

Retrieval of Mass and Sizes of Particles in Sandstorms Using Two MODIS IR Bands: A Case Study of April 7 2001 Sandstorm in China

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Abstract

A thermal infrared remote sensing retrieval method developed by Wen and Rose [1994], which retrieves particle sizes, optical depth, and total masses of silicate particles in the volcanic cloud, was applied to an April 07, 2001 sandstorm over northern China, using MODIS. Results indicate that the area of the dust cloud observed was 1.34 million km^2 , the mean particle radius of the dust was $1.44 \mu\text{m}$, and the mean optical depth at $11 \mu\text{m}$ was 0.79. The mean burden of dust was approximately $4.8 \text{ tons}/\text{km}^2$ and the main portion of the dust storm on April 07, 2001 contained 6.5 million tons of dust. The results are supported by both independent remote sensing data (TOMS) and in-situ data for a similar event in 1998. This paper demonstrates that Wen and Rose's retrieval method could be successfully applied to past and future sandstorm events using IR channels of AVHRR, GOES or MODIS.

Introduction

Upwelling thermal infrared radiation between 10 and $12 \mu\text{m}$ from the earth's surface is selectively scattered and absorbed by airborne particles. Volcanologists have found that clouds with silicate ash can be discriminated by using the dual thermal infrared bands found on meteorological satellites [Prata, 1989a], because ice or liquid water particles preferentially absorb longer wavelengths while silicates preferentially absorb shorter wavelengths (Figure 1). Silicate particles in the size range of 1 - $15 \mu\text{m}$ in diameter cause a

negative brightness temperature difference (BTD<0) between 10 μm and 12 μm for the volcanic cloud region with the longer wavelength channel recording a higher brightness temperature. Using BTD to discriminate the volcanic cloud from meteorological clouds is called the “split window” method [Prata, 1989a]. Wen & Rose [1994] adapted this method to retrieve particle sizes, cloud optical depth and ash mass in volcanic clouds from thermal infrared satellite data, such as the data collected by GOES (Geostationary Operational Environmental Satellites), AVHRR (Advanced Very High Resolution Radiometer), and MODIS (Moderate Resolution Imaging Spectroradiometer) detectors.

Sandstorms contain large amounts of dust and sand particles which are mainly silicates and present health and transportation hazards. Many dust aerosols are small enough to be inhaled and deposit in the alveolar region of the lung which can cause serious health problems (U. S. Environmental Protection Agency, 1995). Thick dust reduces visibility and can make it hazardous to travel by air or road. For Asian dust transported to the West Coast of North America, about 30-50% of the dust mass has a diameter of 2.5 μm [McKendry *et al.*, 2001], which represents a significant public health hazard (especially to people with chronic respiratory problems) [Simpson *et al.*, 2003].

Remote sensing has been successfully used to detect and monitor the location and the trajectories of sandstorms [Zheng, *et al.*, 1998, Simpson, *et al.*, 2003]. Sokolik [2002] recently studied how the loading and composition of dust affects IR radiances observed by satellite sensors and found that mineral dust has a unique radiative signature which separates the effect of dust from that of clouds and gases. Because we know from laboratory work [e.g. Walter & Salisbury, 1989] that both volcanic glass and most silicate minerals including quartz and feldspar have “reststrahlen” absorption effects, related to

the Si-O bonds, that will produce $BTD < 0$ effects, we have decided to apply the quantitative retrievals developed for volcanic clouds to dust clouds. We note that work by Sokolik [2002] has demonstrated that the detection of sand storms using MODIS data is optimized by using 8.6 μm data. In this study we do not use 8.6 μm data because our method is designed for volcanic clouds which also contain SO_2 . It is not based on the 8.6 μm band because SO_2 absorption is strong at that wavelength and causes an interference with ash detection. Since sandstorms do not contain anomalous SO_2 , it is likely that algorithms using that channel should be investigated.

