clouds than for clear sky. We set a lower limit for clear-sky ratio value for each pixel in the image, and the pixels for which the red/blue ratio exceeds the clear limit are counted as "cloudy." The results of this processing are depicted in the "cloud decision image" shown below the color sky image, again with the camera arm and sun blocking strip masked out. In this image, the blue represents retrieved clear sky, and the gray/red and white depict retrieved thin and opaque cloud, respectively.

2. *Aerosol*. This encompasses all daytime sky elements that are not clear and do not have radiance values that definitively indicate that a cloud is present. As currently defined, very thin clouds and hazy aerosol sky elements fall in this category. The specific limits are $Z < 2.111*X - 0.528$, $X > 0.2$, and $Y > 0.25$. Mixed aerosol and cloud: This category is daytime sky elements that have radiance properties characteristic of both thin clouds and aerosol-laden skies. *It is currently not used*.

3. *Mixed aerosol and cloud*. This category is daytime sky elements that have radiance properties characteristics of both thin clouds and aerosol-laden skies. *It is currently not used*.

4. *Bright cloud*. This is for daytime definitive cloudy sky elements that are very bright such as the sunlit sides of cumulus or cirrus near the sun. Specifically, these are cloudy elements whose 450-nm radiance is more than three times brighter than expected for pristine skies. The actual daytime limits are $Z > 2.11*X - 0.528$, $Y > 0.25$, and $X > 3.0$.

5. *Intermediate cloud*. This is for daytime definitive cloudy sky elements that have typical cloudy sky radiance values. Specifically, these are cloudy elements whose 450nm radiance is greater than expected for pristine skies but less than three times brighter. The actual limits are Z > 2.11*X - 0.528, Y > 0.25, X > 1.0 and X < 3.0.

6. *Dark cloud*. This is for daytime definitive cloudy sky elements that have unusually low cloudy sky radiance values such as low status with very high optical thickness. Specifically, these are cloudy elements whose 450nm radiance is less than expected for pristine skies. The actual limits are Z > 2.11*X - 0.528, Y > 0.25, X > 0.2 and X < 1.0.

7. *Indeterminate*. This category includes all daytime conditions that fall outside the values defined above, and specifically has a radiance ratio that is excessively bright (e.g., specular reflection) or dark (e.g., building side).

8. *Undefined*. This category includes all daytime conditions for which radiance values are not measured and no retrieval is performed. Such elements may be behind the occultor or a building on the horizon, or too near the sun for proper camera functioning.

Procedure for TSI/WSI Cloud Fraction Comparisons

1. The TSI had a 1-minute repeat time for acquiring images, while the WSI was operated with a 6-minute repeat interval, necessitating time synchronization. All time differences between TSI and WSI images are required to be less than 5 seconds in this study.

2. Whereas the TSI reports cloud cover fraction for the entire 160° sky dome within an 80° zenith angle, the WSI reports cloud cover in eight sectors of the sky: Zenith to 45°, and 45° to 80° zenith angle for each of the N/E/S/W directional quadrants. Each of the cloud fractions reported by the WSI in these quadrants were weighted, dependent on its total projected sky area (steradians), and summed with the others to yield a percentage of the pixels that are categorized as a particular cloud type. This is made possible because the WSI optics produce an equidistant projection image. In addition, the ‘indeterminate’ and ‘undefined’ portions of each sector are added and used to modify the cloud cover estimates to approximate the percentage that would be assessed were obstacles not in the field of view or areas whose color ratio exceeds those allowed by the processing software. For the WSI, the sky classifications summed were ‘bright,’ ‘intermediate,’ and ‘dark.’ ‘Aerosol’ classification by the WSI was not included in this work because of the uncertainty of the distinction between aerosol and thin cloud, though we believe this to be a major factor in cloud estimate differences. For the TSI, the sum of ‘thin’ and ‘opaque’ classifications was used for comparison.

3. Initially, comparisons were made using the earliest data available, yielding approximately 2500 coincidences. The results reported here consist of comparisons made using the quality-controlled, reprocessed data, which produced approximately 2000 coincidences. This count was also effected by restricting cloud estimates to intervals when the solar elevation angle exceeded 10° due to increased difficulties of sky classifications for low sun angles.

