Detecting Thin Cirrus from MISR with Oblique Camera Analysis

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Abstract – We report improved detection of thin cirrus clouds over clear ocean in the Tropics using oblique camera stereo retrieval of cloud-top heights (CTH) from the Multiangle Imaging SpectroRadiometer (MISR) instrument on the Terra Satellite. MISR misses thin cirrus clouds of optical depth < 0.3 with its standard nadir stereo processing. Thin cirrus is transparent to incoming solar radiation but is sensitive to the outgoing longwave radiation (OLR). The differences in modeled and measured thermal irradiance emitted to space is used to compute the fractional cover and optical depth of thin cirrus over clear ocean using MISR oblique derived heights corrected for winds and parallax. For special cases over clear skies in the Tropics, the differences between modeled and measured OLR (Cirrus Forcing) is ≈ 17W/m^2. This can be accounted for with the addition of thin cirrus of coverage 60%.

Keywords: Cirrus, Cloud-Heights, Cloud-Radiative-Forcing

1. INTRODUCTION

Cirrus clouds play a major role in the Earth's climate system. Thin, high cirrus are especially important. They have relatively low albedos, a strong greenhouse effect due to their high altitudes and low emission temperatures, and tend to warm the climate system. These clouds contribute as one of the leading sources of uncertainty in the study of global radiation budgets (Liou, 1986). Unlike water clouds, high level cirrus contain a significant amount of large, nonspherical ice crystals having low concentrations that are optically thin. The amount of sunlight that cirrus clouds reflect, absorb, and transmit depends on their coverage, position, thickness, and ice crystal size and shape distributions. Cirrus clouds can also reflect and transmit the thermal infrared emitted from the surface and the atmosphere and, at the same time, emit infrared radiation according to their temperature structure. The ice crystal size and shape distributions and cloud thickness are fundamental cirrus parameters that determine the relative strength of the solar-albedo and infrared-greenhouse effects. To comprehend the impact of cirrus clouds on the radiation field of the Earth and the atmosphere and thus climate, the term "cloud radiative forcing" is used to quantify the relative significance of the solar-albedo and infrared-greenhouse effects. Cloud radiative forcing is the difference between the radiative fluxes at the top of the atmosphere in clear and cloudy conditions.

Based on theoretical calculations, it has been shown that the infrared greenhouse effect for cirrus clouds generally outweighs their solar albedo counterpart. Hartmann et al. (2001) examined various cloud types of the International Satellite Cloud Climatology Project (ISCCP) and found that individual convective cloud elements have a strong positive effect on the longwave (LW) radiation and a strong negative effect on the shortwave (SW) radiation. On the basis of satellite-observed radiation and clouds, numerous studies suggest that, in tropical regions, the SW and LW contributions to cloud radiative effects (CRE) almost cancel each other in the aggregate. However, there remain reasons to question this apparent cancellation, and some studies have proposed could feedbacks that rely on the changes in the distribution of cloud types, particularly optically thick or thin cirrus be related to deep convection (Ramanathan and Collins, 1991). Clearly, in order to understand the extent to which various regulatory hypotheses can operate in a real climate system, it is necessary to establish the actual radiative effects of cirrus clouds with varying optical depths in terms of their relative distribution as well as the changes in their absolute amounts (Choi and Ho, 2006).

Climate models have illustrated that high clouds that move higher in the atmosphere could exert a positive feedback, amplifying the temperature increase. However, the extent and degree of this feedback and temperature amplification have not been reliably quantified. The prediction of cirrus cloud cover and position based on physical principles is a difficult task, and successful prediction using climate models has been limited. This difficulty is also associated with the uncertainties and limitations of inferring cirrus cloud cover and position from current satellite radiometers. In fact, there is not sufficient cirrus cloud data to correlate with the greenhouse warming that has occurred so far (Liou, 1986).

Over the past two decade or so, visible-IR bispectral techniques (Minnis et al, 1990) and multispectral technique (Wylie and Menzel, 1989) have been developed and improved for retrieving cirrus coverage, altitudes, and optical depths from operational satellite measurements. But almost all satellites observe in the visible and 10-12 μm IR atmospheric window region, and thin cirrus clouds are particularly difficult to detect in these regions because of their lack of opacity and consequent small perturbation on the high background signal (Wylie and Menzel, 1989). However, the identification of an optically very thin cirrus (τ<<1) in the upper troposphere was resolved to a great extent by a cirrus detection method incorporating a 1.38-mm reflectance from a Moderate Resolution Imaging Spectroradiometer (MODIS) instrument (Gao et al, 2002; Meyer et al, 2004). The 1.38-mm channel was specially designed to detect thin cirrus. However, with this method there were errors involved in retrieving the optical depth that introduced uncertainties. Other active methods, such as lidars, can detect thin clouds with unprecedented resolution (Winker and Trepte, 1998; Nee et al., 1998; McFarquhar et al., 2000; Sassen and Cho, 1992), but these data are presently limited in both time and space.