The MODIS was launched in December 1999 aboard the Terra satellite. It has a spatial resolution of 1 km (channels 8-36) at nadir and 36 spectral channels. Channel 31 and 32 (centered at 11.03 and 12.02 μm) are used to analyze the dust cloud in this paper.

April 07, 2001 Sandstorm in China

Sandstorms are well-known phenomena during the springtime in China. The sources of the dust are from the deserts of Mongolia and China [Zheng *et al.*, 1998]. On April 6 and 7, 2001, a series of huge sandstorm events developed over Mongolia, spread to the Inner Mongolia region of China, and swept across northern China. This was the strongest sandstorm in China during the 2001 springtime [http://www.enviroinfo.org.cn/Disasters/Sand_storm/index.html], and affected a large area of China. The visibility in Erlianhaote City (Inner Mongolia province) was less than 50 meters, and the maximum instantaneous wind speed in that region reached 30 m/s (Xinhua News Agency, April 08, 2001). Large dust clouds and powerful gales made the visibility very low, many stores were closed and some airline flights had to be cancelled during that time. This sandstorm reached the U.S. two weeks later, blanketing areas from

Canada to Arizona with a layer of fine particles

(<http://www.noaanews.noaa.gov/stories/s624.htm>).

Methodology

Our retrieval of the particle sizes, optical depth, and total masses of particles from infrared two-band data follows the methods of Wen and Rose [1994]. Radiative transfer calculations were used with a semitransparent cloud model based on three assumptions: the shapes of the particles are spherical, the particle size distribution is uniform and monodisperse within each pixel, and the cloud forms a well-defined homogeneous single layer in each pixel [Wen and Rose, 1994]. The BTM retrieval method assumes that the particle is within the Mie region (about 1-15 μm diameter) [Prata, 1989b]. Accurate retrievals of silicates require knowledge of refraction index data for the silicate minerals. For volcanic cloud work we use data from Pollack et al. [1973], but for the dust clouds we use refraction index data for Sahara dust [Volz, 1973].

In situ data for this sandstorm event have not yet appeared in the literature. However, major element analysis of Chinese dust indicate the dust contains 60% wt of SiO_2 [Goudie, 1978]. We use the physical characteristics and the chemical composition of Asian dust observed from in-situ observations for an event in April 1998 [Simpson et al., 2003]. The observed dust size distribution had a sharp peak between 1-5 μm with a mean diameter of 2 μm [Chun et al., 2001]. The chemical composition of the dust was described by SEM X-ray analysis as containing Si, Fe, Al, and Ca [McKendry et al., 2001]. The particle size distribution and the chemical composition of the Asian dust are broadly similar to andesitic volcanic ash, which could produce a strong negative BTM signal and could discriminate the dust cloud from meteorological clouds. Using Sahara

dust refractive index data, we assume that the dust particle size, total dust mass in the dust cloud and the optical depth of the Chinese dust cloud could be retrieved by Wen and Rose's method [Wen and Rose, 1994].

Preliminary results and analyses

The “split window” method was used to discriminate the April 07, 2001 dust cloud. In the MODIS band31-band32 image (Figure 2a), the strong negative BTD signals that indicate the dust cloud covered the Northern-east area of China. The box in Figure 2 (a) is the study area we selected, about 2 million km². Figure 2 (b) shows the near simultaneous aerosol index (AI) image obtained from TOMS (Total Ozone Mapping Spectrometer) satellite data. The AI is the difference of the measured and theoretical N-values at 340 and 380 nm, and can represent the amount of silicate aerosol within the cloud qualitatively [Krotkov et al., 1997]. Higher AI values reflect larger amounts of silicate aerosols in the cloud [Seftor et al., 1997]. The high aerosol index values and general distribution of the cloud in NE China are in good agreement with the MODIS retrieval shown in Figure 2 (a). An enhanced visible wavelength MODIS image made by Prata [2003, personal communication] showed the dust cloud has the same shape as Figure 2 (a).