Comparison Results

Several examples of the corresponding cloud cover estimates made by the TSI and WSI are presented in Figure 3. These data represent all available coincidences of the processed data (those data remaining after quality control procedures) during the three days shown and when the solar elevation angle exceeded 10°. Certainly the temporal behavior is quite consistent between the WSI and TSI derived cloud fractions, as are the 'total' cloud estimates. There does appear to be a general tendency for TSI estimates to slightly exceed those from the WSI; this is a common feature that we attribute to slightly different thresholds applied in the processing to define very thin clouds.

The total number of coincidences acquired during the March 9 through April 06, 2000, interval, amounted to 2004 pairs of estimates. The resulting comparison is shown in Figure 4 that illustrates the 'total' cloud fraction of the WSI versus both the 'total' and 'opaque' of the TSI processing. As previously mentioned, the TSI appears to routinely produce slightly higher estimates than the WSI. The WSI processing yields two sky classifications that were not included in sums used for this study: 'aerosol' and 'mixed aerosol and cloud,' though the latter is currently not being populated by the ARM Program.

In order to identify any obvious trends of WSI - TSI cloud fraction differences, we have plotted these differences as functions of TSI 'total' cloud cover (Figure 5a), TSI 'thin' cloud cover (Figure 5b), and GMT (Figure 5c). There appears to be a slight trend towards an increased TSI estimate of cloud cover relative to the WSI during partially cloudy conditions, though there is also increased scatter of the differences as compared to both fully cloudy and clear conditions (Figure 5a). This is most likely the result of the process for estimating 'thin' cloud conditions as evidenced in Figure 5b, where the WSI - TSI difference is seen to increase with TSI 'thin' cloud classification. The magnitude of differences seems to have almost no correlation with time of day, as shown in Figure 5c. Finally, in Figure 5d, the percentage difference of 'total' cloud fraction is illustrated for the entire set of 2,004 coincident observations in terms of the number and probability of occurrence.

Examples of Coincident Images Demonstrating the Thin Cloud/Aerosol Problem'

As shown in Figure 6, cloud fraction estimates yield slightly higher values using the TSI processing when compared to the WSI. Figure 7 shows two composite images during times when the TSI 'thin' cloud estimates were reasonably high:

Time	WSI Total	TSI Total	TSI Thin
Mar 26 19:54	67%	95%	29%
Apr 03 14:12	75%	98%	47%

TSI 'opaque' clouds are shown in white, while 'thin' clouds are depicted as light blue. Clear areas are shown in deeper blue. In both cases, the TSI seems to have a lower threshold of what is interpreted as 'thin' cloud, though because of the differing cloud classifications between the TSI and WSI, this is difficult to quantify.

