JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 113, XXXXXX, doi:10.1029/2008JD010278, 2008

Estimating fractional sky cover from spectral measurements

Qilong Min,[1] Tianhe Wang,[1,2] Charles N. Long,[3] and Minzheng Duan[4]

Received 15 April 2008; revised 14 August 2008; accepted 29 August 2008; published XX Month 2008.

[1] A method for estimating fractional sky cover from spectral measurements has been developed. The spectral characteristics of clouds and clear-sky aerosols are utilized to partition sky fraction. As illustrated in our sensitivity study and demonstrated in real measurements, the transmittance ratio at selected wavelengths is insensitive to solar zenith angle and major atmospheric gaseous absorption. With a localized baseline procedure, retrievals of this ratio method are independent of absolute calibration and weakly sensitive to changes in cloud and aerosol optical properties. Therefore this method substantially reduces the retrieval uncertainty. The uncertainty of this method, estimated through the sensitivity study and intercomparison, is less than 10%. With globally deployed narrowband radiometers, this simple ratio method can substantially enhance the current capability for monitoring fractional sky cover.

Citation: Min, Q., T. Wang, C. N. Long, and M. Duan (2008), Estimating fractional sky cover from spectral measurements, *J. Geophys. Res.*, *113*, XXXXXX, doi:10.1029/2008JD010278.

1. Introduction

[2] Clouds remain the greatest sources of uncertainty in global climate change research [*IPCC*, 2007]. The impact of greenhouse warming on cloud amount through climate feedback will have significant changes on the global radiative energy balance [*Randall et al.*, 1984]. Variations of cloud cover have significantly contributed to contemporary climatic changes. Thus it is crucial to accurately monitor fractional sky cover of clouds globally.

[3] Monitoring cloud amount has a long history: from earlier human-empirical sky observations, to surface passive and active measurements [*Fairall and Hare*, 1990; *Clothiaux et al.*, 1999; *Long and Ackerman*, 2000; *Pfister et al.*, 2003; *Long et al.*, 2006a, 2006b], to recent satellite retrievals [*Minnis*, 1989; *Rossow et al.*, 1993]. Satellite observations provide the global coverage of cloud amount to study global climate change. Their limits in spatial/temporal resolution and issues with surface influences manifest the need for surface measurements to verify satellite retrievals and to fill the gaps between satellite observations. Current technology has advanced in surface observations of cloud amounts from human-empirical sky observations, to spatial estimation from sky imagers, to temporal estimation of cloud occurrences from passive and active sensors. However, even with an increasing number of sky imagers and other passive and active sensors for monitoring cloud fraction, there are still limited surface measurements available to date.

[1]Atmospheric Sciences Research Center, State University of New York, Albany, New York, USA.
[2]College of Atmospheric Sciences, Lanzhou University, Lanzhou, China.
[3]Pacific Northwest National Laboratory, Richland, Washington, USA.
[4]Institute of Atmospheric Physics, Chinese Academy of Science, Beijing, China.

0148-0227/08/2008JD010278$09.00

[4] Since shortwave (SW) radiation is strongly modulated by clouds, widely deployed spectral and broadband shortwave radiometers provide the potential to estimate cloud fraction in large geographic distribution. *Long et al.* [2006a] proposed a methodology for inferring fractional sky cover from broadband SW diffuse irradiance measurements during daylight hours. Their method utilizes the enhancement of diffuse irradiance under cloudy conditions to partition cloudy and clear-sky fractions, through a normalization procedure to remove solar zenith angle dependences. Since clouds and aerosols (clear-sky) with different particle sizes exhibit significant differences of spectral dependences of optical properties, there is a possibility to estimate sky cover using spectral measurements of narrowband radiometers.