The temperature difference and brightness temperatures at 11.03 μm for individual pixel values are shown in Figure 3, indicating a large proportion of pixels with negative BTD values. The lookup table of the effective radius and optical depth are also shown in Figure 3. The cloud temperature and the temperature of the surface below the cloud were determined by MODIS brightness temperature image [Wen and Rose, 1994], which were 230K and 290K respectively. The parameters used in the retrieval are summarized in

Table 1.

The retrieval results indicate a total of 53,514 pixels within the dust cutoff criteria ($BTD < -0.5K$) of the study area, corresponding to 1.34 million km^2 covered by the sandstorm at 02:40 UTC, April 07, 2001. The mean particle radius is 1.44 μm and the mean optical depth at 11 μm is 0.79. The mean particle radius obtained here is within the 1-5 μm diameter range observed for the large 1998 dust storm event by Chun et al. [2001]. Our MODIS retrieval results are compared with analogous studies in Table 2. The mean burden of the dust is 4.8 tons/km^2 and the dust mass in the imaged dust storm on April 07, 2001 is estimated at 6.5 million tons. We emphasize that this mass estimate is not the total for this dust storm, because the MODIS image does not completely cover the area of the storm. For comparison, we recalculated the mean optical depth, particle radius and mass using refractive index data from quartz [Spitzer, 1961; Holland et al., 1975] and derived values of 1.16, 1.25 μm , and 8.4 million tons (Table 2). Thus the mass retrievals of the dust cloud are not significantly different if different refractive index values are used. These results may be compared with the total annual dust emission of 25 million tons and the spring season estimates of 15 million tons in the Northern China area using a “U.S. EPA formula” [Xuan, 1999; Xuan et al., 2000]. Table 3 lists error ranges in the mass retrievals based on different refractive indices, particle size distribution, shape of the particles, surface temperature, and cloud temperature. This shows that estimates of mass using this technique have precision errors (1σ) of the order of $\pm 10 - 40\%$, because of uncertainties and assumptions.

Conclusion

The mass and sizes of the particles in large Chinese sandstorms can be retrieved using

two IR bands from MODIS. Spatial mapping of the cloud with MODIS agrees with ultraviolet remote sensing data (TOMS) and with in-situ observations of a similar event in 1998. This paper demonstrates that two band “split window” retrievals of dust events could be used to routinely quantify the intensity of the past and future sandstorm events. Because we can measure the mass and synoptic area of dust clouds, the degree of the hazard caused by the sandstorm could potentially be rapidly evaluated by remote sensing data using this method and serve as a warning system of detection. The major uncertainty for this technique comes from lack of data for IR refractive index of Chinese dust. In-situ sample collection and the laboratory study of measuring the refractive index of Chinese dust are suggested for future work.

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Figure captions:

Figure 1. Schematic diagram showing how two band thermal IR transmission through meteorological and ash laden volcanic clouds is different. Bands 4 and 5 refer to AVHRR or GOES detectors; the equivalent bands for MODIS are 31 and 32 respectively.

Figure 2(a). MODIS BTM (band31-band32) image at 02:40 UTC, April 07, 2001, showing the dust cloud distribution over northern China.

Figure 2(b). TOMS ultraviolet aerosol index image on April 07, 2001. The Chinese dust cloud is observed in two orbits at 01:45 UTC and 03:23 UTC respectively. High AI values, which represent larger amount of silicate aerosol in the cloud, show a similar pattern to the infrared image in Figure 2a.

Figure 3. The temperature difference and brightness temperatures at 11.03 μm for individual pixel values (red dots) in MODIS data indicating a large proportion of pixels with negative BTM values.

Table 1. The parameters used in the retrieval process.