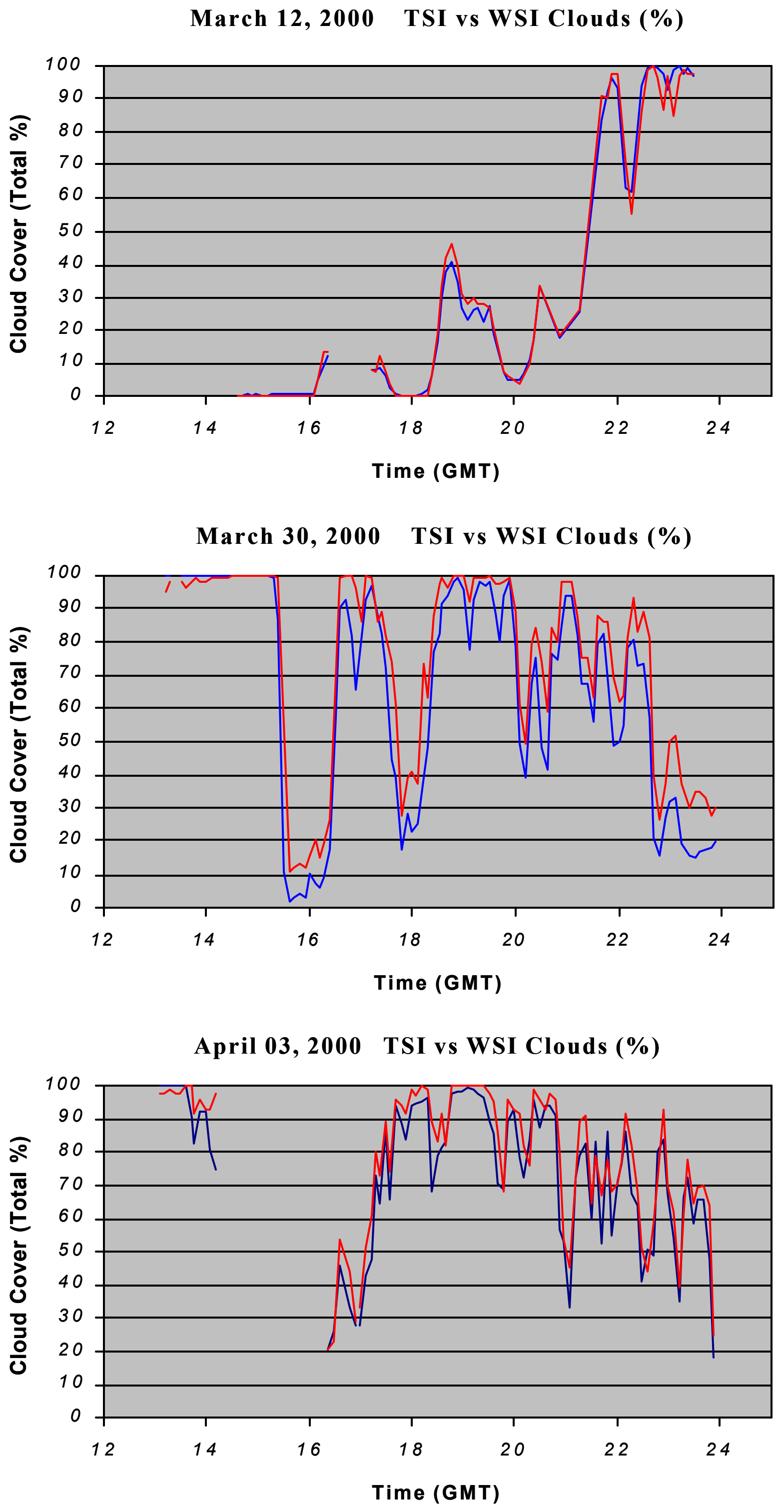
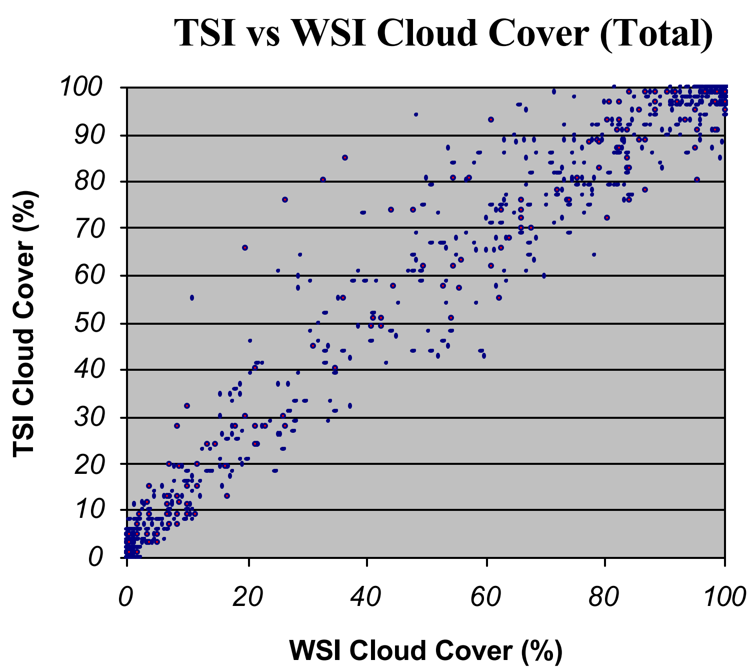


Figure 3. Examples of cloud cover estimates made by the TSI and WSI.