2. Spectral Ratio and Retrieval Algorithm

[5] The spectral dependence of optical depth of atmospheric scatterers generally follows Angstrom's empirical relationship [*Angstrom*, 1929]:

$$\tau_{sca}(\lambda) = \beta\lambda^{-\alpha} \quad (1)$$

where $\tau_{sca}(\lambda)$ is the optical depth of atmospheric scatterers at wavelength λ, β and α are constants. More importantly, the Angstrom exponent α is an indicator of the size of the scatterers. For molecules in the Rayleigh scattering regime, its value approaches 4, while for cloud particles in the Mie scattering regime, it is close to 0. For aerosol particles, the Angstrom exponent varies between Rayleigh and clouds, with a typical value of about 1.3. Because of such spectral dependence of optical depth, the diffuse transmittance ratio between a longer wavelength and a short wavelength is about 1 for clouds, and less than 1 for aerosols, respectively, as illustrated in Figure 1. On the basis of this physical principle and further sensitivity study below, the baselines of transmittance ratio under both aerosol and cloud

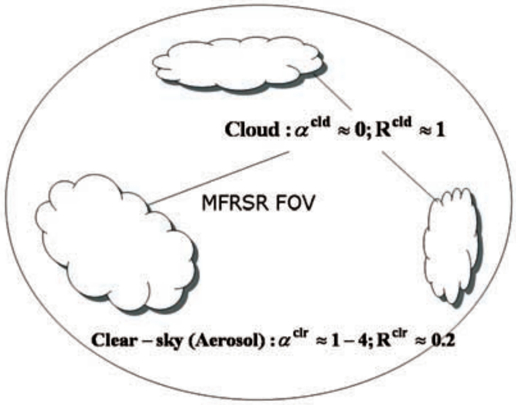

Figure 1. Sketch of retrieval principle of cover fractional cover. α is the Angstrom exponent and R is the transmittance ratio at two wavelengths; cld and clr represent cloud and clear-sky conditions, respectively.

conditions are well defined and less sensitive to variations of both aerosol and cloud properties. A measured transmittance ratio in reality is weighted by the cloud amount in the sky and can be assumed as a linear partition between cloud transmittance ratio and clear-sky transmittance ratio:

$$R^{obs} = (1 - \phi)R^{clr} + \phi R^{cld} \quad (2)$$

where ϕ is the fractional sky cover in the atmosphere. Therefore fractional sky cover can be inferred from a simple analytical expression

$$\phi = \frac{R^{obs} - R^{clr}}{R^{cld} - R^{clr}} \quad (3)$$

[6] As solar transmittances at different wavelengths vary with solar zenith angle systematically, the transmittance ratio at two wavelengths is less dependent on solar zenith angle (or time). If a basic set of cloudy and clear-sky transmittances is defined at any given time (or solar zenith angle), the set is applicable to other daylight times (or solar zenith angles). Thus this simple expression provides a reasonably accurate estimate of fractional sky cover. It is worth emphasizing that for a good estimation the wavelength pair for the transmittance ratio should be separated enough to have a substantial contrast of aerosol optical depth between the two wavelengths. Moreover, at both wavelengths the potential interference of gaseous absorption, particularly water vapor due to cloud–water vapor interaction, should be minimal.

[7] To illustrate the underlying principles and sensitivity, a pair of multifilter rotating shadowband radiometer (MFRSR) channels at 415 and 860 nm, where gaseous absorption is minimal, is selected for forward simulation. The MFRSR is a seven-channel radiometer with six passbands 10 nm Full Width Half Maximum (FWHM) centered near 415, 500, 610, 665, 860, and 940 nm, and an unfiltered silicon pyranometer [*Harrison et al.*, 1994]. It uses an automated shadowbanding technique to measure the total-horizontal, diffuse-horizontal, and direct-normal spectral irradiances through a single optical path. The diffuse-horizontal irradiance represents downwelling hemispheric irradiance with an effective 160° field of view. The Langley regression of the direct-normal irradiance taken on clear stable days can be used to extrapolate the instrument's response to the top of the atmosphere, and this calibration can then be applied to all components of irradiance. Transmittances can be subsequently calculated under cloudy conditions as the ratio of the uncalibrated output to the extrapolated top-of-the-atmosphere value. The diffuse transmittance is a normalized diffuse radiation by the corresponding solar constant inferred from Langley regression. Therefore the transmittance ratio at two wavelengths is independent of absolute calibration. Accurate measurements of atmospheric transmittance from a MFRSR will ensure the accuracy of retrieval of aerosol optical depth during the clear-sky periods and cloud optical depth under cloud conditions [*Harrison et al.*, 1994; *Min and Harrison*, 1996; *Min et al.*, 2004; *Wang and Min*, 2008].