2. MISR STEREO MATCHING

The Multi-angle Imaging SpectroRadiometer (MISR) instrument launched into the sun-synchronous polar orbit aboard Terra views the Earth simultaneously at nine widely spaced angles and provides radiometrically and geometrically calibrated images in four spectral bands at each of the angles. MISR can detect clouds from changes in reflection at different viewing angles and can determine the height of such clouds using stereoscopic techniques. A significant advantage of the MISR CTH retrieval is that the technique is purely geometric and has little sensitivity to the sensor calibration. Di Girolamo and Davies (1994) developed a new approach to cirrus cloud detection that used the differences between two solar spectral reflectances as a function of view angle. The resulting band-differenced angular signature (BDAS) was sensitive to Rayleigh scattering from above the top of the clouds and was used to discriminate high clouds from lower level clouds and clear sky. BDAS was found to work best over ocean and snow surfaces with minimum detectable cloud optical thickness of 0.5. As we see in Figure 1, the radiometric images obtained from different cameras show different sensitivity to thin cirrus.

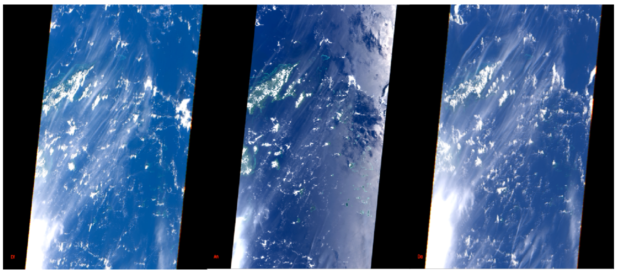

Figure 1. Clouds seen from different cameras (Orbit 6168)

MISR's nadir (An) view misses thin high cloud while the oblique cameras (Df and Da) show increased detection due to an increased optical path length with each view. The standard MISR stereo product uses the near nadir camera pairs as inputs to the stereo matching algorithm for height retrievals. However, the standard product produced heights that missed high thin cirrus. Therefore, the stereo codes were rerun with the oblique cameras as inputs to the stereo matching algorithm to produce new oblique analyzed stereo product.

3. DATA

In this study, thin cirrus detection required stereo heights produced from MISR. The standard MISR Level 2 TOA/Cloud Stereo-MIL2TCST product was compared to the oblique analyzed stereo product. To quantify the cirrus detected from oblique analysis (OA), the merged Single Scanner Footprint TOA/Surface Fluxes and Clouds (SSF) dataset was used. The SSF product contains one hour of instantaneous Clouds and the Earth's Radiant Energy System (CERES) data. The SSF combines instantaneous CERES data with scene information from Moderate-Resolution Imaging Spectroradiometer (MODIS) on Terra. It includes surface fluxes and cloud optical properties. The CERES-MISR-MODIS SSF-SSFM data set integrates measurements from CERES, MISR and MODIS by matching MISR pixels in the footprint domain. The retrieval is performed for all merged CERES, MISR and MODIS data between 20°S and 20°N latitudes from years 2000 to 2004. The CERES footprints had a resolution of 20 km at Nadir. The NCEP Reanalysis dataset was used for the temperature and atmospheric water vapor profiles for the radiative transfer modeling of each footprint while the u and v components of winds allowed for corrections to stereo retrievals due to cloud motion.

4. METHODOLOGY

Oblique analysis enhances thin cirrus detection by MISR. However, these heights are geo-registered with respect to the oblique camera. Moreover, the time difference between alternate cameras allows time for cloud movement due to winds. Mapping the oblique stereo heights onto the nadir camera requires corrections for parallax and cloud motion due to winds. The "preliminary feature-referenced stereo height without winds" dataset is used to correct for parallax. To make corrections for winds, the across-track and along-track cloud motion is accounted for using the relevant NCEP wind vectors. After these corrections, all heights beyond 10km get screened for clear skies within the CERES-MISR-MODIS merged dataset.

Thin cirrus is sensitive to the outgoing longwave radiation since it absorbs significant amount of the terrestrial infrared radiation emitted from earth to space. It then re-emits a portion of the absorbed radiation back to the earth, enhancing the greenhouse effect. In order to quantify thin cirrus, we investigate the differences between satellite measured OLR and simulated clear sky OLR. The difference between modeled and measured OLR accounts for the presence of thin cirrus and the extent of thin cirrus forcing reflects the extent of thin cirrus present in the modeled atmosphere.

5. RESULTS

5.1 Oblique Analysis

Thin cirrus clouds reside at relatively high altitudes. To screen thin cirrus with highest probability over clear ocean in the tropics, nearly 50 specific footprints were selected that appeared to be more than 95% clear. Figure 2 depicts the mean height trends across the tropics for MISR orbit 7187.