Total study area (million km ²)	2.09
Cloud temperature (Kelvin)	230.00
Temperature of surface below cloud (Kelvin)	290.00
Central wavelength of band31 (μm)	11.03
Central wavelength of band32 (μm)	12.02
Specific gravity of Sahara dust (g/cm ³)	2.50
Refractive index of Sahara dust at Band31	1.860 + 0.302i
Refractive index of Sahara dust at Band32	1.800 + 0.182i
Refractive index of quartz at Band31	2.021 + 0.016i
Refractive index of quartz at Band32	1.437 + 0.222i

Table 2. Retrieval results and compare with the other sources

	Retrieval results (Sahara dust)	Retrieval results (Quartz)	Other sources
Number of dust pixels (BTD<-0.5K)	53514	53514	
Total area of dust cloud (Million km ²)	1.34	1.34	
Mean Particle Radius (μm)	1.44	1.25	~1.0 ¹
Pixel Mean Optical Depth (at 11 μm)	0.79	1.16	~3.2 ² (at 500 nm)
Pixel Mean Mass (Metric tons)	120.80	156.75	
Total Dust Mass (Million tons)	6.46	8.39	~15.0 ³

¹ From April, 1998 Asia dust storm [*Chun, et al., 2001*].

² Mean aerosol optical depth (at 500 nm) in the early morning of April 08, 2001 at XiangHe station, China [<http://aeronet.gsfc.nasa.gov>].

³ Total dust loading in spring season [*Xuan, et al., 2000*].

Table 3. Error analysis of the mass loading retrieval based on using different refractive indices, particle size distribution, particle shape, surface temperature and cloud temperature.

Parameters	Resulting error range in total mass retrieval	Source
Refractive index	9-13%	Wen & Rose [1994] and this study
Particle size distribution	17-32%	Wen & Rose [1994]
Particle shape	5-20% *	Krotkov et al. [1999]
Surface temperature (5K change)	10-34%	Schneider et al. [1999]
Cloud temperature (10K change)	7-10%	this study

* The effects of particle shape are not well known. We know from Okada et al. [2001] that Chinese sandstorm particles have aspect ratios of 1.3 to 1.4. We also know that volcanic ash particles with similar aspect ratios (1.5) produce slight inaccuracy in UV retrievals [Krotkov et al., 1999]. But we are unsure of the effects of IR retrievals.