[8] Using a radiative transfer model [*Min et al.*, 2004], transmittance ratios at the two chosen nongaseous absorption wavelengths are simulated under various cloudy and clear-sky conditions for different solar zenith angles. In the simulation, surface albedos of 0.036 and 0.25 are used for 415 and 860 nm, respectively, representing normal vegetated surface. Under clear-sky conditions with climatologic background aerosols (Angstrom exponents of 1.12 and 1.58, and optical depth up to 0.35), as shown in Figure 2a, the transmittance ratio varies from 0.10 to 0.35. Changes of aerosol size and optical depth as well as solar zenith angle within the normal ranges would result in an uncertainty of about 0.1 around the clear-sky baseline of transmittance ratio. In reality, the clear-sky baseline, as well as aerosol property, can be accurately determined from the measurements during the clear-sky periods. Thus uncertainty of the clear-sky baseline should be substantially smaller.

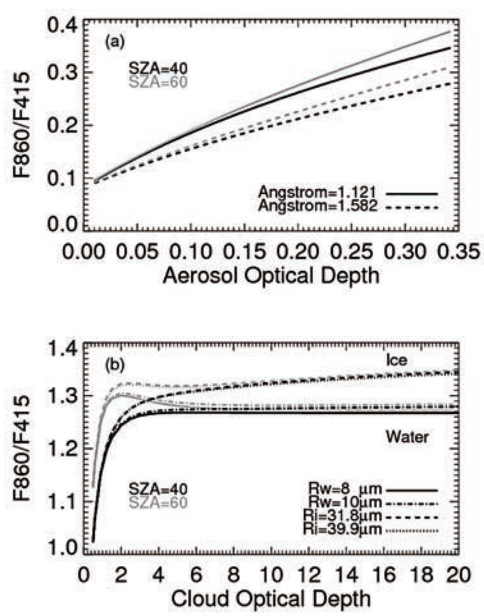

Figure 2. Simulated spectral ratios for various aerosol (a) and cloud (b) conditions.

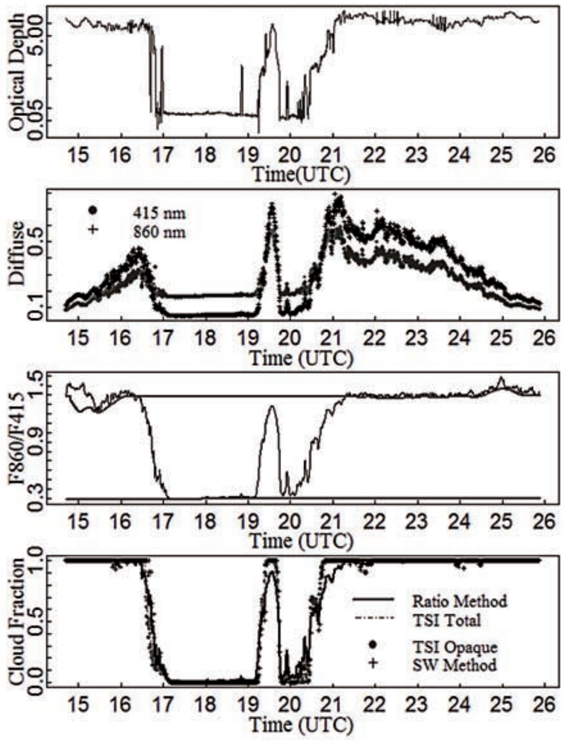

Figure 3. Retrieved aerosol and cloud optical depths (logarithmic scale), measured diffuse irradiances for 415 and 860 nm, spectral ratio and associated cloudy (the upper line) and clear-sky (the lower line) baselines, and retrieved and observed cloud fractions on 10 July 2005 at Pt. Reyes.