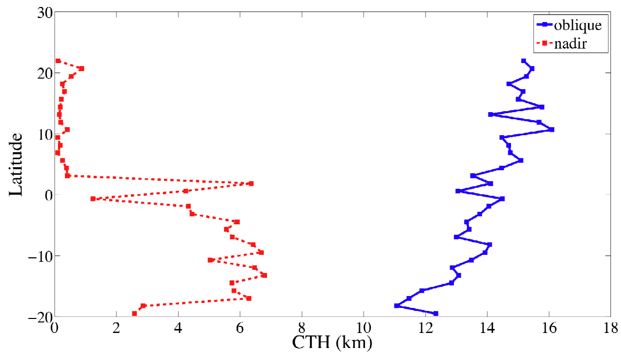

Figure 2. Mean CTH after oblique analysis

The oblique heights detect high clouds quite efficiently compared to clouds detected by the standard stereo approach. Oblique analysis is much more sensitive to CTH > 10 km while lower clouds have low magnitude of parallax which causes blunders due to the reflected radiances from edge of the clouds. The effect of sunglint can also introduce error when it gets interpreted as cloud height. In such cases, oblique analysis tends to perform better by shading out the effects of sunglint. To test the heights detected from oblique analysis, each footprint is modeled for clear skies with known atmospheric profiles and gases. The difference in OLR from the modeled and the measured footprint after adding known clouds is referred to the forcing due to thin cirrus (*CiF*). Alternatively, if there were no thin cirrus present in the footprint, the measured OLR ($OLR_{Measured}$) should be equal to the OLR from the column model (OLR_{Model}) that accounts for all the atmospheric constituents within the observed footprint.

$$CiF = OLR_{Model} - OLR_{Measured} \qquad (1)$$

5.2 Measured OLR

The merged dataset from CERES, MISR and MODIS provides an excellent platform to map OLR fluxes from CERES footprint onto the MISR and MODIS pixels. The CERES footprints are elliptical in nature with a resolution of 20km at nadir. Its resolution is dependent on the viewing zenith of CERES. The

LW flux at the top of the atmosphere is deduced from the measured longwave radiance after applying an anisotropic correction factor to it. This provides an estimate of the instantaneous thermal flux emitted to space from the centered footprint.

5.3 Modeled OLR

Chou's radiative transfer code (2001) for longwave parameterization was used to model OLR. It has a high degree of accuracy and speed that computes fluxes to within 1% of the high spectral resolution line by line calculations such as MODTRAN5. The thermal infrared spectrum is divided into nine bands (0-3000 cm^{-1}) and the parameterization includes absorption due to major gases (water vapor, CO_2, O_3) and most of the minor trace gases (CFC's, CH_4, N_2O) as well as clouds and aerosols. The NCEP reanalysis products for air temperature, specific humidity and surface temperature profiles that were coincident to the footprint location were used as inputs to the model.

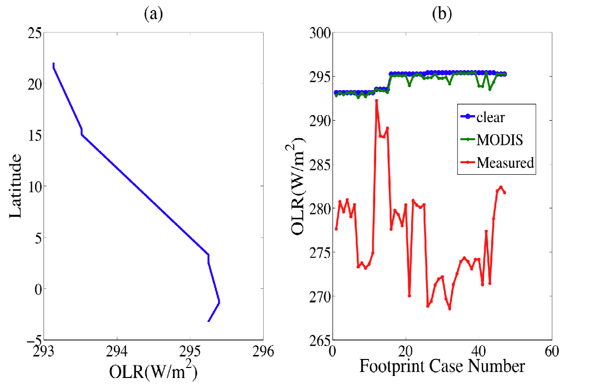

Figure 3. OLR flux for (a) Modeled clear skies latitudinal variation (b) comparison of modeled clear skies, known MODIS clouds and satellite measured.

As expected, OLR for clear sky conditions are typically higher near the equator (Figure 3(a)). The clouds in the model were aptly parameterized with cloud optical depth and cloud fractional amount. For the footprints that were not 100% clear, the known cloud properties from merged dataset were utilized. Figure 3. (b) outlines the response of the model to OLR for clear and known cloudy conditions for each of the footprint under investigation. The known clouds were MODIS high and MODIS low clouds that were bundled with the merged dataset. The parameters that defined the known clouds into the model were its height, fractional coverage and the optical depth. When compared with the measured OLR, the modeled OLR was higher in magnitude. The differences in the measured and modeled OLR had to be compensated with thin cirrus clouds.