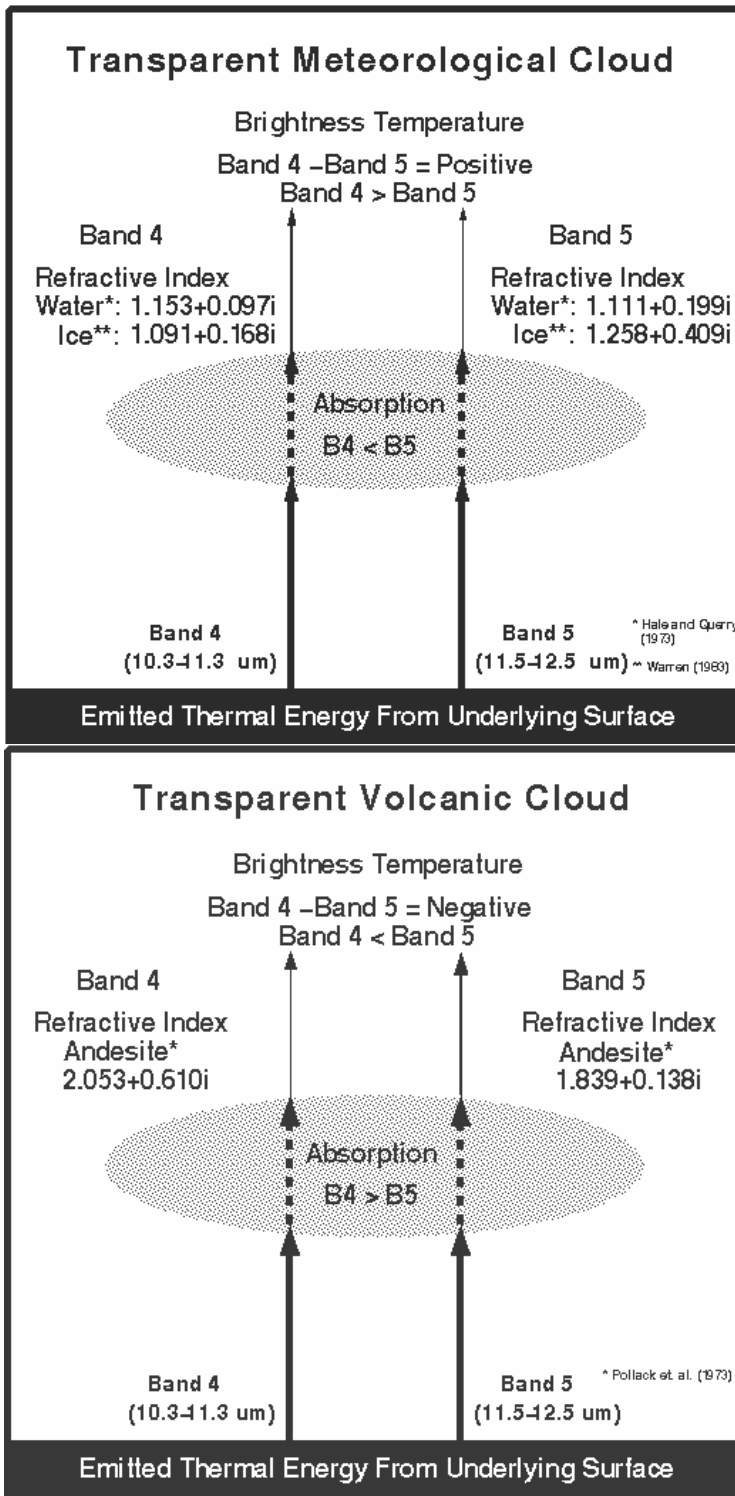


Figure 1