[9] As shown in Figure 2b, the transmittance ratio for both ice and water clouds varies from 1 to the asymptote values of 1.25 and 1.34 for water and ice clouds, respectively. The surface albedo, a, impact on diffuse irradiance can be simply parameterized as $F/(1 - a)$, where F is diffuse irradiance with the dark surface ($a = 0$). The transmittance ratio with assumed albedos of 0.036 and 0.25 for 415 and 860 nm, respectively, can expressed as

$$\left(\frac{F_{860}}{1-a_{860}}\right) \bigg/ \left(\frac{F_{415}}{1-a_{415}}\right) = \frac{F_{860}}{F_{415}}(1-a_{415})/(1-a_{860}) = 1.28 * \frac{F_{860}}{F_{415}}$$

[10] Because of $\frac{F_{860}}{F_{415}} \approx 1$ under cloudy conditions, the transmittance ratios are greater than 1 as a result of a higher surface albedo at 860 nm.

[11] It is clear that the asymptote value, reached at modest cloud optical depth of 6, is insensitive to the solar zenith angles. The difference of transmittance ratio because of a 20-degree change of solar zenith angle is about 0.01 when the cloud optical depth is greater than 6. The maximum difference of transmittance ratio because of a 20-degree change of solar zenith angle, occurred at cloud (or aerosol) optical depths between 0.35 and 3, is about 0.1. Furthermore, different effective sizes of cloud particles within the same cloud thermodynamic phase have negligible effect on the transmittance ratio. Again, the cloudy baseline of transmittance ratio can be directly determined during periods with large cloud optical depths from the time series of the measurements. Changes of cloud property (effective radius and optical depth) during broken periods will have very small effect on the localized cloudy baseline. Overall uncertainty associated with cloud, aerosol, and solar zenith angle variations using a climatologic baseline set are about 0.2, 20% of the dynamic range of transmittance ratio. Therefore the maximum uncertainty for the fractional sky cover is 20%. As pointed out previously, in reality, both clear-sky and cloudy baselines can be directly determined from the time series of measurements, and thus the uncertainty of cloud fraction retrieval should be substantially reduced. Given possible changes of cloud, aerosol, and solar zenith angle during the broken cloud periods, as estimated from real measurements, the uncertainty is estimated at about 10%.

3. Validation

[12] Validation and evaluation of retrieved products are key to showing the effectiveness of a retrieval algorithm. We processed the MFRSR measurements taken during the MArine Stratus Radiation Aerosol and Drizzle (MASRAD) field campaign at Point Reyes, California in 2005, where a Total Sky Imager (TSI) with a hemispherical field of view (FOV) was deployed and provided time series of fractional sky cover. Also the estimation of fractional sky cover from measured surface broadband SW radiation was available during the field campaign for intercomparison [*Long et al.*, 2006a]. The TSI cloud classifications are dependent on pixel color, as are clear-sky and clouds themselves depending on their optical depth. Roughly, distinctly blue pixels are labeled as clear-sky, where white/gray/dark gray colors produced by optically thick clouds are labeled as opaque cloud [*Long et al.*, 2006b]. The SW method was developed using sky imager retrievals that were carefully manually screened for consistent classification results as a training reference [*Long et al.*, 2006a]. The SW retrieval methodology uses the effect of clouds on the diffuse downwelling SW (measured minus clear-sky diffuse SW), normalized by the corresponding clear-sky downwelling total SW to remove the solar zenith angle dependence. Thus rather than a pixel-by-pixel determination of cloud/no cloud associated with sky imager retrievals, the aggregate hemispheric effect on the downwelling SW irradiance is used to estimate sky cover. Thus the SW method is far more similar to the MFRSR method described here than are sky imager retrievals.