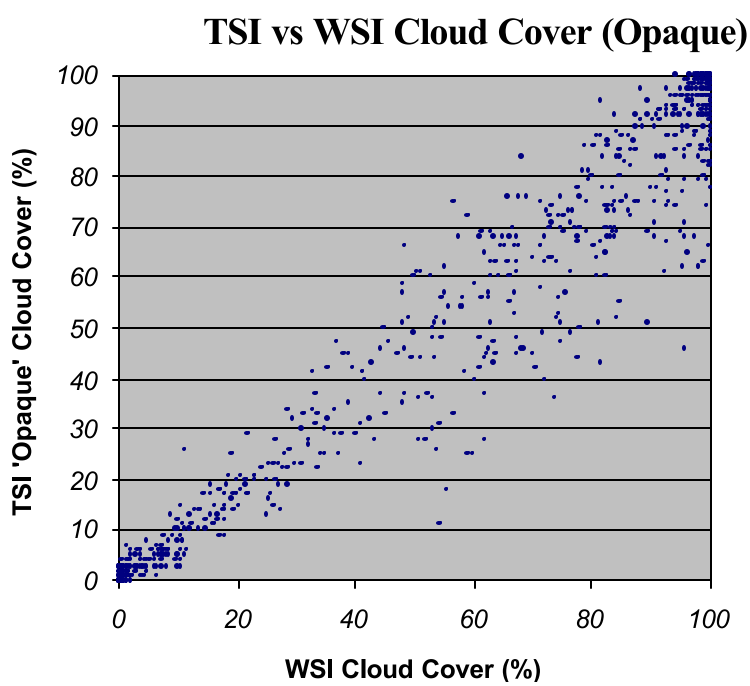


Figure 4. The ‘total’ cloud fraction of the WSI vs. both the ‘total’ and ‘opaque’ of the TSI processing.