5.4 Compensating for Cirrus Forcing

Based on Equation (1), the mean cirrus forcing for all the cases investigated was 17 Wm^{-2}. The magnitude of cirrus forcing indicates a measure of thin cirrus present. We define cirrus factor (*cf*) as the product of thin cirrus optical depth (τ) and fractional cover (*f*).

$$cf = \tau . f \qquad (2)$$

For each footprint case, the cirrus factor is calculated after compensating for the thin cirrus forcing. This is done by tuning the model for $0 < f < 1$ and $\tau < 0.3$ since MODIS picks optical depth beyond 0.3 in its cloud properties retrievals. The heights of the cirrus clouds used were the average heights detected from MISR oblique analysis within the concerned footprint. Table 1 provides a summary of all the footprints under investigation.

Table 1. Quantifying thin cirrus

Clouds	Height (km)	Cloud Fraction (%)	Optical Depth
MODIS Low	1.9 ± 0.8	16 ± 10	2 ± 1
MODIS High	9 ± 2	10 ± 9	0.6 ± 0.3
MISR (OA)	16 ± 2	60 ± 23	0.18 ± 0.07

The results suggests that MISR misses thin cirrus of optical depth less than 0.3 with its standard retrievals while oblique analysis enhances the detection of cirrus clouds to an optical depth of 0.1, which makes up around 60% of clouds present. We apply the same method to 556 orbits spanning 45 daily cases from 2000 to 2004 in the tropics. The distribution of cirrus height and forcing due to thin cirrus is shown in Figure 4. The cirrus height distribution has a mean height of 14km. The maximum cirrus heights detected are ≈ 24km as seen in Figure 4. (a). The distribution of cirrus forcing across the tropics is Gaussian in nature with a mean of 27 Wm^{-2} as indicated in Figure 4. (b). The tail ends of the distribution indicate the possible existence of multiple cirrus layers of variable optical depths that were not picked up by oblique analysis. This includes the possibility of having thinner cirrus below thicker cirrus.

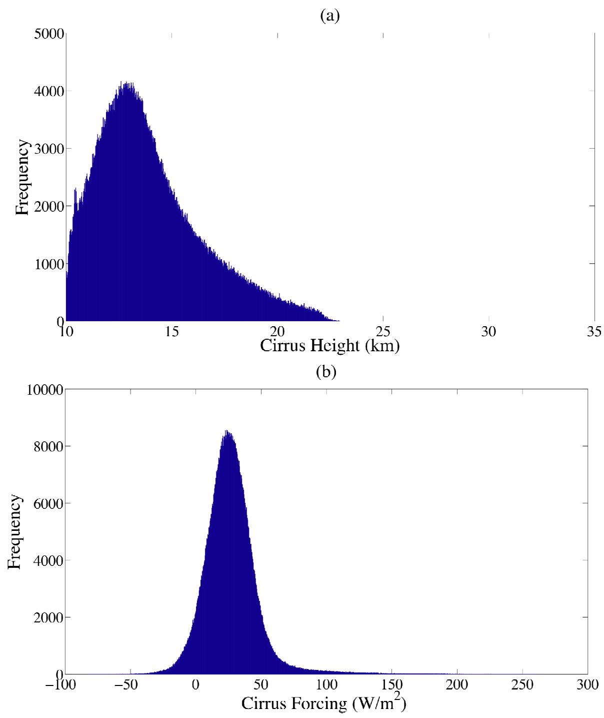

Figure 4. Frequency distribution of Tropical (a) cirrus height (b) cirrus forcing

This also opens the possibility of calculating the amount of cirrus clouds actually picked by MISR and the amount of cirrus clouds totally missed by MISR.

6. CONCLUSION

In this study, thin cirrus clouds that were typically missed by MISR standard stereo matching algorithms mainly because they were too thin get detected using oblique camera analysis. Oblique camera analysis picks thinner cirrus clouds more efficiently due to increased parallax effect resulting from high clouds. It has been shown that standard MISR misses clouds of optical depth < 0.3, but oblique analysis enhances cloud detection to an optical depth of 0.1. From the cloud heights measured by the MISR oblique analysis and by using the cloud properties from a merged CERES, MISR and MODIS dataset, we accurately calculated the amount of cirrus in a footprint by using a column model with known atmospheric profiles and clouds. For the tropics, thin cirrus missed over clear skies amounts to 60%. This accounts for a longwave forcing of 17 Wm^{-2} due to thin cirrus clouds.

The distribution of cirrus forcing reflects the distribution of cirrus factor. The model itself is fairly sensitive to optical depth and the cloud fraction. However, the cirrus factor provides a clear means of stratifying cirrus clouds. The maximum cirrus heights detected were 24km. The model versus measured approach for OLR can be used to precisely quantify cirrus. This study would be used to determine the effects of thin cirrus on the long-term cloud height trends from MISR. Future work also involves investigation of tropical cirrus forcing on the sea-surface temperature.

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