[13] 10 July 2005 was a partly cloudy day, with overcast conditions occurring in both early morning and afternoon and several hours of clear-sky periods in between. The sum of aerosol optical depth and cloud optical depth, retrieved from direct and global radiation measurements [*Min and Harrison*, 1996; *Min et al.*, 2004; *Wang and Min*, 2008], shown in Figure 3a, varied from 18.5 to 0.05. The diffuse radiation at 860 nm, shown in Figure 3b, changed from greater than to less than the diffuse radiation at 415 nm, corresponding to the atmospheric optical depth variation. Although the diffuse radiation at both 415 and 860 nm varied systematically with solar zenith angle (Figure 3b), the ratio between the two was fairly constant at a value of 1.38

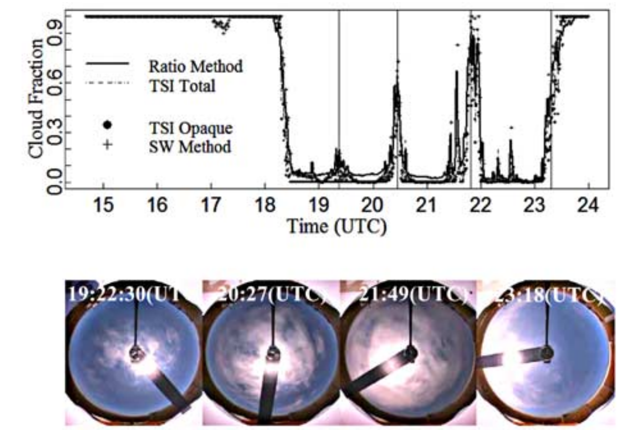

Figure 4. Retrieved and observed cloud fractions and corresponding TSI cloud imagers on 8 July 2005 at Pt Reyes.

when cloud optical depths were greater than 6 (Figure 3c). This result verifies our assertion in the sensitivity study that transmittance ratio approaches an asymptote value for thick clouds and such a value is insensitive to the solar zenith angle as the solar zenith angle varied from 17 to 75 degrees. Therefore the cloudy baseline is defined as the minimum value during overcast thick cloud periods.

[14] Clouds generally change much more rapidly than clear-sky aerosols, allowing one to distinguish clear-sky periods based on temporal variation of atmospheric optical depth derived from direct beam measurements. In practice we define a clear-sky period as the standard deviation of optical depths inferred from direct beam radiation during the period is less than 0.01, which implies that the detection threshold of minimal cloud optical depth is 0.01. The retrieved aerosol optical depths between 17:20 to 19:00 UTC were about 0.06 with very small variation (less than 0.006), combined with the low values and small variation of diffuse transmittance, indicating it was a clear-sky period. The mean transmittance ratio of 0.30 during the period therefore is defined as the clear-sky baseline. Thus, for a typical broken cloudy day, both clear-sky and cloudy baselines are determined directly from the time series of measurements. As surface albedos will not change dramatically in days, if a day has no long-term (∼one hour) clear-sky or overcast cloudy periods to define the baseline, the baselines defined before or after that day will provide good estimates for the day. Furthermore, such a localized baseline procedure of the transmittance ratio does not require a good absolute calibration of the radiometer as long as the instrument is stable and has a good reproducibility at the two wavelength channels. Therefore the ratio method with the localized baseline procedure will tend to reduce the uncertainty of the sky cover retrievals.

[15] With defined baselines, the fractional sky cover is readily retrieved using equation 3. Figure 3d shows comparison among three different instruments and four different results of fractional sky cover. The TSI reports both thick opaque cloud cover and total cloud cover that includes thin clouds. In this case, the total and opaque cloud covers are the same from TSI, indicating the clouds present were opaque. It is clear that retrievals of the ratio method agree well with the other three results.

[16] 8 July 2005 is another broken cloudy day with several clear-sky periods, shown in Figure 4. Various cloud distributions in the sky, illustrated by TSI images at four particular times, are well monitored by the ratio method. Overall agreement of retrieved cloud fraction is very good with both TSI measurements and SW method, absolute differences of 0.030 and 0.028, respectively.