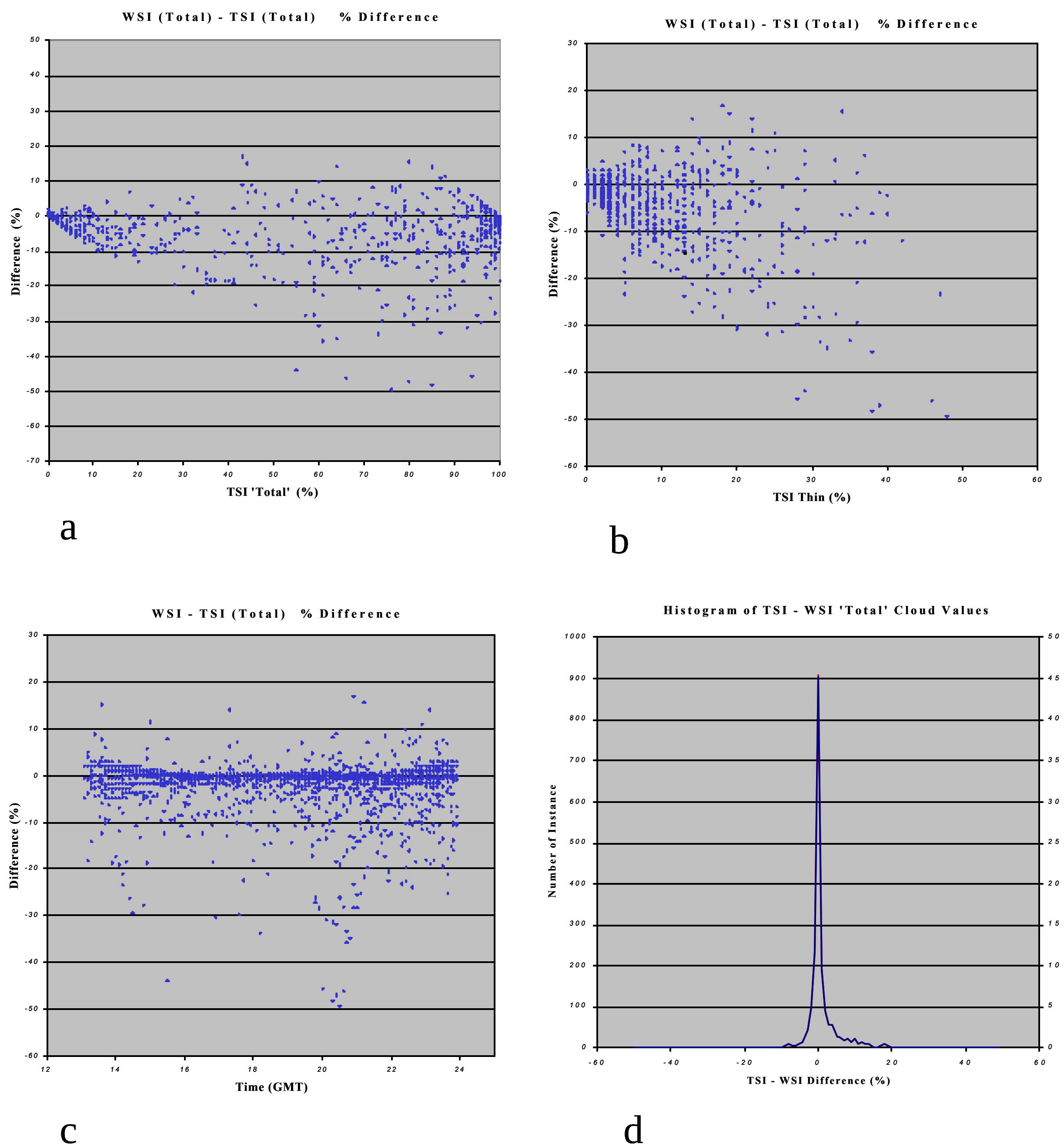


Figure 5. Plots of WSI-TSI cloud fraction differences as functions of (a) TSI 'total' cloud cover, (b) TSI 'thin' cloud cover, (c) GMT, and (d) 'total' cloud fraction.

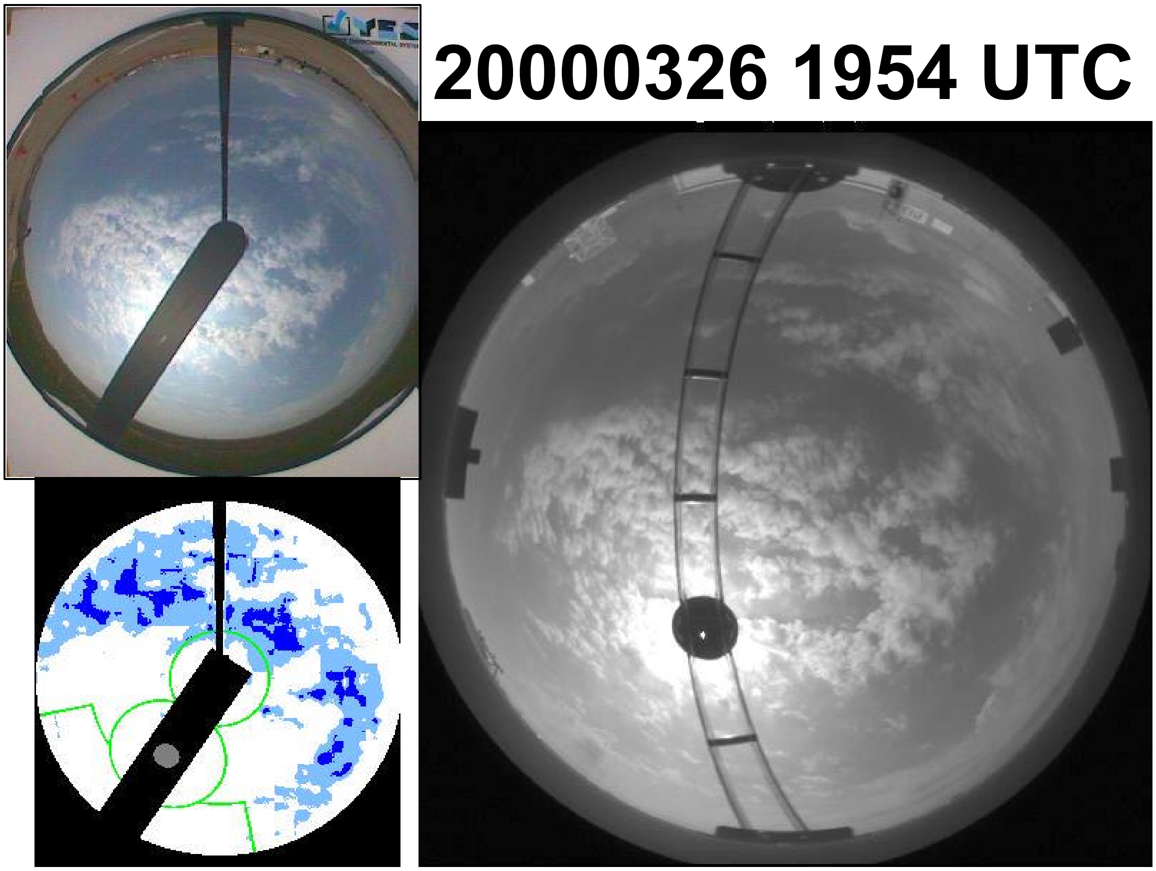


Figure 6. Images showing TSI processing yielding slightly higher values than the WSI.