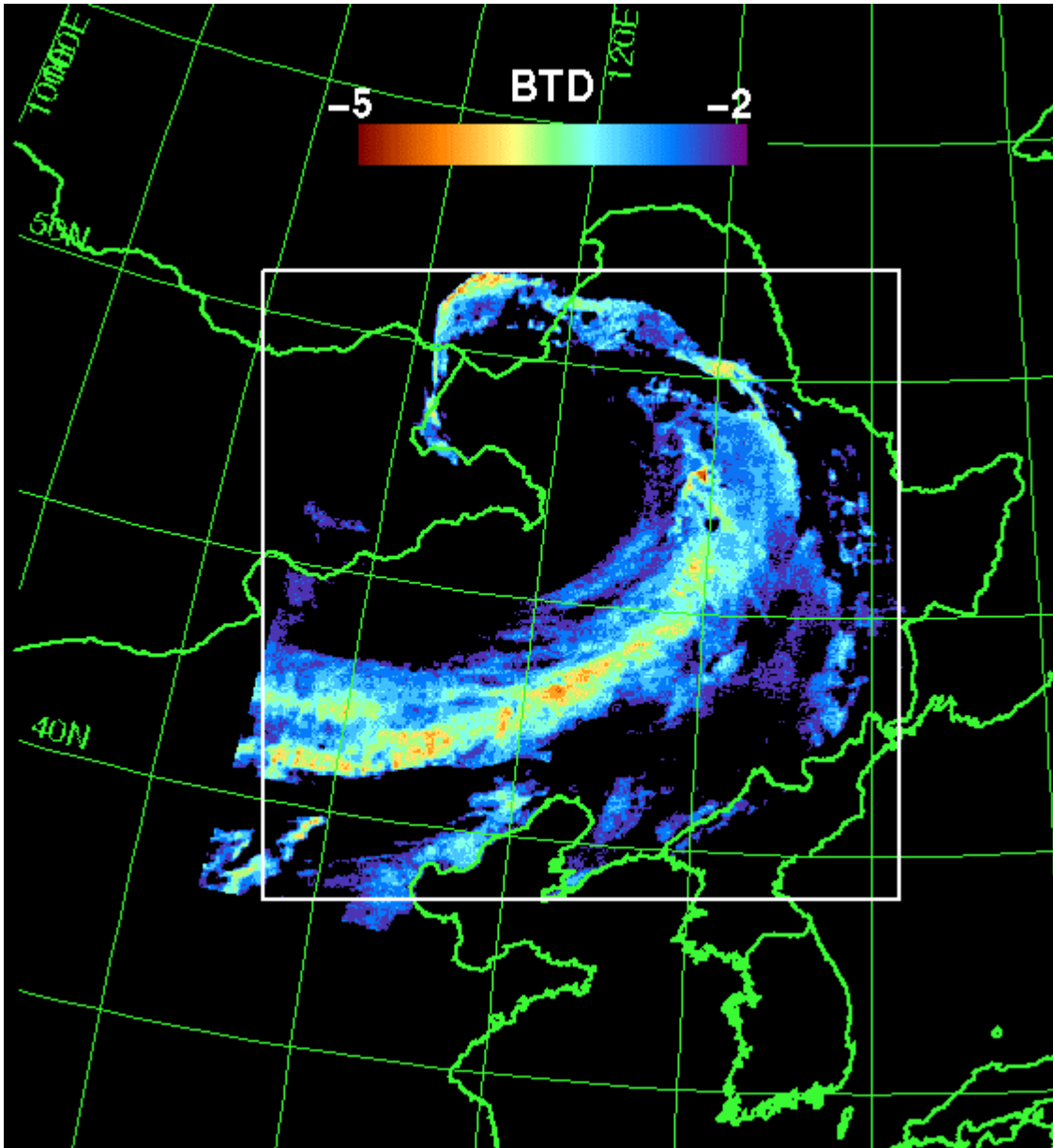


Figure 2 (a)