[17] However, there are some occasions that differences among these methods are substantial, for example on 16 March 2005, shown in Figure 5. For the cloudy condition illustrated by the TSI image at 16:24 UTC, the TSI total cloud cover is larger than the TSI opaque cloud cover, indicating some thin clouds present at the time. Both the ratio and SW methods agree with the TSI total cloud cover. However, at 17:24 and 19:30 UTC, shown in TSI images, sky cover retrieved by the ratio method agrees better with the TSI opaque sky cover and is substantially lower than the TSI total cloud cover. The SW retrievals tend to agree with results of the ratio method. The classification as thin cloud (optically thinner cloud that is blue-tinted because the clear-sky background can be seen through them) for a TSI is less robust, in part due to the proprietary auto white balance function of the commercial camera used in the TSI which adjusts the overall image color rendering dependent on how much of the image contains white pixels. In effect, less opaque cloudiness in the image produces slightly more sensitivity to optically thin clouds in the retrievals. Additionally, each camera differs slightly in image color rendering characteristics, yet the baseline clear-sky library included in the processing software was generated using one particular camera at YES headquarters in Connecticut, USA. Thus individual camera behavior and characteristics effectively make the clear/thin threshold less robust than the classification of obviously clear skies and opaque clouds. In this case, the threshold of thin clouds for the TSI algorithms may be too low, resulting in an overestimation of the total sky cover. There is a period around 20:00 UTC, however, where the four retrievals differ significantly. The differences may be due in part to previously discussed threshold issues of thin and opaque clouds and different effective fields of view of the three instruments. The retrievals of the ratio

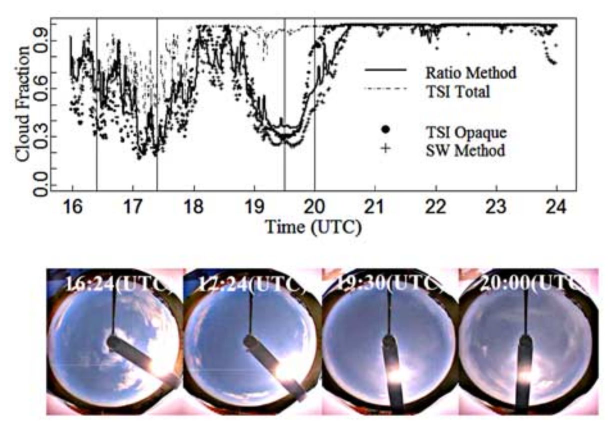

Figure 5. Retrieved and observed cloud fractions and corresponding TSI cloud imagers on 16 March 2005 at Pt Reyes.

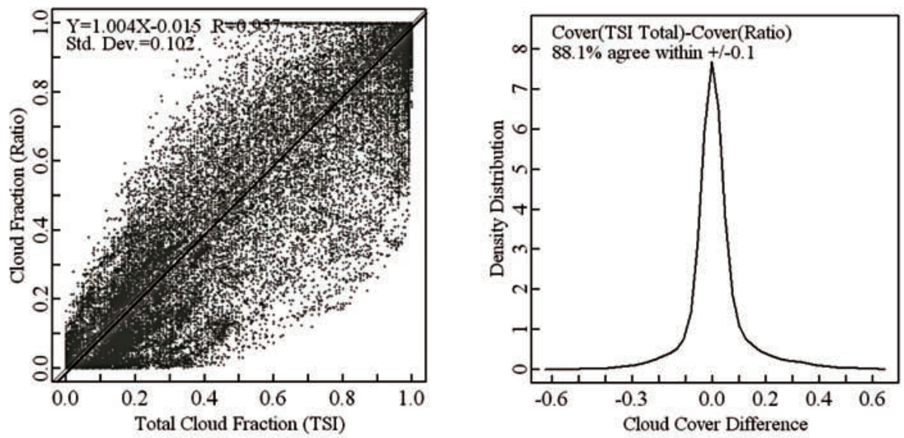

Figure 6. Scatterplot of TSI measurements and retrieved cloud fraction from spectral ratio method, and cloud fraction difference distribution for the entire field campaign.

method lie in between the TSI and SW values, and are closer to the SW retrievals.