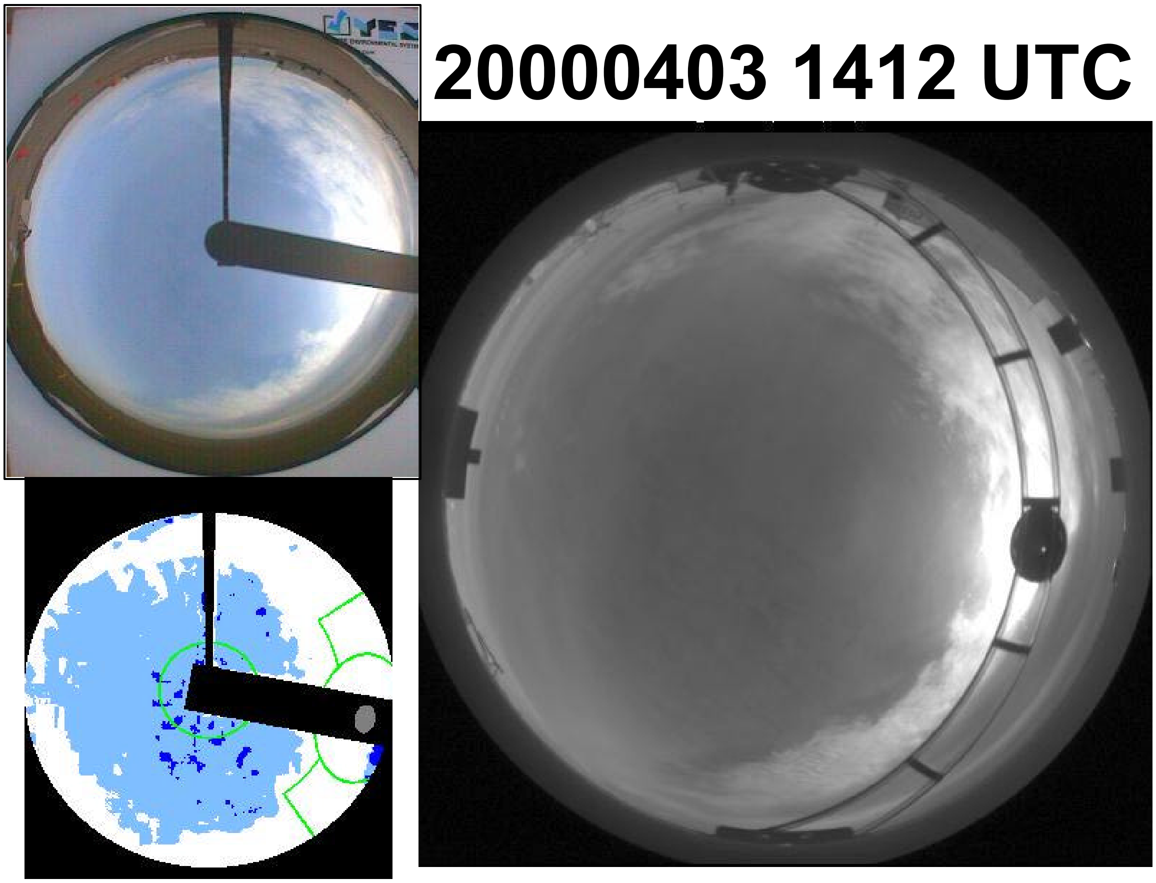


Figure 7. Images during times when the TSI 'thin' cloud estimates were high. TSI 'opaque' clouds are shown in white, 'thin' clouds are depicted as light blue, and clear areas are shown in darker blue.

Results

1. Comparison of cloud fraction estimates from the WSI and TSI using independent methods of analysis illustrates that a consistent estimate of cloud fraction can be routinely generated with current analysis techniques.

2. The TSI does favor a slightly higher estimate than the WSI, which we attribute to the user-defined threshold that identifies the 'thin' cloud classification. The decision process by which one defines aerosol or very thin cloud is not necessarily unique.

3. The probability of agreement between the TSI and WSI to within 5 percent cloud fraction for the entire data set is quite high, nearly 87 percent. The probability of agreement for clear and fully cloudy conditions is nearly 100 percent, falling off somewhat for partially cloudy conditions when thin clouds or aerosol are prominent.

4. Judging from the total number of observations during this nearly month-long period and the number of final cloud fraction estimates, the WSI seems to have a more restrictive quality control mechanism. Further comparisons will be made with the much larger data archives available since the deployment of a TSI to the SGP Central Facility on July 1, 2000, in close proximity to the ARM WSI. This will provide a wide range of sky conditions for investigation.