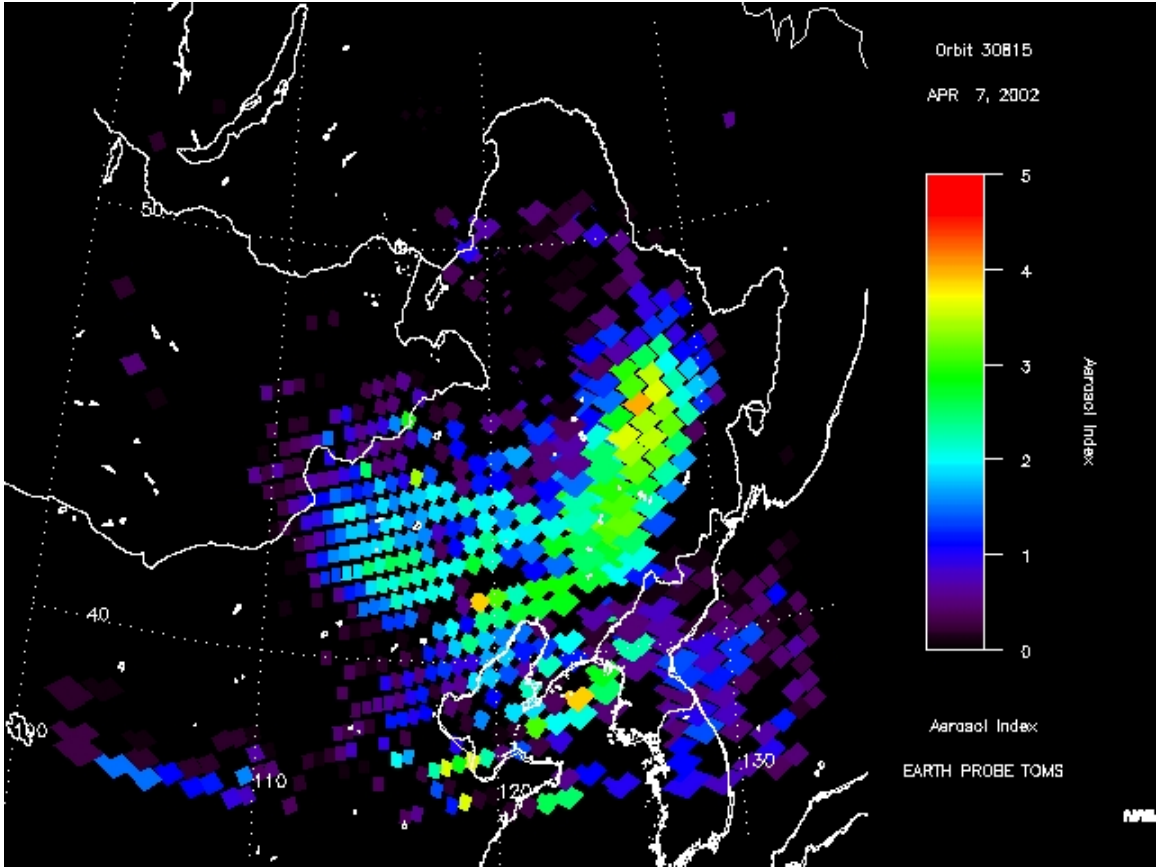


Figure 2 (b)

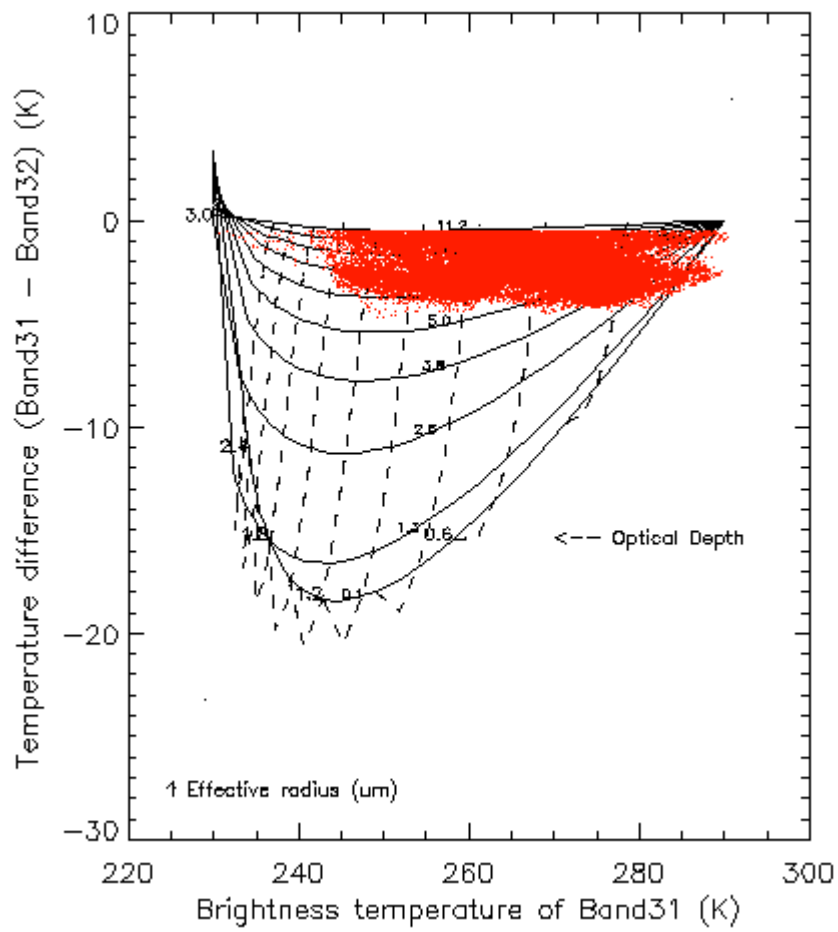


Figure 3