[18] While the case studies provide insight on the performance of this new retrieval algorithm, a more extensive evaluation is required. Statistical evaluation has been conducted using measurements over the entire MASRAD field campaign from March to September 2005. Since different instruments have different sampling rates, synchronization of measurements and data quality control have been applied to produce a 1-minute sky cover data set with 85498 samples from all three instruments. Figure 6 shows the comparison between TSI total sky cover and the ratio-method retrievals. The slope of regression is 1.004 with an intercept of 0.015, indicating our assumption of linear partition between cloud transmittance ratio and clear-sky transmittance ratio is practical. The correlation coefficient is 0.957 with a standard deviation of 0.102 and a mean bias of 0.02. These statistics indicate good agreement between the two methods. As shown in Figure 6b, over 88.1% of data samples agree within 0.1. The residual differences may be due to (1) different sensitivities to very thin clouds; (2) different FOVs; and (3) the calibration issue of TSI.

[19] The statistics between the ratio and SW methods, shown in Figure 7, have a better correlation coefficient (0.975) and smaller standard deviation (0.075) with a slightly smaller slope (0.961) than that between TSI and ratio methods. Over 92.5% of the samples have a difference smaller than 0.1. The better agreement between the ratio and SW methods is not surprising, given that both methods are based on radiometry measurements. Nonetheless these longer-term comparisons demonstrate that the simple ratio method provides a good estimate of fractional sky cover under various conditions.

4. Discussion and Conclusion

[20] Clouds remain the greatest sources of uncertainty in global climate change research. Changes in cloud amount through climate feedback may well be one of the signs of climate change. It is crucial to accurately monitor fractional sky cover with high spatial and temporal resolution globally. In this study, a ratio method for estimating fractional sky cover from spectral radiation measurements has been proposed. It is based on spectral characteristics of clouds and clear-sky aerosols to partition sky fraction. As illustrated

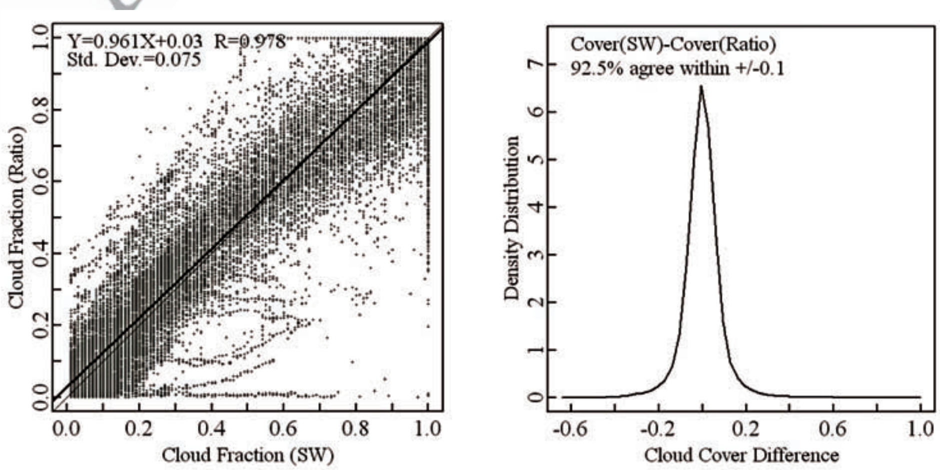

Figure 7. Scatterplot of retrieved cloud fraction from spectral ratio method and SW method, and cloud fraction difference distribution for the entire field campaign.

in our sensitivity study and demonstrated in real measurement comparisons, the transmittance ratio at selected wavelengths is insensitive to solar zenith angle and major atmospheric gaseous absorption. With a localized baseline procedure, retrievals of this ratio method are independent of absolute calibration and weakly sensitive to changes of cloud and aerosol optical properties, and thus substantially reduce the retrieval uncertainty. The uncertainty of this ratio method once localized, estimated through sensitivity study and intercomparison, is less than 10%.

[21] Narrowband spectral measurements are now widely available, for example, hundreds of MFRSRs have been deployed globally. This simple ratio method will substantially enhance current capability of monitoring fractional sky cover in large geographic distribution, providing a great opportunity to monitor climate change in terms of cloud amount.

[22] **Acknowledgments.** This research was supported by the Office of Science (BER), U.S. Department of Energy, Grant DE-FG02-03ER63531, and by the NOAA Educational Partnership Program with Minority Serving Institutions (EPP/MSI) under cooperative agreements NA17AE1625 and NA17AE1623. Surface data were obtained from the Atmospheric Radiation Measurement (ARM) Program sponsored by the U.S. Department of Energy, Office of Energy Research, Office of Health and Environmental Research, Environmental Sciences Division.

References

Angstrom, A. (1929), On the transmission of sun radiation and on dust in the air, *Geogr. Ann.*, *2*, 156–166.
Clothiaux, E., et al. (1999), The atmospheric radiation measurement program cloud radars: Operational modes, *J. Atmos. Sci.*, *56*, 819–827.
Fairall, C., and J. Hare (1990), An eight-month sample of marine stratocumulus cloud fraction, albedo and integrated liquid water, *J. Clim.*, *3*, 847–864.
Harrison, L. C., J. J. Michalsky, and J. Berndt (1994), Automated multifilter rotating shadowband radiometer: An instrument for optical depth and radiation measurements, *Appl. Opt.*, *33*(22), 5118–5125.
IPCC (2007), Climate Change.
Long, C. N., and T. P. Ackerman (2000), Identification of clear skies from broadband pyranometer measurements and calculation of downwelling shortwave cloud effects, *J. Geophys. Res.*, *105*(D12), 15,609–15,626.
Long, C. N., T. P. Ackerman, K. L. Gaustad, and J. N. S. Cole (2006a), Estimation of fractional sky cover from broadband shortwave radiometer measurements, *J. Geophys. Res.*, *111*, D11204, doi:10.1029/2005JD006475.
Long, C. N., J. M. Sabburg, J. Calbo, and D. Pages (2006b), Retrieving cloud characteristics from ground-based daytime color all-sky images, *J. Tech.*, *23*(5), 633–652.
Min, Q. L., and L. C. Harrison (1996), Cloud properties derived from surface MFRSR measurements and comparison with GOES results at the ARM SGP site, *Geophys. Res. Lett.*, *23*(13), 1641–1644.
Min, Q., E. Joseph, and M. Duan (2004), Retrievals of thin cloud optical depth form a multifilter rotating shadowband radiometer, *J. Geophys. Res.*, *109*, D02201, doi:10.1029/2003JD003964.
Minnis, P. (1989), Viewing zenith angle dependence of cloudiness determined from coincident GOES EAST and GOES WEST data, *J. Geophys. Res.*, *94*(D2), 2303–2320.
Pfister, G., R. L. McKenzie, J. B. Liley, A. Thomas, B. W. Forgan, and C. N. Long (2003), Cloud coverage based on all-sky imaging and its impact on surface solar irradiance, *J. Appl. Meteorol.*, *42*(10), 1421–1434.
Randall, D., J. Coakley Jr., C. Fairall, R. Kropfli, and D. Lenschow (1984), Outlook for research on subtropical marine stratiform clouds, *Bull. Am. Meteorol. Soc.*, *65*, 1290–1301.
Rossow, W., A. Walker, and L. Garder (1993), Comparison of ISCCP and other cloud amounts, *J. Clim.*, *6*, 2394–2418.
Wang, T., and Q. Min (2008), Retrieving optical depths of optically thin and mixed-phase clouds from MFRSR measurements, *J. Geophys. Res.*, doi:10.1029/2008JD009958, in press.

M. Duan, Institute of Atmospheric Physics, Chinese Academy of Science, Beijing, China.
C. N. Long, Pacific Northwest National Laboratory, Richland, WA, USA.
Q. Min and T. Wang, Atmospheric Sciences Research Center, State University of New York, Room L215, 251 Fuller Road, Albany, NY 12203, USA. (min@asrc.cestm.albany.edu)

American Geophysical Union
Author Query Form

Journal: **Journal of Geophysical Research - Atmospheres**
Article Name: Min **(2008JD010278)**

Please answer all author queries.

1. Please provide division/department of affiliation 3.

2. Please provide complete mailing address (building/street address/department/division/PO Box/postal code) of authors M. Duan and C.N. Long.

3. Please provide complete reference information of reference "*IPCC*, 2007".

4. Please check if journal title of reference "*Long et al.*, 2006b" was captured correctly.